APPLICATION OF NEW PROCEDURES TO RE-ASSESS RESERVOIR CAPACITY

Texas Water Development Board

Texas Water Development Board

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Prepared for:

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

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Executive Summary

The Hydrographic Survey Program of the Texas Water Development Board (TWDB) has been conducting volumetric surveys since 1992 and sedimentation surveys since 2003. As of September 2016, the TWDB has completed 174 hydrographic surveys on 110 unique reservoirs. This includes 103 of the 188 major water supply reservoirs listed in the 2017 State Water Plan and 88 of the 114 reservoirs reported in the TWDB's monthly Water Conditions Report. These 114 reservoirs represent 96 percent of the total conservation storage capacity of the major water supply reservoirs in Texas. By definition, a major reservoir has a conservation storage capacity of 5,000 acre-feet or greater.

Reservoirs lose capacity over time due to sedimentation. With statewide water demand projected to increase 17 percent by 2070, current estimates of reservoir capacity and rates of sedimentation are essential for statewide water planning. One method to determine loss of capacity and to calculate sedimentation rates is to compare past survey volume estimates with more recent survey estimates. However, this method relies on the use of consistent processes for estimating capacity and sedimentation between distinct survey efforts. Evaluations of the TWDB survey methodology and equipment used from 1992 until 2006 suggest that the TWDB surveys completed during this period may contain inherent error resulting from the Delaunay method of triangulation used in triangulated irregular network model creation. Beginning in 2006, the TWDB began developing methods to better interpolate data between survey transects to improve model accuracy and reduce the error in volumetric and sedimentation estimates.

This report details the methodology used to re-assess reservoir surveys conducted by the TWDB prior to the development and implementation of the interpolation methods known as Self-Similar Interpolation and Anisotropic Elliptical Inverse Distance Weighted Interpolation. A total of 88 surveys on 76 unique reservoirs were re-evaluated and the volume estimates re-calculated. Resulting volumes ranged from an increase of 11.2 percent to a decrease of 5.71 percent, with an average increase in individual reservoir volume estimates of 1.89 percent. It is important to note that while the reassessment methodology reduces error associated with interpreting the raw bathymetric data, water levels during the surveys, patterns of data collection, and availability of historical maps and aerial photography for insight into pre-impoundment topography also introduce sources of error in the overall estimate of reservoir volume.

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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. Texas Water Code section 15.804 authorizes the TWDB to perform surveys to determine reservoir storage capacity, sedimentation levels, rates of sedimentation, and projected water supply availability.

The TWDB has been conducting volumetric surveys since 1992 and sedimentation surveys since 2003. As of September 2016, the TWDB has completed 174 hydrographic surveys on 110 unique reservoirs. This includes 103 of the 188 major water supply reservoirs listed in the 2017 State Water Plan and 88 of the 114 reservoirs reported in the TWDB's monthly Water Conditions Report. These 114 reservoirs represent 96 percent of the total conservation storage capacity of the major water supply reservoirs in Texas. By definition, a major reservoir has a conservation storage capacity of 5,000 acre-feet or greater.

Reservoirs lose capacity over time due to sedimentation. With population increasing and statewide water demand expected to increase 17 percent by 2070 (Texas Water Development Board, 2016), current estimates of reservoir capacity and rates of sedimentation are essential for statewide water planning. One method for determining loss of capacity and for calculating sedimentation rates is to compare past volume estimates with more recent estimates. Studies of the TWDB survey methodology and equipment used from 1992 until 2006 suggest that the TWDB surveys conducted during this period may contain inherent error resulting from the Delaunay method of triangulation used in triangulated irregular network (TIN) model creation (Payne and Holley, 1997; Texas Water Development Board, 2010). Beginning in 2006, the TWDB began developing various data interpolation methods to address these errors, including the removal of artificial artifacts in the reservoir models that created intermittent representations of submerged stream channel connectivity or artificially-curved contour lines extending into the reservoir where reservoir walls are steep or the reservoir is relatively narrow. Together, these artifacts reduced the accuracy of the estimates generated by the resulting volumetric and sediment TIN models. The interpolation methods are known as Self-Similar Interpolation and Anisotropic Elliptical Inverse Distance Weighted Interpolation. Self-Similar Interpolation uses linear interpolation to increase the density of points input into the TIN model and directs the TIN interpolation to better represent the reservoir topography (Furnans, 2006). Anisotropic Elliptical Inverse Distance Weighted Interpolation applies an inverse-distance weighted algorithm to user defined parameters to add a high resolution, uniform grid of interpolated bathymetric elevation points throughout a majority of the reservoir (McEwen and others, 2011a). These data interpolation methods improve model accuracy and reduce error in capacity loss and sedimentation rate estimates (Texas Water Development Board, 2009).

In December 2009, the TWDB entered into agreement with the U.S. Army Corps of Engineers, Fort Worth District, to re-assess older hydrographic surveys by applying Self-Similar Interpolation and Anisotropic Elliptical Inverse Distance Weighted Interpolation to the survey data. A total of 88 surveys on 76 unique reservoirs were identified as priority reservoirs to re-assess based on the criteria that the original data was available and no dredging of the reservoir had occurred since the TWDB survey. A list of the re-evaluated surveys is included in Appendix A.

The hydrographic surveying process

The TWDB survey data collection and processing procedures have changed over time as technology has advanced. New methods have been developed as more information, such as aerial photography and Light Detection and Ranging (LiDAR) data, becomes available for inclusion in the TWDB's hydrographic survey assessments.

Datum

The vertical datum of each reservoir is determined by the available gage datum. The United States Geological Survey (USGS) maintains gages on many reservoirs in Texas and reports in both the National Geodetic Vertical Datum 1929 (NGVD29) and the North American Vertical Datum 1988 (NAVD88) (U.S. Geological Survey, 2016). The U.S. Army Corps of Engineers (USACE), Tulsa District, maintains gages on many reservoirs in its jurisdiction which includes north Texas (U.S. Army Corps of Engineers, 2016). These gages are reported in feet above mean sea level or NGVD29. For reservoirs that have a USGS or USACE gage, volume and area calculations are referenced to water levels provided by these gages. For reservoirs that do not have a USGS or USACE gage, volume and area calculations are referenced to water levels provided by the clients. Specifics regarding survey datum and source of water surface elevations can be found in each respective original survey report. Each re-calculated elevation-capacity and elevation-area table and curve in Appendix C indicates the associated vertical datum. The horizontal datum for all surveys is North American Datum 1983 (NAD83), and the horizontal coordinate system is State Plane Texas (feet). The specific zone, North, North Central, Central, South Central, or South, varies by reservoir depending on its location.

Data collection

The TWDB collects bathymetric survey data with a depth sounder integrated with differential global positioning system equipment. Data collection occurs while navigating along pre-planned survey lines oriented perpendicular to the assumed location of the original river channels and spaced approximately 500 feet apart. The depth sounder is calibrated daily using a velocity profiler to measure the speed of sound in the water column and a weighted tape or stadia rod to verify depth. The TWDB has used several depth sounders over the years including an Innerspace Technology Depth Sounder, an Odom Hydrotrac single frequency depth sounder, a Knudsen Engineering Ltd. single-frequency depth sounder, and a Specialty Devices, Inc. single-beam, multi-frequency (208 kHz, 50 kHz, and 24 kHz) sub-bottom profiling depth sounder. The original survey report for each reservoir lists the specific equipment used in that survey.

Model boundaries

Boundary sources include scanned USGS 7.5 minute quadrangle maps (known as digital raster graphics), hypsography files (the vector format of USGS 7.5 minute quadrangle map contours), and aerial photographs, also known as digital orthophoto quarter-quadrangle images (DOQQs), taken when the reservoir is full or very close to it. All are available from the Texas Natural Resources Information System (Texas Natural Resources Information System, 2016). Boundaries are digitized from the best source available using Environmental Systems Research Institute (ESRI) ArcGIS software. Surveys conducted during 1992 and 1993 may have been processed in MicroStation, a computer aided design and drafting software by Bentley Systems, Incorporated.

The USGS quadrangle maps have a stated accuracy of ± ½ the contour interval (U.S. Geological Survey, 1999). According to the associated metadata, the 1995–1996 DOQQs have a resolution of 1 meter, with a horizontal positional accuracy that meets the National Map Accuracy Standard for 1:12,000-scale products. According to metadata associated with the 2004 DOQQs, the photographs have a resolution or ground sample distance of 1.0 meters and a horizontal accuracy within ±5 meters of reference DOQQs from the National Digital Ortho Program (U.S. Department of Agriculture, 2013).

Spatial interpolation of reservoir bathymetry

Triangulated irregular network model

Following completion of data collection, the raw bathymetric data files collected by the TWDB are edited to remove data anomalies. Hypack software is used to edit single frequency depth sounder data. Multi-frequency depth sounder data is edited in DepthPic©, software developed by Specialty Devices, Inc. The water surface elevation at the time of each sounding are used to convert sounding depths to corresponding bathymetric elevations, and the sounding coordinates and elevations are exported to a single X, Y, Z data file. To create a model of the reservoir bathymetry, ESRI Geographic Information Systems mapping software is used to create a triangulated irregular network (TIN) model. Prior to 2005, the TIN model was created using ESRI Arc/Info Workstation's TIN software module. Since 2005, all of the TWDB's hydrographic assessments have used the 3D Analyst

Extension of ArcGIS to create TIN models. ESRI's TIN model is based on an algorithm using Delaunay's criteria for triangulation to create a grid composed of triangles from non-uniformly spaced points, including the boundary vertices (Environmental Systems Research Institute, 1995).

Spatial interpolation methods

The Delaunay method used in ESRI's TIN model creation is unable to suitably interpolate bathymetries between the data collection 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 TIN model. These artifacts include intermittent representations of submerged stream channel connectivity and artificially-curved contour lines extending into the reservoir where the reservoir walls are steep and the reservoir is relatively narrow. Additionally, in areas inaccessible by boat such as small coves, marsh-like areas, or areas too shallow for the boat or depth sounders to work properly, the TIN model generates anomalous flat triangles. A flat triangle is defined as a triangle where all three vertices are equal in elevation, generally the elevation of the reservoir boundary. These artifacts and flat triangles lead to anomalous calculations of surface area and volume.

To improve the accuracy of bathymetric representation between survey lines, the TWDB developed various anisotropic spatial interpolation techniques known as the Self-Similar Interpolation method and the Anisotropic Elliptical Inverse Distance Weighted Interpolation method. Both techniques effectively increase the density of points input into the TIN model and direct the TIN interpolation to better represent the reservoir topography (Furnans, 2006). The interpolation techniques operate on the basic assumption that the reservoir profile in the vicinity of a particular location has upstream and downstream similarity. The sinuosity and directionality of submerged stream channels can be determined by directly examining the survey data, or more robustly by examining scanned USGS 7.5 minute quadrangle maps (known as digital raster graphics), hypsography files (the vector format of USGS 7.5 minute quadrangle map contours), or scanned historical USGS 15 minute quadrangle maps, when available, and aerial photography, if flown when reservoir levels were low enough to reveal channels, roads, and other topographic features.

The Self-Similar Interpolation method linearly interpolates between user-defined cross-sections or series of survey data points. This method also allows the user to extend the interpolation to the reservoir boundary, even though the survey data does not reach the boundary. For areas that are not accessible by boat, linear interpolation lines are digitized in ArcGIS to estimate bathymetry in those areas. The elevation at the beginning of the line is user defined, and points are linearly interpolated between the starting point and the reservoir boundary along the line as well as perpendicularly between each point on the line and the boundary.

The Anisotropic Elliptical Inverse Distance Weighted Interpolation method uses an inverse distance-weighted interpolation algorithm. Using the survey data, polygons are created in ArcGIS to partition the reservoir into segments with centerlines defining directionality of interpolation within each segment. For surveys with similar spatial coverage, these interpolation definition files are in principle independent of the survey data and can be applied to past and future survey data of the same reservoir. In practice, minor revisions of the interpolation definition files may be needed to account for differences in spatial coverage and boundary conditions between surveys. Using the interpolation definition files and survey data, a high resolution, uniform grid of interpolated bathymetric elevation points are generated throughout a majority of the reservoir (McEwen and others, 2011a). For areas that were not accessible by boat, linear interpolation lines are digitized linking the survey points file to the reservoir boundary file (McEwen and others, 2011b).

The Self-Similar Interpolation method was used until 2010, when the TWDB developed and began using the Anisotropic Elliptical Inverse Distance Weighted Interpolation method. The main reason for this change was ease of applying the Anisotropic Elliptical Inverse Distance Weighted Interpolation method and shorter analysis times.

Discussion of spatial interpolation

While every effort is made to model the reservoirs accurately, water levels during the surveys, patterns of data collection, and availability of historical maps and aerial photography for insight into pre-impoundment topography, may introduce error into the interpolation results and the volume estimates. Multiple techniques have been used to reduce anomalous data as assessment procedures have changed over time. For many reservoirs, the survey point files and boundary files were modified for a more accurate re-analysis. For some reservoirs that were analyzed using the Self-Similar Interpolation method, the raw data was re-edited using customized MATLAB processing scripts and the HydroEdit software package. HydroEdit applies a median filter to the raw survey data and removes individual data anomalies or points with incorrect GPS coordinates. HydroEdit also uses the water surface elevations at the times of each sounding to convert sounding depths to corresponding bathymetric elevations. The MATLAB processing scripts then are used to visually inspect each of the filtered cross-sections to identify and rectify any series of data anomalies that were not edited using the HydroEdit filters. In other survey data sets, data that had significantly different elevations from neighboring data points was simply deleted. For some data sets, data collected while the boat was traversing the reservoir at high speeds also were deleted if it did not agree with data collected along pre-planned survey lines. Boundaries were modified in cases where islands were missing or no evidence was found that an island should be present, or where modeling of the reservoir would not make sense without the presence of features such as marina jetties, for example. Other boundary edits included removing the outtake channels from power plant reservoirs because they are separated from the main reservoir by a weir or using a more recent survey boundary if the original file was corrupted. The new volumetric TIN models were converted to raster format using a cell size of one foot by one foot for reservoirs less than 5,000 acres in size, and a cell size of two feet by two feet for larger reservoirs. The TIN model for Sam Rayburn Reservoir, over 100,000 acres in size, was converted using a cell size of five feet by five feet. One foot contours were generated from the raster.

Area, volume, and contour calculation

Using ArcInfo software and reservoir TIN models, volumes and areas were computed for each reservoir at 0.1 foot intervals. While linear interpolation was used to estimate the topography in areas that were inaccessible by boat or too shallow for the instruments to work properly, development of anomalous flat triangles (triangles whose vertices all have the same elevation) in the TIN model are unavoidable. The flat triangles in turn lead to anomalous calculations of surface area and volume at the boundary elevations. To eliminate the effects of the flat triangles on area and volume calculations, represented in the area curve as a flat line at boundary elevations, areas were linearly interpolated between the computed values to smooth the curve, and corresponding volumes were calculated based on the corrected areas using the formula:

$$Capacity_1 = Capacity_0 + \left(\frac{Area_0 + Area_1}{2}\right) \times (Elevation_1 - Elevation_0)$$

Where:

$Area_0$ = *area corresponding to* $Elevation_0$
$Area_1$ = *area corresponding to* $Elevation_1$
$Capacity_0$ = *capacity corresponding to* $Elevation_0$
$Capacity_1$ = *capacity corresponding to* $Elevation_1$

On four of the re-assessed reservoirs, Lake Stamford, Lake Meredith, Sam Rayburn Reservoir, and Gibbons Creek Reservoir, linear interpolation was not appropriate to smooth the area curve. The area curves for these reservoirs resembled stair steps as a result of the contour data used to model the reservoirs where bathymetric survey data could not be collected due to low water surface elevations at the time of the surveys. In these cases, a cubic spline interpolation was applied. Capacities were calculated using the formula above.

Results

The results of each re-calculation compared to the original published area and capacity estimates, including whether the point files and boundaries were modified, are presented in Appendix A. The re-calculated elevation-capacity and elevation-area tables, capacity curves, and area curves are presented in Appendix C. Results of re-assessed studies previously published in a more recent survey report are identified in Appendix A. It should be noted that the re-calculated estimates presented in Appendix A and Appendix C may differ because the area curves have since been adjusted to account for flat triangles.

Additionally, because interpolating the area curve and calculating the capacities from the corrected areas to eliminate the effects of flat triangles has only been standard practice since 2013, the TWDB applied this process to 27 recent surveys that were not included in the scope of the re-assess project. The resulting area and capacity estimates are provided in Appendix B. Many of these recent surveys were also sedimentation surveys, therefore, the pre-impoundment area and capacity were also re-calculated using this same methodology to allow average sedimentation rates to be calculated. The resulting pre-impoundment estimates are provided in Appendix B. The re-calculated elevation-capacity and elevation-area tables, capacity curves, and area curves for the re-calculated volumetric estimates are included in Appendix C.

Because two different interpolation methods were used it is useful to understand the differences between these methods and how they affect the area and capacity calculations. Figure 1 illustrates typical results from application of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation methods as they were applied to the 2008 survey of Aquilla Lake. Table 1 compares the resulting elevation-area-capacity tables of each interpolation method. Figures 2 and 3 compare the elevation-capacity curves and elevation-area curves, respectively, of each interpolation method for the 2008 survey of Aquilla Lake. A similar comparison is made for the 2002 survey of Granger Lake (Table 2, Figures 4 and 5) and the 2010 survey of Wright Patman Lake (Table 3, Figures 6 and 7). While the percent difference between the areas and capacities seems large at the lower elevations, these capacities represent a small fraction of the total reservoir volume at conservation pool elevation. Overall, differences between the Self-Similar and the Anisotropic Elliptical Inverse Distance Weighted interpolation methods are minimal. The total reservoir capacity of Aquilla Lake at elevation 542.0 feet differs by 1.04 percent, Granger Lake at elevation 504.2 feet differs by 0.68 percent, and Wright Patman Lake differs by 0.05 percent at elevation 226.0 feet.

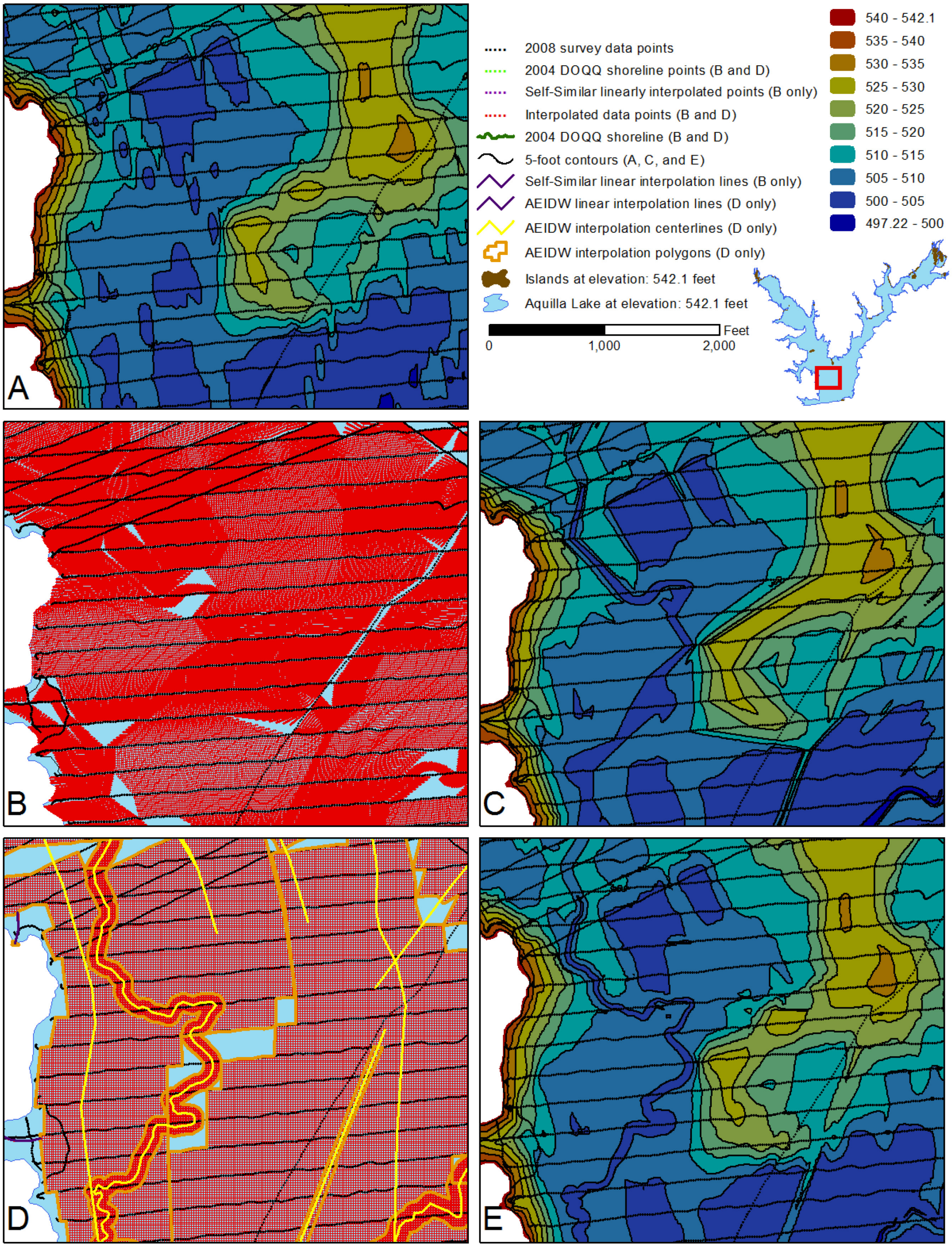

Figure 1. Application of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation methods as applied to the 2008 survey of Aquilla Lake; A) bathymetric contours without interpolated points, B) sounding points *(black)* and Self-Similar Interpolation points *(red)*, C) bathymetric contours with the Self-Similar Interpolation points, D) sounding points *(black)* and Anisotropic Elliptical Inverse Distance Weighted Interpolation points *(red)*, E) bathymetric contours with the Anisotropic Elliptical Inverse Distance Weighted Interpolation points.

Table 1. Comparison of Self-Similar (SSI) and Anisotropic Elliptical Inverse Distance Weighted (AEIDW) interpolation methods as applied to Aquilla Lake 2008 survey.

Elevation (feet NGVD29)	SSI Area (acres)	AEDIW Area (acres)	Percent difference (SSI-AEIDW/SSI*100)(%)	SSI Capacity (acre-feet)	AEIDW Capacity (acre-feet)	Percent difference (SSI-AEIDW/SSI*100)(%)
497	0.00	0.00	0.00	0.00	0.00	0.00
498	0.49	0.05	88.72	0.10	0.01	89.25
499	3.89	2.20	43.35	2.13	0.92	56.72
500	8.62	5.84	32.27	8.39	4.81	42.67
501	18.30	15.21	16.86	20.28	13.87	31.58
502	42.85	38.41	10.38	51.04	40.61	20.43
503	72.53	67.71	6.65	106.21	91.37	13.98
504	112.60	108.26	3.85	198.12	178.98	9.66
505	157.20	152.81	2.79	334.27	310.20	7.20
506	204.76	201.66	1.51	515.03	487.23	5.40
507	252.41	252.28	0.05	744.47	714.82	3.98
508	303.27	301.93	0.44	1,021.43	991.31	2.95
509	356.48	356.32	0.04	1,351.19	1,320.03	2.31
510	411.98	412.60	-0.15	1,734.39	1,703.68	1.77
511	479.73	478.79	0.20	2,179.52	2,149.18	1.39
512	543.60	539.82	0.69	2,690.64	2,658.32	1.20
513	619.16	618.87	0.05	3,269.24	3,235.08	1.04
514	711.68	712.65	-0.14	3,936.06	3,903.07	0.84
515	778.75	779.78	-0.13	4,682.27	4,650.43	0.68
516	843.69	844.59	-0.11	5,493.92	5,462.32	0.58
517	912.10	913.78	-0.18	6,369.90	6,340.14	0.47
518	992.70	995.72	-0.30	7,319.47	7,291.97	0.38
519	1,085.70	1,085.50	0.02	8,360.27	8,333.83	0.32
520	1,166.33	1,167.42	-0.09	9,487.11	9,461.31	0.27
521	1,236.10	1,234.10	0.16	10,688.78	10,662.36	0.25
522	1,307.50	1,305.39	0.16	11,960.95	11,932.70	0.24
523	1,379.27	1,378.15	0.08	13,303.83	13,274.31	0.22
524	1,450.84	1,447.65	0.22	14,717.44	14,686.21	0.21
525	1,553.41	1,551.18	0.14	16,217.59	16,184.01	0.21
526	1,660.74	1,662.36	-0.10	17,824.72	17,788.48	0.20
527	1,755.38	1,754.50	0.05	19,533.04	19,497.47	0.18
528	1,866.03	1,864.99	0.06	21,342.17	21,305.44	0.17
529	1,982.28	1,978.92	0.17	23,268.57	23,230.43	0.16
530	2,088.70	2,083.90	0.23	25,304.85	25,261.62	0.17
531	2,191.12	2,193.29	-0.10	27,443.83	27,398.75	0.16
532	2,318.85	2,318.83	0.00	29,697.91	29,653.56	0.15
533	2,460.14	2,462.88	-0.11	32,084.75	32,042.09	0.13
534	2,595.39	2,597.07	-0.07	34,614.66	34,572.19	0.12
535	2,733.34	2,741.69	-0.31	37,276.53	37,240.62	0.10
536	2,891.73	2,903.94	-0.42	40,088.67	40,062.25	0.07
537	3,016.84	3,035.39	-0.61	43,045.02	43,034.52	0.02
538	3,104.90	3,161.31	-1.82	46,109.32	46,132.31	-0.05
539	3,288.19	3,345.09	-1.73	49,321.32	49,379.09	-0.12
540	3,388.29	3,544.90	-4.62	52,659.31	52,825.96	-0.32
541	3,493.36	3,718.74	-6.45	56,099.53	56,459.39	-0.64
542	3,612.89	3,905.09	-8.09	59,650.16	60,273.47	-1.04

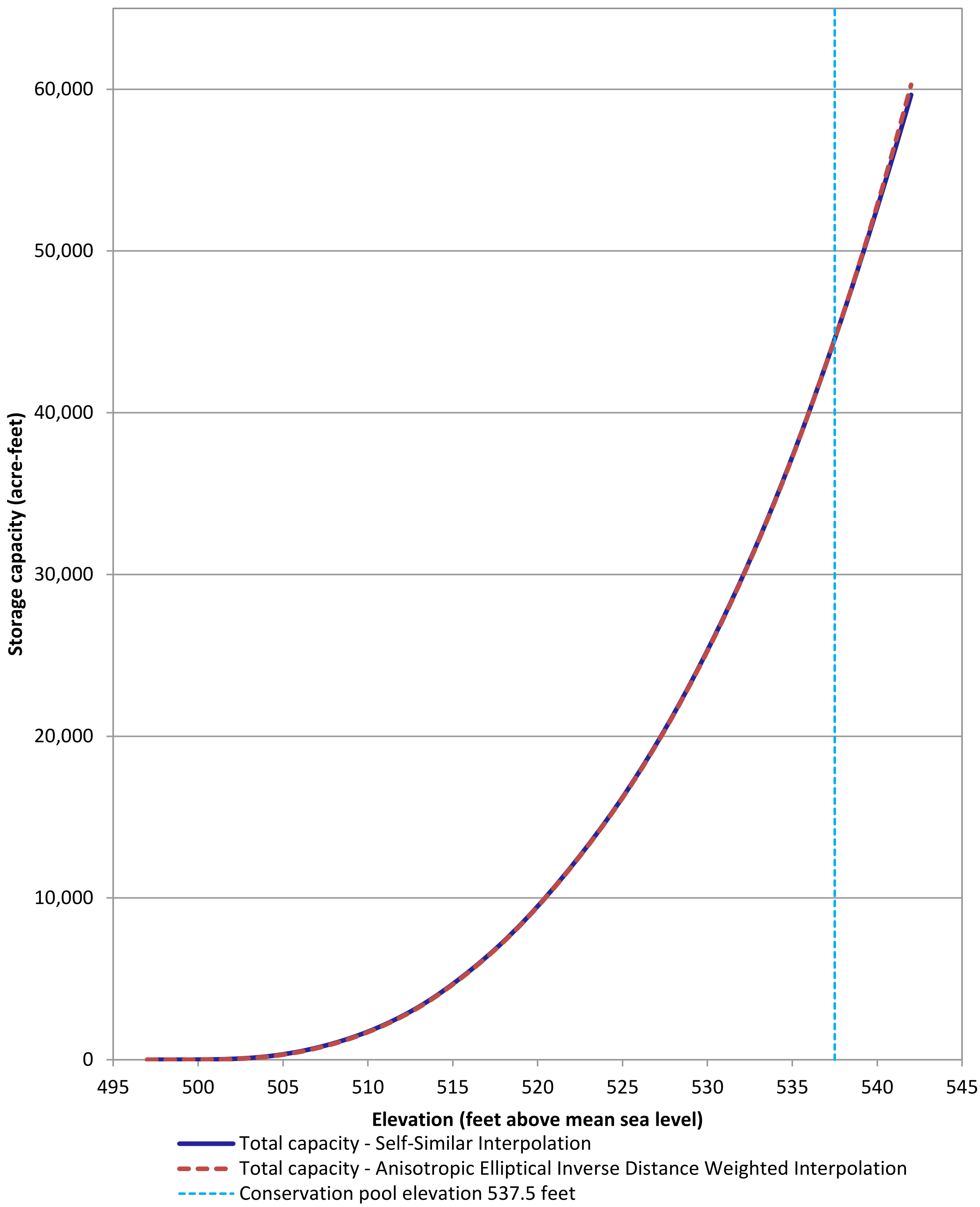

Figure 2. Comparison of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation capacity curves for Aquilla Lake 2008 survey.

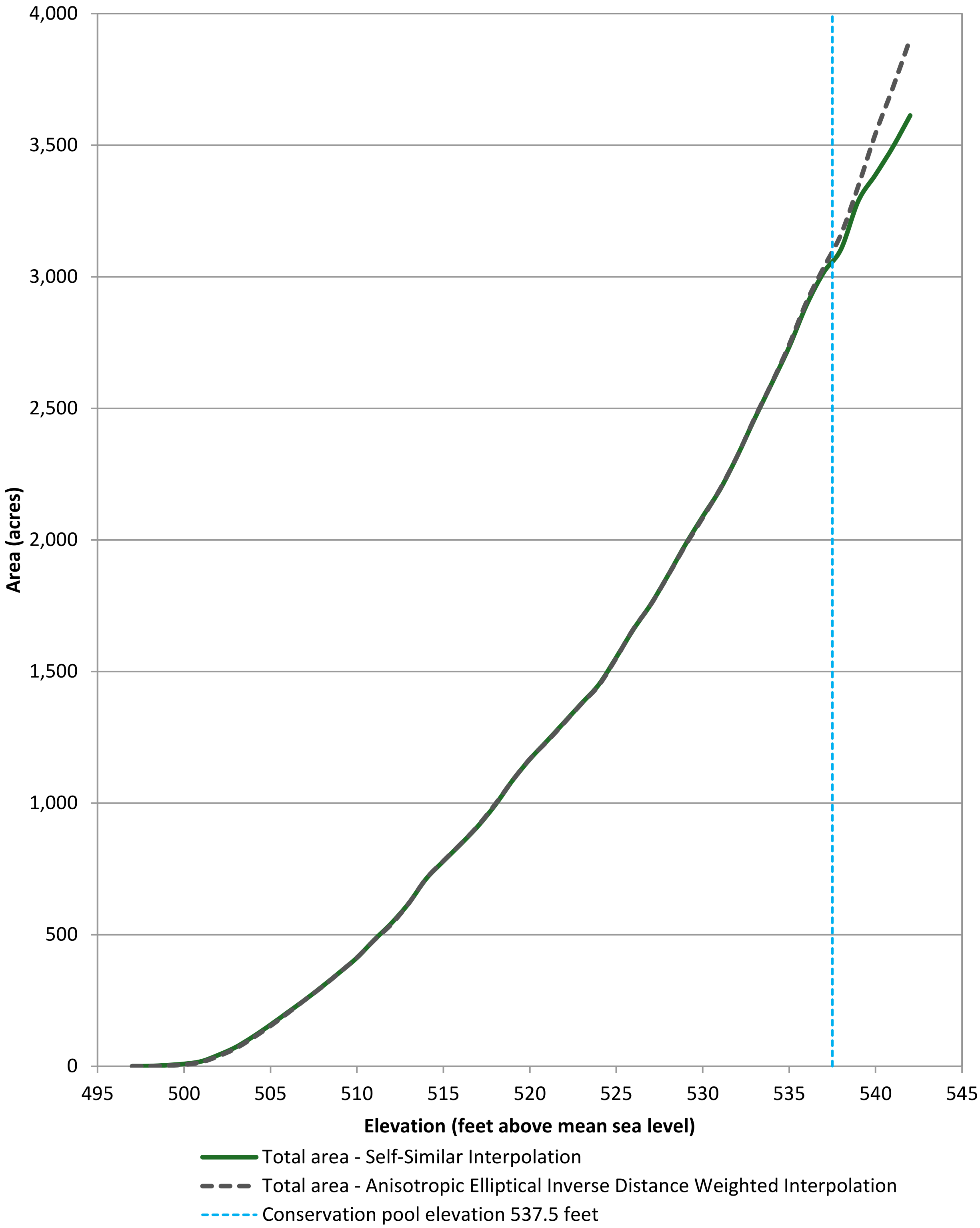

Figure 3. Comparison of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation area curves for Aquilla Lake 2008 survey.

Table 2. Comparison of Self-Similar (SSI) and Anisotropic Elliptical Inverse Distance Weighted (AEIDW) interpolation methods as applied to Granger Lake 2002 survey.

Elevation (feet NGVD29)	SSI Area (acres)	AEDIW Area** (acres)	Percent difference (SSI-AEIDW/SSI*100)(%)	SSI Capacity (acre-feet)	AEIDW Capacity** (acre-feet)	Percent difference (SSI-AEIDW/SSI*100)(%)
465	0.01	0.31	0.00	0.00	0.00	0.00
466	0.56	3.99	-608.19	0.21	2.09	-899.23
467	3.09	7.97	-157.59	1.69	7.46	-341.66
468	25.74	30.39	-18.07	16.81	26.15	-55.55
469	45.91	59.51	-29.61	52.04	69.41	-33.36
470	70.53	83.60	-18.53	109.89	140.57	-27.92
471	102.10	114.41	-12.06	196.40	238.89	-21.63
472	133.39	145.40	-9.01	313.15	369.66	-18.04
473	164.35	167.99	-2.21	463.03	526.80	-13.77
474	190.45	195.31	-2.55	640.02	706.87	-10.45
475	232.58	238.35	-2.48	851.73	925.00	-8.60
476	279.84	280.15	-0.11	1,106.25	1,182.15	-6.86
477	350.04	349.45	0.17	1,417.96	1,493.79	-5.35
478	436.19	429.52	1.53	1,811.45	1,882.78	-3.94
479	531.36	533.53	-0.41	2,294.29	2,363.64	-3.02
480	643.47	646.44	-0.46	2,882.85	2,952.56	-2.42
481	740.15	751.49	-1.53	3,576.82	3,652.95	-2.13
482	824.75	832.10	-0.89	4,362.19	4,444.86	-1.90
483	898.58	915.24	-1.85	5,224.73	5,319.46	-1.81
484	983.10	1,001.35	-1.86	6,165.12	6,276.85	-1.81
485	1,084.22	1,102.70	-1.70	7,196.87	7,328.13	-1.82
486	1,201.53	1,210.65	-0.76	8,340.15	8,485.17	-1.74
487	1,313.64	1,325.02	-0.87	9,599.24	9,752.81	-1.60
488	1,420.31	1,428.71	-0.59	10,964.27	11,129.38	-1.51
489	1,536.88	1,542.78	-0.38	12,443.06	12,614.70	-1.38
490	1,640.97	1,656.01	-0.92	14,032.08	14,213.74	-1.29
491	1,763.85	1,780.31	-0.93	15,731.62	15,931.82	-1.27
492	1,902.55	1,913.90	-0.60	17,565.82	17,777.70	-1.21
493	2,047.41	2,060.76	-0.65	19,539.68	19,764.35	-1.15
494	2,199.82	2,221.30	-0.98	21,662.19	21,903.54	-1.11
495	2,359.11	2,382.74	-1.00	23,939.24	24,204.41	-1.11
496	2,540.37	2,560.78	-0.80	26,386.64	26,672.53	-1.08
497	2,744.70	2,753.48	-0.32	29,030.41	29,330.07	-1.03
498	2,918.79	2,923.39	-0.16	31,865.77	32,169.24	-0.95
499	3,089.98	3,087.59	0.08	34,866.64	35,172.72	-0.88
500	3,286.19	3,285.31	0.03	38,051.66	38,355.11	-0.80
501	3,496.67	3,488.75	0.23	41,442.69	41,739.37	-0.72
502	3,706.31	3,721.67	-0.41	45,047.34	45,353.12	-0.68
503	3,941.59	3,959.06	-0.44	48,876.87	49,197.08	-0.66
504	4,122.60	4,172.54	-1.21	52,905.37	53,262.88	-0.68
504.2	4,207.06	4,215.24	-0.19	53,734.62	54,101.66	-0.68

**Note: Areas between 503.0 and 504.2 feet linearly interpolated and capacities above elevation 503.0 feet calculated from interpolated areas

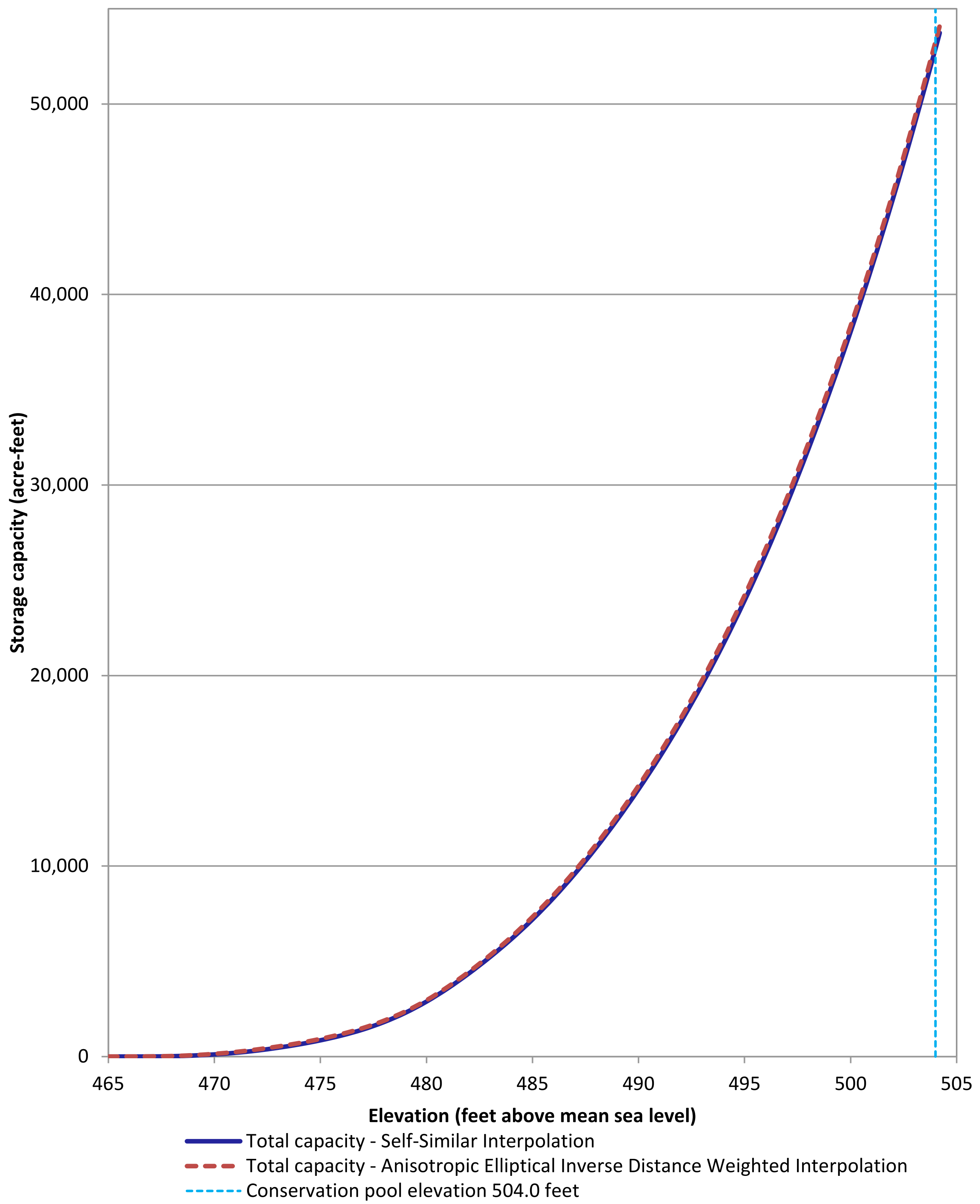

Figure 4. Comparison of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation capacity curves for Granger Lake 2002 survey.

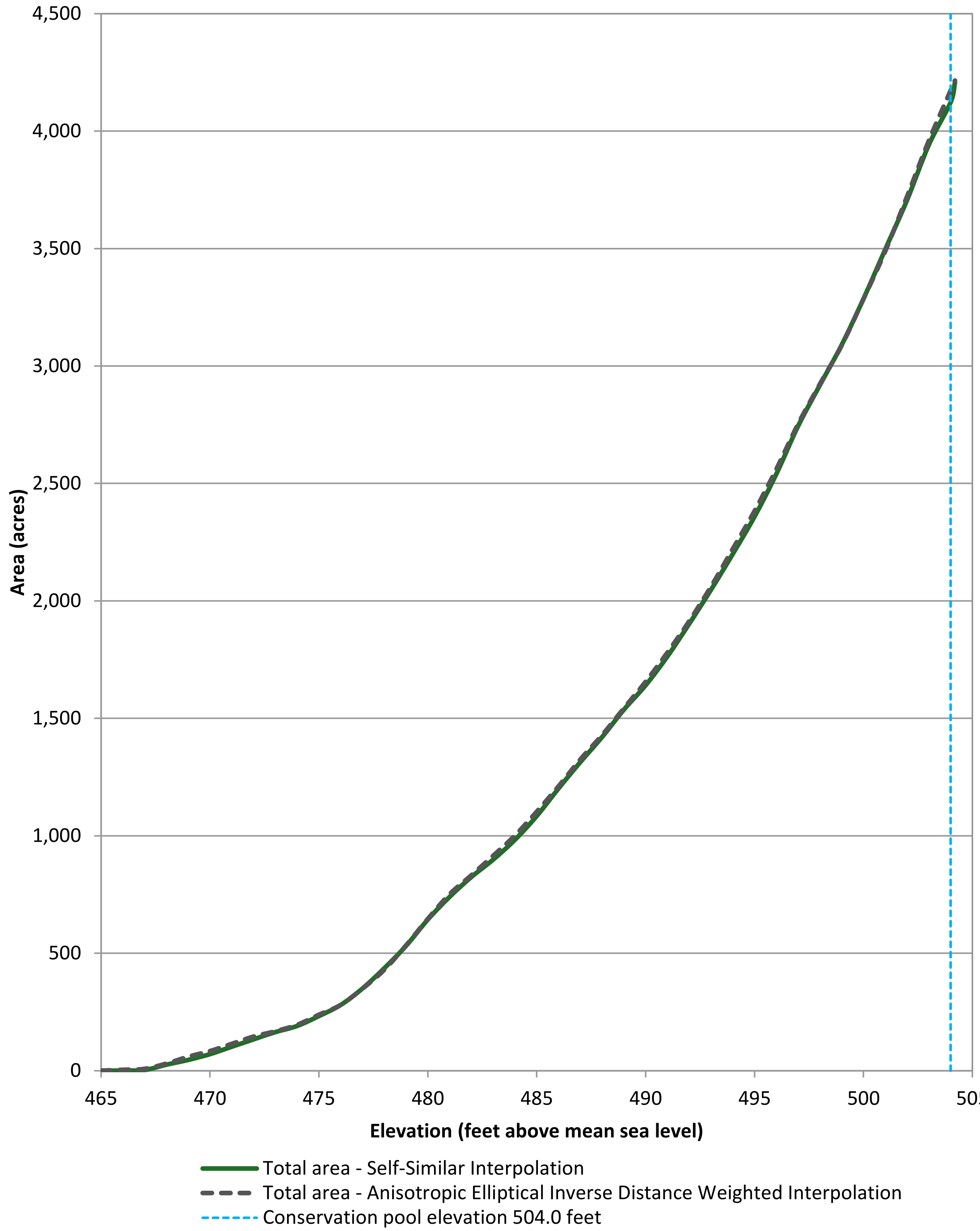

Figure 5. Comparison of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation area curves for Granger Lake 2002 survey.

Table 3. Comparison of Self-Similar (SSI) and Anisotropic Elliptical Inverse Distance Weighted (AEIDW) interpolation methods as applied to Wright Patman Lake 2010 survey.

Elevation (feet NGVD29)	SSI Area** (acres)	AEDIW Area** (acres)	Percent difference (SSI-AEIDW/SSI*100)(%)	SSI Capacity** (acre-feet)	AEIDW Capacity** (acre-feet)	Percent difference (SSI-AEIDW/SSI*100)(%)
190	0.01	0.00	0.00	0.00	0.00	0.00
191	0.06	0.05	11.67	0.03	0.01	58.04
192	0.13	0.21	-67.16	0.12	0.14	-15.61
193	0.22	0.40	-78.36	0.29	0.44	-51.98
194	0.37	0.59	-56.81	0.59	0.94	-60.28
195	0.60	0.84	-40.17	1.06	1.65	-54.95
196	1.00	1.19	-19.51	1.85	2.63	-42.62
197	1.56	2.04	-30.75	3.11	4.13	-33.11
198	4.39	6.28	-42.92	5.66	7.79	-37.53
199	10.12	12.29	-21.48	12.80	17.00	-32.86
200	20.39	23.67	-16.04	27.34	34.24	-25.27
201	38.50	42.99	-11.67	56.17	66.96	-19.19
202	64.90	69.41	-6.95	107.16	122.51	-14.33
203	97.81	102.67	-4.97	188.68	208.03	-10.26
204	136.27	136.58	-0.23	304.98	327.69	-7.45
205	177.14	176.48	0.38	461.75	484.14	-4.85
206	219.02	216.55	1.13	659.09	679.60	-3.11
207	285.89	290.68	-1.68	906.25	928.43	-2.45
208	596.99	602.49	-0.92	1,296.05	1,324.08	-2.16
209	1,209.74	1,225.32	-1.29	2,192.28	2,230.67	-1.75
210	1,780.07	1,783.54	-0.19	3,705.14	3,749.26	-1.19
211	2,462.22	2,451.94	0.42	5,803.92	5,844.25	-0.69
212	3,562.45	3,510.12	1.47	8,775.43	8,788.54	-0.15
213	4,886.03	4,828.73	1.17	12,996.27	12,951.02	0.35
214	6,242.86	6,207.87	0.56	18,530.58	18,456.44	0.40
215	7,680.96	7,670.63	0.13	25,521.84	25,424.72	0.38
216	9,493.12	9,494.28	-0.01	34,078.79	33,973.95	0.31
217	11,185.12	11,252.68	-0.60	44,367.79	44,290.74	0.17
218	13,290.51	13,333.61	-0.32	56,551.05	56,549.91	0.00
219	15,396.86	15,411.14	-0.09	70,924.96	70,948.33	-0.03
220	17,239.56	17,239.92	0.00	87,300.03	87,336.32	-0.04
221	19,142.47	19,123.38	0.10	105,402.84	105,423.60	-0.02
222	21,231.35	21,179.63	0.24	125,610.82	125,593.80	0.01
223	22,792.97	22,740.33	0.23	147,682.04	147,608.94	0.05
224	23,923.75	23,875.70	0.20	171,068.98	170,938.22	0.08
225	24,705.12	24,698.71	0.03	195,398.34	195,244.09	0.08
226	25,741.73	25,938.00	-0.76	220,542.49	220,436.01	0.05

**Note: Areas between 225.5 and 226.3 feet linearly interpolated and capacities above elevation 225.5 feet calculated from interpolated areas

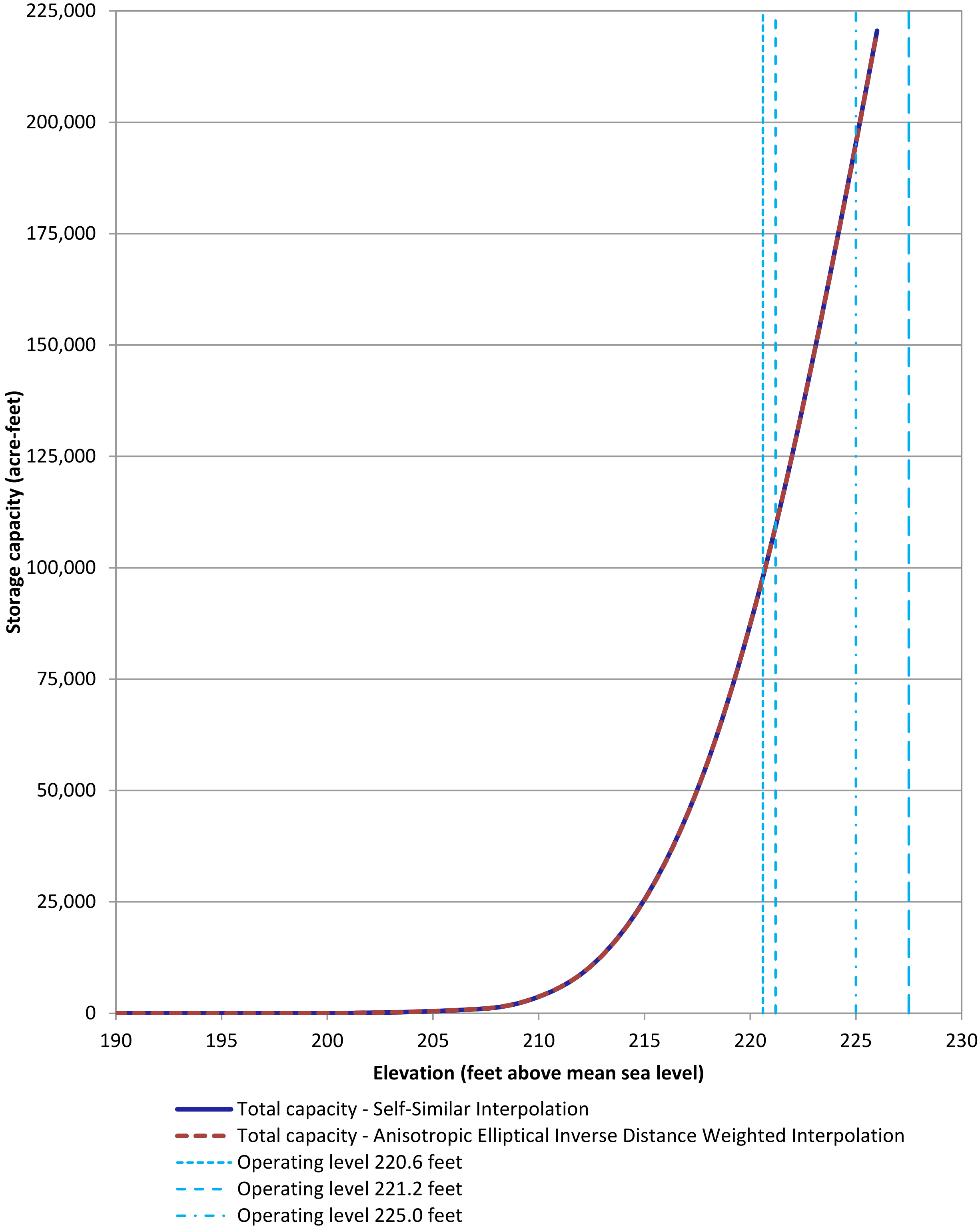

Figure 6. Comparison of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation capacity curves for Wright Patman Lake 2010 survey.

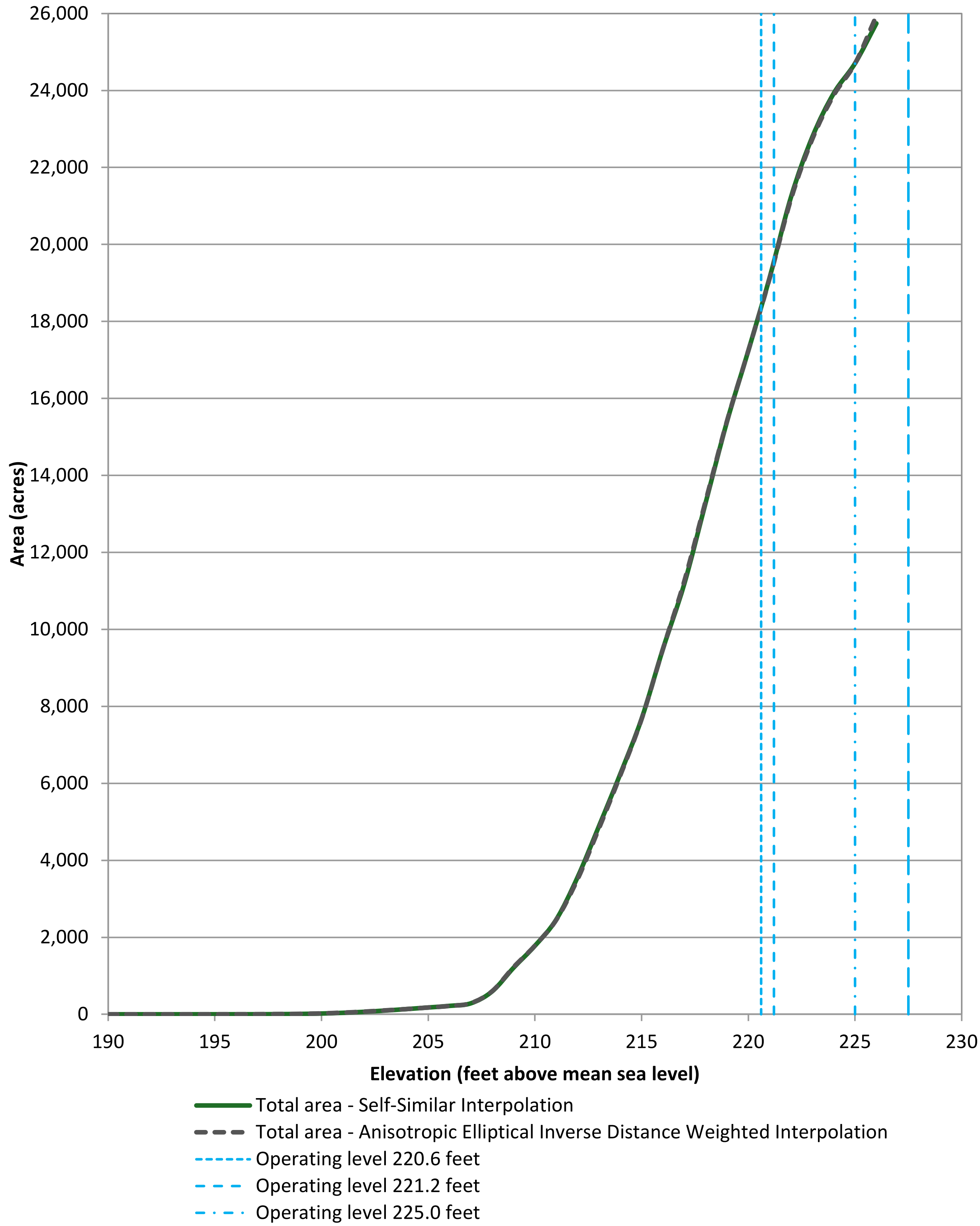

Figure 7. Comparison of Self-Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation area curves for Wright Patman Lake 2010 survey.

As evident in over 80 percent of the 88 re-assessments, application of spatial interpolation typically resulted in capacity estimate differences within 3 percent. Further review of reservoirs with capacity estimate differences greater than 3 percent suggests spatial interpolation becomes more influential on reservoir capacity as topography of the reservoir becomes increasingly variable. Survey data edits and boundary edits were also potential causes for atypical estimate differences. For example, Lake Austin (1999 survey), B.A. Steinhagen Lake (2003 survey), Lake Gladewater (2000 survey), and Wright Patman Lake showed volume differences of 11.20, 6.77, 7.32, and -5.71 percent, respectively.

Lake Austin is a narrow riverine reservoir with steep walls, a topography that is poorly represented by the TIN model. Spatial interpolation corrects artificially-curved contour lines created by the TIN model that extend into the reservoir where reservoir walls are steep. The increase in estimated capacity of 11.20 percent is likely due to better representation of the reservoir bathymetry in between survey lines as a result of spatial interpolation. B.A. Steinhagen Lake is overgrown with dense vegetation in the upper reaches making much of the reservoir inaccessible by boat and nearly impossible to accurately delineate in aerial photography. The increase in estimated capacity of 6.77 percent for B.A. Steinhagen Lake (2003 survey) is likely due to a combination of adding linear interpolation to the TIN model in areas inaccessible by boat and linear interpolation of the area curve to correct for extensive flat triangles. Lake Gladewater is also a narrow reservoir with a prominent submerged river channel. The increase in estimated capacity of 7.32 percent is likely a result of modeling a complete river channel throughout the reservoir and deleting anomalous data in the main basin of the reservoir near the dam. This anomalous data represented significant portions of six lines of survey data. Deletion of the data was supported by intersecting survey data and aerial photographs.

The Wright Patman Lake (1997 survey) estimate indicating a 5.71 percent reduction in capacity at operating level 220.6 feet can be fully or partially explained by changes made to the reservoir boundary. The boundary used in the re-calculation was digitized from aerial photographs and indicates the surface area of the reservoir is 6.53 percent smaller than originally estimated at operating level 220.6 feet.

Summary and Conclusions

Studies of the TWDB survey methodology and equipment used from 1992 until 2006 suggest that the TWDB surveys conducted during this period may contain inherent error resulting from the Delaunay method of triangulation used in TIN model creation (Payne and Holley, 1997; Texas Water Development Board, 2010). To address this source of error, the TWDB developed spatial interpolation tools to mitigate the errors associated with modeling the reservoir. Self-Similar Interpolation or Anisotropic Elliptical Inverse Distance Weighted Interpolation was applied to 88 TWDB reservoir surveys conducted between 1993 and 2006. The application of spatial interpolation to these reservoir surveys resulted in an average increase in individual reservoir volume estimate of 1.89 percent.

Re-assessment of the TWDB's hydrographic surveys using the Self Similar and Anisotropic Elliptical Inverse Distance Weighted interpolation reduces error in estimates of capacity and provides better estimates of capacity loss and sedimentation rates as more current surveys are completed. The TWDB recommends each reservoir is resurveyed using a similar methodology every 10 years or after a major flood event to assess changes in reservoir capacity and to further improve estimates of sediment accumulation rates.

References

Environmental Systems Research Institute, 1995, ARC/INFO Surface Modeling and Display, TIN Users Guide: ESRI, California.

Furnans, J., 2006, HydroEdit User's Manual: Texas Water Development Board.

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

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

Payne, H.W. and Holley, E.R., 1997, An Assessment of a Hydrographic Survey Technique: Center for Research in Water Resources, Bureau of Engineering Research, The University of Texas at Austin.

Texas Natural Resources Information System, 2016, Maps & Data, accessed November 1, 2016, at http://www.tnris.org/maps-and-data/

Texas Water Development Board, 2009, Contract No. 1004801050 with U.S. Army Corps of Engineers: Fort Worth District.

Texas Water Development Board, 2010, Hydrographic Survey Program Assessment, accessed November 1, 2016, at http://www.twdb.texas.gov/hydro_survey/LyndonBJohnson/2007-05/HydrographicSurveyProgramAssessment_LakeLBJ.pdf

Texas Water Development Board, 2016, Water for Texas, 2017 State Water Plan, accessed December 13, 2016, at http://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf

U.S. Army Corps of Engineers, 2016, Tulsa District Water Control Home Page, accessed December 12, 2016, at http://www.swt-wc.usace.army.mil/

U.S. Department of Agriculture, 2013, National Agricultural Imagery Program (NAIP) Information Sheet, accessed November 1, 2016, at http://www.fsa.usda.gov/Internet/FSA_File/naip_info_sheet_2013.pdf

U.S. Geological Survey, 1999, United States National Map Accuracy Standards, accessed December 15, 2016, at https://pubs.usgs.gov/fs/1999/0171/report.pdf

U.S. Geological Survey, 2016, National Water Information System (NWIS Web) data available on the World Wide Web: accessed November 2, 2016, at http://waterdata.usgs.gov/tx/nwis/nwis