VOLUMETRIC SURVEY OF BENBROOK LAKE

Prepared for:

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

In Cooperation with

Tarrant Regional Water District

Prepared by:

The Texas Water Development Board

March 10, 2003

Texas Water Development Board

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Published and Distributed
by the
Texas Water Development Board
P.O. Box 13231
Austin, Texas 78711-3231

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INTRODUCTION

Staff of the Hydrographic Survey Unit of the Texas Water Development Board (TWDB) conducted a hydrographic survey of Benbrook Lake during the period of January 13 – 15, 1998. The purpose of the survey was to determine the capacity of the lake at the conservation pool elevation. From this information, future surveys will be able to determine the location and rates of sediment deposition in the conservation pool over time. Survey results are presented in the following pages in both graphical and tabular form. All elevations presented in this report will be reported in feet above mean sea level based on the National Geodetic Vertical Datum of 1929 (NGVD '29) unless the elevation is noted otherwise. The conservation pool elevation for Benbrook Lake is 694.0 feet. The 1945 design information/field survey estimates the original surface area at this elevation to be 3,770 acres and the storage volume to be 88,250 acre-feet of water.

HISTORY AND GENERAL INFORMATION OF THE RESERVOIR

Tarrant Regional Water District (formerly Tarrant County Water Control and Improvement District No.1) owns the water rights to Benbrook Lake. Benbrook Dam and the surrounding shoreline of Benbrook Lake are owned by the United States of America and maintained by the U. S. Army Corps of Engineers, Fort Worth District. The lake is located on the Clear Fork Trinity River, in Tarrant County approximately 10 miles southwest of downtown Fort Worth, Texas (see Figure 1). Records indicate the drainage area is approximately 429 square miles. At the conservation pool elevation, the lake has approximately 40 miles of shoreline and is 3.8 miles long. The widest point of the reservoir is approximately 2 miles (located about 2.75 miles upstream of the dam).

Federal authorization was granted for Benbrook Dam and Lake under the River and Harbor Act, March 2, 1945, and later modified by Law 782. The reservoir's storage capacity was originally designated for flood control, flood regulation and conservation uses that include navigation and recreation.

The Texas Water Commission issued two Certificates of Adjudication for water rights of Benbrook Lake on April 5, 1987. Certificate of Adjudication # 08-3365 was issued to the Benbrook Water and Sewer Authority. Authorization was granted to impound not to exceed 16,460 acre-feet of water in an existing 72,500 acre-feet capacity reservoir. The owner was authorized to divert and use not to exceed 1,646 acre-feet of water per annum for municipal purposes in Tarrant County. Certificate of Adjudication # 08-3366 was issued to the City of Fort Worth. The owner was authorized to impound not to exceed 7,250 acre-feet of water. Authorization was granted to divert and use not to exceed 725 acre-feet of water per annum for municipal purposes.

Pursuant to a 1986 "Settlement Agreement" and, at that time, a proposed "Tarrant County Regional Water Supplies Facilities Benbrook Reservoir Contract", Tarrant Regional Water District contracted to acquire the water rights under Certificate of Adjudication #'s 08-3365 and 08-3366. The District was also contracted to acquire the rights under the pending Application #'s 2126A and 4240.

The Texas Water Commission granted Permit # 5157 to the Tarrant Regional Water District on October 27, 1987. The District was granted authorization to impound 72,500 acre-feet of water (includes 23,710 acre-feet of storage included in Certificate #'s 08-3365 and 08-3366) between elevations 665 and 694 feet in Benbrook Lake. The water "USE" section of Permit 5157 was rather involved but an attempt to summarized is as follows: The District was authorized to divert and use, on a priority basis, not to exceed 6,833 acre-feet of water per annum for irrigation and municipal purposes. This use included the 2,371 acre-feet of water authorized for use per annum in Certificate #'s 08-3365 and 08-3366. The District was granted the right to use 72,500 acre-feet of Benbrook Lake storage space for terminal storage of water diverted from the District's Cedar Creek and/or Richland-Chambers Reservoirs. This water was to be re-diverted to the District's municipal customers in Tarrant County, Benbrook Water and Sewer Authority and to the City of Weatherford. Tarrant Regional Water District was authorized to overdraft Benbrook Lake on a non-priority basis for municipal purposes using a detailed formula. The bottom line amounted to the combined total annual diversions from Benbrook Lake would not exceed 72,500 acre-feet of water.

Records indicate the construction for the Benbrook project started on May 27, 1947 and was completed in December 1950. Deliberate impoundment of water began September 29, 1952. The U. S. Army Corps of Engineers designed the project and List & Clark Construction Company was the general contractor. The estimated project cost was $12,000,000.

Benbrook Dam and appurtenant structures consist of an earthfill embankment 9,130 feet in length (including spillway) with a maximum height of 130 feet and a crest width of 20 feet at elevation 747.0 feet. The service spillway is an uncontrolled concrete ogee type located near the left (northwest) end of the embankment. The crest of the spillway is 500 feet in width at elevation 724.0 feet. There is a 100 feet wide notch in the center of the spillway that has a crest elevation of 710.0 feet. The outlet works structure consists of a concrete tower located near the right (southeast) end of the embankment. There are two 6.5 feet by 13 feet openings, controlled by "broome–type" gates with invert elevations of 622.0 feet. There are also two 30-inch diameter pipes, controlled by slide gates that have an invert elevation of 656.0 feet. All discharges pass through a 13-feet diameter conduit and are released to a stilling basin downstream of the embankment.

HYDROGRAPHIC SURVEYING TECHNOLOGY

The following sections will describe the theory behind Global Positioning System (GPS) technology and its accuracy. Equipment and methodology used to conduct the subject survey and previous hydrographic surveys are also addressed.

GPS Information

The following is a brief and simple description of Global Positioning System (GPS) technology. GPS is a relatively new technology that uses a network of satellites, maintained in precise orbits around the earth, to determine locations on the surface of the earth. GPS receivers continuously monitor the broadcasts from the satellites to determine the position of the receiver. With only one satellite being monitored, the point in question could be located anywhere on a sphere surrounding the satellite with a radius of the distance measured. The observation of two satellites decreases the possible location to a finite number of points on a circle where the two spheres intersect. With a third satellite observation, the unknown location is reduced to two points where all three spheres intersect. One of these points is obviously in error because its location is in space, and it is ignored. Although three satellite measurements can fairly accurately locate a point on the earth, the minimum number of satellites required to determine a three dimensional position within the required accuracy is four. The fourth measurement compensates for any time discrepancies between the clock on board the satellites and the clock within the GPS receiver.

The United States Air Force and the defense establishment developed GPS technology in the 1960's. After program funding in the early 1970's, the initial satellite was launched on February 22, 1978. A four-year delay in the launching program occurred after the Challenger space shuttle disaster. In 1989, the launch schedule was resumed. Full operational capability was reached on April 27, 1995 when the NAVSTAR (NAVigation System with Time And Ranging) satellite constellation was composed of 24 Block II satellites. Initial operational capability, a full constellation of 24 satellites, in a combination of Block I (prototype) and Block II satellites, was achieved December 8, 1993. The NAVSTAR satellites provide data based on the World Geodetic System (WGS '84) spherical datum. WGS '84 is essentially identical to the 1983 North American Datum (NAD '83).

The United States Department of Defense (DOD) is currently responsible for implementing and maintaining the satellite constellation. In an attempt to discourage the use of these survey units as a guidance tool by hostile forces, the DOD has implemented means of false signal projection called Selective Availability (S/A). Positions determined by a single receiver when S/A is active result in errors to the actual position of up to 100 meters. These errors can be reduced to centimeters by performing a static survey with two GPS receivers, one of, which is set over a point with known coordinates. The errors induced by S/A are time-constant. By monitoring the movements of the satellites over time (one to three hours), the errors can be minimized during post processing of the collected data and the unknown position computed accurately.

Differential GPS (DGPS) is an advance mode of satellite surveying in which positions of moving objects can be determine in real-time or "on-the-fly." This technological breakthrough was the backbone of the development of the TWDB's Hydrographic Survey Program. In the early stages of the program, one GPS receiver was set up over a benchmark with known coordinates established by the hydrographic survey crew. This receiver remained stationary during the survey and monitored the movements of the satellites overhead. Position corrections were determined and transmitted via a radio link once per second to another GPS receiver located on the moving boat. The boat receiver used these corrections, or differences, in combination with the satellite information it received to determine its differential location. This type of operation can obtain a horizontal positional accuracy of within one meter. In addition, the large positional errors experienced by a single receiver when S/A is active are negated. Since a greater accuracy is needed in the vertical direction, the depth sounder supplies vertical data during a survey. The lake surface during the survey serves as the vertical datum for the readings from the depth sounder.

The need for setting up a stationary shore receiver for current surveys has been eliminated by registration with a fee-based satellite reference position network (OmniSTAR). This service works in a differential mode basically the same way as the shore station, except on a worldwide basis. For a given area in the world, a network of several monitoring sites (with known positions) collect GPS signals from the NAVSTAR network. GPS corrections are computed at each of these sites to correct the GPS signal received to the known coordinates of the site. The corrections from each of the sites within the network are automatically sent via a leased line to a "Network Control Center" where the data corrections are checked and repackaged for up-link to a "Geostationary" L-band satellite. The "real-time" corrections for the entire given area in the world are then broadcast by the satellite to users of the system in the area covered by the satellite. The OmniSTAR receiver translates the information and supplies it to the on-board Trimble receiver for correction of the boat's GPS positions. The accuracy of this system in a real-time mode is normally 1 meter or less.

Equipment and Methodology

The equipment used in the performance of the hydrographic survey consisted of a 23-foot aluminum tri-hull SeaArk craft with cabin, equipped with twin 90-Horsepower Johnson outboard motors. Installed within the enclosed cabin are an Innerspace Helmsman Display (for navigation), an Innerspace Technology Model 449 Depth Sounder and Model 443 Velocity Profiler, a Trimble

Navigation, Inc. 4000SE GPS receiver, an OmniSTAR receiver, and an on-board 486 computer. A water-cooled generator through an in-line uninterruptible power supply provided electric power. Reference to brand names does not imply endorsement by the TWDB.

The GPS equipment, survey vessel, and depth sounder combine together to provide an efficient hydrographic survey system. As the boat travels across the lake surface, the depth sounder gathers approximately ten readings of the lake bottom each second. The depth readings are stored on the survey vessel's on-board computer along with the corrected positional data generated by the boat's GPS receiver. The daily data files collected are downloaded from the computer and brought to the office for editing after the survey is completed. During editing, bad data is removed or corrected, multiple data points are averaged to get one data point per second, and average depths are converted to elevation readings based on the daily-recorded lake elevation on the day the survey was performed. Accurate estimates of the lake volume can be quickly determined by building a 3-D model of the reservoir from the collected data. The level of accuracy is equivalent to or better than previous methods used to determine lake volumes, some of which are discussed below.

Previous Survey Procedures

Originally, reservoir surveys were conducted with a rope stretched across the reservoir along pre-determined range lines. A small boat would manually pole the depth at selected intervals along the rope. Over time, aircraft cable replaced the rope and electronic depth sounders replaced the pole. The boat was hooked to the cable, and depths were again recorded at selected intervals. This method, used mainly by the Soil Conservation Service, worked well for small reservoirs.

Larger bodies of water required more involved means to accomplish the survey, mainly due to increased size. Cables could not be stretched across the body of water, so surveying instruments were utilized to determine the path of the boat. Monumentation was set for the end points of each line so the same lines could be used on subsequent surveys. Prior to a survey, each end point had to be located (and sometimes reestablished) in the field and vegetation cleared so that line of sight could be maintained. One surveyor monitored the path of the boat and issued commands via radio to insure that it remained on line while a second surveyor determined depth measurement locations by turning angles. Since it took a major effort to determine each of the points along the line, the depth readings were spaced quite a distance apart. Another major cost was the land surveying required prior to the reservoir survey to locate the range line monuments and clear vegetation.

Electronic positioning systems were the next improvement. If triangulation could determine the boat location by electronic means, then the boat could take continuous depth soundings. A set of microwave transmitters positioned around the lake at known coordinates would allow the boat to receive data and calculate its position. Line of site was required, and the configuration of the transmitters had to be such that the boat remained within the angles of 30 and 150 degrees with respect to the shore stations. The maximum range of most of these systems was about 20 miles. Each shore station had to be accurately located by survey, and the location monumented for future use. Any errors in the land surveying resulted in significant errors that were difficult to detect. Large reservoirs required multiple shore stations and a crew to move the shore stations to the next location as the survey progressed. Land surveying remained a major cost with this method.

More recently, aerial photography has been used prior to construction, to generate elevation contours from which to calculate the volume of the reservoir. Fairly accurate results could be obtained, although the vertical accuracy of the aerial topography was generally one-half of the contour interval or ± five feet for a ten-foot contour interval. This method could be quite costly and was only applicable in areas that were not inundated.

PRE-SURVEY PROCEDURES

The reservoir's surface area was determined prior to the survey by digitizing with AutoCad software the lake's pool boundary (elevation 694.0). The boundary file was created from the following 7.5 minute USGS quadrangle maps: BENBROOK, TX (photo-revised 1981), PRIMROSE, TX (photo-revised 1968), and CRESSON, TX (photo-revised 1968). The graphic boundary file created was then transformed into the proper datum, from NAD '27 datum to NAD '83, using Environmental Systems Research Institute's (ESRI) Arc/Info project command with the NADCOM (standard conversion method within the United States) parameters. The area of the lake boundary was checked to verify that the area was the same in both datums. Above this elevation, National Aerial Photography Program color infrared photographic diapositives from 1995 were used to determine areas at various contour elevations. Each image covered 7.5 minutes of latitude and longitude in geographic extent and was oriented on the Universal Transverse Mercator Projection on the North American Datum of 1983. The photos were produced by VARGIS of Herndon, Va., for the Texas Orthoimagery Program administered by the Texas Department of Information Resources.

The survey layout was designed by placing survey track lines at 500-foot intervals across the lake. The survey design for this lake required approximately 45 survey lines to be placed along the length of the lake. Survey setup files were created using Coastal Oceangraphics, Inc. Hypack software for each group of track lines that represented a specific section of the lake. The setup files were copied onto diskettes for use during the field survey.

SURVEY PROCEDURES

The following procedures were followed during the hydrographic survey of Benbrook Lake performed by the TWDB. Information regarding equipment calibration and operation, the field survey, and data processing is presented.

Equipment Calibration and Operation

At the beginning of each surveying day, the depth sounder was calibrated with the Innerspace Velocity Profiler. The Velocity Profiler calculates an average speed of sound through the water column of interest for a designated draft value of the boat (draft is the vertical distance that the boat penetrates the water surface). The draft of the boat was previously determined to average 1.2 ft. The velocity profiler probe is placed in the water to moisten and acclimate the probe. The probe is then raised to the water surface where the depth is zeroed. The probe is lowered on a cable to just below the maximum depth set for the water column, and then raised to the surface. The unit displays an average speed of sound for a given water depth and draft, which is entered into the depth sounder. The depth value on the depth sounder was then checked manually with a measuring tape to ensure that the depth sounder was properly calibrated and operating correctly. During the survey of Benbrook Lake, the speed of sound in the water column remained constant at 4,746 feet per second. Based on the measured speed of sound for various depths, and the average speed of sound calculated for the entire water column, the depth sounder is accurate to within $\pm$0.2 feet, plus an estimated error of $\pm$0.3 feet due to the plane of the boat for a total accuracy of $\pm$0.5 feet for any instantaneous reading. These errors tend to be minimized over the entire survey, since some are positive and some are negative readings. Further information on these calculations is presented in Appendix A.

During the survey, the onboard GPS receiver was set to a horizontal mask of 10° and a PDOP (Position Dilution of Precision) limit of 7 to maximize the accuracy of horizontal positions. An internal alarm sounds if the PDOP rises above seven to advise the field crew that the horizontal position has degraded to an unacceptable level. The lake's initialization file used by the Hypack data collection program was setup to convert the collected DGPS positions on the fly to state plane coordinates. Both sets of coordinates were then stored in the survey data file.

Field Survey

Data were collected at Benbrook Lake during the period of January 13 - 15, 1998. Weather conditions were excellent with moderately cool temperatures and mild winds. Approximately 51,400 data points were collected over the 103 miles traveled along the 65 survey lines run (pre-planned, random, and parallel). These points were stored digitally on the boat's computer in 82 data files. Data were not collected in areas of shallow water (depths less than 3.0 feet) or with significant obstructions unless these areas represented a large amount of water. Random data lines were also collected parallel to the original streambed in the main body of the lake. Figure 2 shows the actual location of all data collection points.

TWDB staff observed many similar features between the lake's bathemetry and the surrounding topography. The terrain around the lake was generally rolling hills with steeper inclines located on the east bank of the lake. Below the water, the bottom continued to fall rapidly on the east side of the lake to around 650 feet near the dam. The bottom was then fairly level as the boat traveled across the old river flood plain. Within this flood plain, the original river and creek channels were easily distinguishable on the depth sounder chart when they were crossed. As the boat approached the western shore, the bottom rose gradual up the shoreline. The survey crew collected extensive data around the existing control tower and the new pump station and platform that was under construction. These structures are located near the dam, nearest to the east bank of the lake.

The was a minimal amount of navigational hazards such as standing trees, brush, submerged trees and stumps encountered during the survey. Sediment deposits and aquatic vegetation were observed mainly in the upper reaches of the lake, especially at the mouth of the Clear Fork Trinity River and Bear Creek. Since the lake level was approximately two feet higher than normal pool elevation during the survey, the crew was able to collect data in these areas, but at a much slower pace. Data collection in the headwaters was discontinued when the boat could no longer maneuver due to shallow water and extensive vegetation. The collected data were stored in individual data files for each pre-plotted range line or random data collection event. These files were downloaded to diskettes at the end of each day for future processing.

Data Processing

The collected data were downloaded from diskettes onto the TWDB's computer network. Tape backups were made for future reference as needed. To process the data, the EDIT routine in the Hypack Program was run on each raw data file. Data points such as depth spikes or data with missing depth or positional information were deleted from the file. The depth information collected every 0.1 seconds was averaged to get one reading for each second of data collection. A correction for the lake elevation at the time of data collection was also applied to each file during the EDIT routine. During the survey, the water surface varied between 696.15 and 696.46 feet. After all changes had been made to the raw data file, the edited file was saved with a different extension. The edited files were combined into a single X,Y,Z data file, representative of the lake, to be used with the GIS software to develop a model of the lake's bottom surface.

The resulting data file was imported into the UNIX operating system used to run Environmental System Research Institute’s (ESRI) Arc/Info GIS software and converted to a MASS points file. The MASS points and the boundary file were then used to create a Digital Terrain Model

(DTM) of the reservoir's bottom surface using Arc/Info's TIN software module. The module builds an irregular triangulated network from the data points and the boundary file. This software uses a method known as Delauney's criteria for triangulation. A triangle is formed between three non-uniformly spaced points, including all points along the boundary. If there is another point within the triangle, additional triangles are created until all points lie on the vertex of a triangle. All of the data points are preserved for use in determining the solution of the model by using this method. The generated network of three-dimensional triangular planes represents the actual bottom surface. Once the triangulated irregular network (TIN) is formed, the software then calculates elevations along the triangle surface plane by solving the equations for elevation along each leg of the triangle. Information for the entire reservoir area can be determined from the triangulated irregular network created using this method of interpolation.

If data points were collected outside the boundary file, the boundary was modified to include the data points. The boundary file in areas of significant sedimentation was also downsized as deemed necessary based on the data points and the observations of the field crew. The resulting boundary shape was used to develop each of the map presentations of the lake in this report.

There were some areas where volume and area values could not be calculated by interpolation because of a lack of information within the reservoir. "Flat triangles" were drawn at these locations. Arc/Info does not use flat triangle areas in the volume or contouring features of the model. Approximately 91 additional points were manually added to allow for interpolation and contouring of the entire lake surface at elevation 694.0. Volumes and areas were calculated from the TIN for the entire reservoir at one-tenth of a foot intervals. From elevation 695.0 to elevation 724.0, the surface areas and volumes of the lake were mathematically estimated. This was done by first distributing uniformly across each elevation increment, the surface areas digitized from USGS topographic maps or from National Aerial Photography Program color infrared photographic diapositives from 1995. Volumes were calculated in a 0.1 foot step method by adding to the existing volume, 0.1 of the existing area, and 0.5 of the difference between the existing area the area for the value being calculated. The computed area of lake at elevation 694.0 was 3,635 surface acres. The computed area was 135 surface acres less than originally calculated in 1945. The computed reservoir volume table is presented in Appendix B and the area table in Appendix C. An elevation-area-volume graph is presented in Appendix D.

Other presentations developed from the model include a shaded relief map and a shaded depth range map. To develop these maps, the TIN was converted to a lattice using the TINLATTICE command and then to a polygon coverage using the LATTICEPOLY command. Using the POLYSHADE command, colors were assigned to the range of elevations represented by the polygons that varied from navy to yellow. The lower elevation was assigned the color of navy, and the 694.0 lake elevation was assigned the color of yellow. Different color shades were assigned to the intermediate depths. Figure 3 presents the resulting depth shaded representation of the lake. Figure 4 presents a similar version of the same map, using bands of color for selected depth intervals. The color increases in intensity from the shallow contour bands to the deep-water bands.

Linear filtration algorithms were then applied to the DTM smooth cartographic contours versus using the sharp-engineered contours. The resulting contour map of the bottom surface at two-foot intervals is presented in Figure 5.

RESULTS

Results from the 1998 TWDB survey indicate Benbrook Lake encompasses 3,635 surface acres and contains a volume of 85,648 acre-feet at the conservation pool elevation of 694.0 feet. The shoreline at this elevation was calculated to be 40.67 miles. The deepest point of the lake, elevation 633.6 or 60.4 feet of depth, was located approximately 1,260 feet southeast from the center of the dam. The dead storage volume, or the amount of water below the lowest outlet in the dam, was calculated to be 0.0 acre-feet based on the low flow outlet invert elevation of 622.0 feet. While this elevation is over 11 feet below the lowest depth measured during the survey, the outlet is still open and used frequently according to lake staff. The conservation storage capacity, or the amount of water between the spillway and the lowest outlet, is therefore calculated to be, 85,650 acre-feet.

SUMMARY

Benbrook Lake was formed in 1950. Initial storage calculations estimated the volume at the conservation pool elevation of 694.0 feet to be 88,250 acre-feet with a surface area of 3,770 acres.

During the period of January 6 - 15, 1998, a hydrographic survey of Benbrook Lake was performed by the Texas Water Development Board's Hydrographic Survey Program. The 1998 survey used technological advances such as differential global positioning system and geographical information system technology to build a model of the reservoir's bathemetry. These advances allowed a survey to be performed quickly and to collect significantly more data of the bathemetry of Benbrook Lake than previous survey methods. Results indicate that the lake's capacity at the conservation pool elevation of 694.0 feet was 85,648 acre-feet and the area was 3,635 acres.

The estimated reduction in storage capacity at the conservation pool elevation of 694.0 feet since 1952 was 2,602 acre-feet or 57.82 acre-feet per year. The average annual deposition rate of sediment in the conservation pool of the reservoir can be estimated at 0.1348 acre-feet per square mile of drainage area. Using available contour information above elevation 694.0, the capacity of the lake at the top of the flood pool, elevation 724.0 feet, was mathematically estimated at 253,910 acre-feet with a surface area of 7,426 acres. The flood pool capacity was 4,690 acre-feet less than originally calculated.

It is difficult to compare the original design information and the TWDB performed survey because little is know about the original design method, the amount of data collected, and the method used to process the collected data. However, the TWDB considers the 1998 survey to be a significant improvement over previous survey procedures and recommends that the same methodology be used in five to ten years or after major flood events to monitor changes to the lake's storage capacity.

CALCULATION OF DEPTH SOUNDER ACCURACY

This methodology was extracted from the Innerspace Technology, Inc. Operation Manual for the Model 443 Velocity Profiler.

For the following examples, $t = (D - d)/V$

where: t_D = travel time of the sound pulse, in seconds (at depth = D)
D = depth, in feet
d = draft = 1.2 feet
V = speed of sound, in feet per second

To calculate the error of a measurement based on differences in the actual versus average speed of sound, the same equation is used, in this format:

$$D = [t(V)]+d$$

For the water column from 2 to 30 feet: V = 4832 fps

$$t_{30} = (30-1.2)/4832$$
$$= 0.00596 \text{ sec.}$$

For the water column from 2 to 45 feet: V = 4808 fps

$$t_{45} =(45-1.2)/4808$$
$$=0.00911 \text{ sec.}$$

For a measurement at 20 feet (within the 2 to 30 foot column with V = 4832 fps):

$$D_{20} = [((20-1.2)/4832)(4808)]+1.2$$
$$= 19.9' \quad (-0.1')$$

For a measurement at 30 feet (within the 2 to 30 foot column with V = 4832 fps):

$$D_{30} = [((30-1.2)/4832)(4808)]+1.2$$
$$= 29.9' \quad (-0.1')$$

For a measurement at 50 feet (within the 2 to 60 foot column with V = 4799 fps):

D_{50} = [((50-1.2)/4799)(4808)]+1.2
= 50.1' (+0.1')

For the water column from 2 to 60 feet: V = 4799 fps Assumed V_{80} = 4785 fps

t_{60} =(60-1.2)/4799
=0.01225 sec.

For a measurement at 10 feet (within the 2 to 30 foot column with V = 4832 fps):

D_{10} = [((10-1.2)/4832)(4799)]+1.2
= 9.9' (-0.1')

For a measurement at 30 feet (within the 2 to 30 foot column with V = 4832 fps):

D_{30} = [((30-1.2)/4832)(4799)]+1.2
= 29.8' (-0.2')

For a measurement at 45 feet (within the 2 to 45 foot column with V = 4808 fps):

D_{45} = [((45-1.2)/4808)(4799)]+1.2
= 44.9' (-0.1')

For a measurement at 80 feet (outside the 2 to 60 foot column, assumed V = 4785 fps):

D_{80} = [((80-1.2)/4785)(4799)]+1.2
= 80.2' (+0.2')

TEXAS WATER DEVELOPMENT BOARD
RESERVOIR VOLUME TABLE

Mar 13 1998

BENBROOK LAKE January 1998 Survey

VOLUME IN ACRE-FEET ELEVATION INCREMENT IS ONE TENTH FOOT

ELEV. FEET	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
634								1	1	1
635	1	1	1	1	2	2	2	2	3	3
636	3	4	4	4	5	5	6	6	7	8
637	8	9	10	10	11	12	14	15	17	18
638	20	22	25	27	30	33	36	40	43	47
639	52	56	61	65	70	76	81	87	93	99
640	105	112	118	125	132	140	147	155	163	171
641	179	187	196	204	213	222	232	241	251	260
642	270	280	291	302	313	324	336	348	361	374
643	388	403	418	434	450	466	483	500	518	536
644	554	573	592	611	631	651	671	691	712	733
645	755	776	798	820	843	865	888	911	935	959
646	983	1007	1032	1057	1082	1108	1134	1161	1188	1216
647	1245	1275	1305	1335	1366	1398	1430	1462	1495	1529
648	1563	1597	1632	1667	1703	1739	1776	1813	1850	1888
649	1926	1964	2003	2043	2083	2123	2163	2204	2245	2287
650	2329	2371	2413	2456	2499	2543	2587	2632	2677	2722
651	2768	2815	2862	2909	2958	3006	3055	3105	3155	3205
652	3256	3307	3359	3411	3464	3517	3570	3624	3679	3734
653	3789	3845	3901	3958	4015	4073	4131	4190	4249	4309
654	4369	4430	4491	4553	4615	4678	4741	4805	4870	4935
655	5000	5066	5132	5199	5267	5335	5403	5472	5542	5612
656	5683	5754	5826	5898	5972	6045	6119	6194	6268	6344
657	6420	6496	6573	6650	6727	6806	6884	6964	7044	7124
658	7205	7286	7368	7451	7534	7617	7701	7785	7870	7955
659	8041	8127	8213	8301	8388	8476	8565	8654	8744	8834
660	8925	9017	9109	9202	9296	9390	9485	9580	9677	9774
661	9871	9970	10068	10168	10268	10368	10470	10572	10675	10778
662	10882	10987	11093	11199	11306	11413	11521	11630	11739	11849
663	11959	12071	12183	12295	12408	12522	12637	12752	12867	12984
664	13101	13218	13336	13455	13574	13695	13816	13937	14060	14183
665	14307	14433	14559	14685	14813	14942	15072	15203	15335	15467
666	15600	15734	15869	16005	16141	16279	16417	16555	16695	16836
667	16977	17119	17262	17406	17550	17696	17842	17990	18138	18288
668	18438	18590	18742	18896	19051	19206	19363	19522	19681	19841
669	20002	20165	20328	20493	20659	20826	20993	21162	21332	21503
670	21675	21848	22023	22198	22374	22551	22729	22908	23089	23270
671	23452	23635	23820	24005	24191	24378	24565	24754	24943	25134
672	25325	25517	25710	25904	26098	26294	26491	26689	26887	27087
673	27288	27490	27692	27896	28100	28306	28512	28719	28927	29135
674	29345	29555	29766	29978	30191	30404	30618	30833	31048	31264
675	31481	31698	31916	32135	32354	32574	32795	33016	33238	33461
676	33685	33909	34134	34359	34585	34812	35039	35267	35496	35725
677	35955	36185	36416	36648	36880	37113	37346	37580	37814	38049
678	38285	38521	38758	38995	39233	39472	39711	39951	40192	40433
679	40675	40917	41160	41404	41648	41893	42139	42385	42633	42880
680	43129	43378	43628	43879	44131	44383	44636	44890	45144	45399
681	45655	45912	46169	46427	46686	46945	47205	47466	47728	47990
682	48253	48517	48782	49047	49313	49580	49847	50116	50385	50655

BENBROOK LAKE January 1998 Survey

	VOLUME IN ACRE-FEET				ELEVATION INCREMENT IS ONE TENTH FOOT					
ELEV. FEET	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
683	50926	51197	51469	51742	52016	52290	52566	52842	53118	53396
684	53674	53953	54234	54514	54796	55079	55362	55647	55931	56217
685	56503	56790	57078	57367	57656	57945	58236	58527	58819	59112
686	59405	59699	59994	60289	60586	60882	61180	61479	61778	62077
687	62378	62679	62981	63284	63587	63891	64196	64502	64808	65116
688	65424	65733	66043	66353	66665	66977	67291	67605	67920	68236
689	68553	68871	69189	69509	69829	70151	70473	70797	71121	71447
690	71774	72102	72431	72761	73092	73424	73757	74092	74427	74764
691	75101	75439	75779	76119	76461	76803	77146	77490	77834	78180
692	78526	78873	79221	79570	79919	80269	80620	80972	81324	81677
693	82031	82386	82741	83097	83459	83821	84184	84549	84914	85281
694	85648	86017	86388	86760	87134	87508	87884	88262	88640	89020
695	89402	89784	90168	90553	90939	91326	91715	92105	92497	92889
696	93283	93678	94074	94472	94871	95271	95672	96075	96479	96884
697	97291	97699	98108	98518	98929	99342	99756	100172	100588	101006
698	101425	101846	102267	102690	103115	103540	103967	104395	104824	105255
699	105686	106120	106554	106989	107426	107864	108304	108744	109186	109630
700	110074	110520	110968	111417	111867	112319	112773	113227	113684	114141
701	114600	115060	115522	115985	116450	116916	117383	117852	118322	118793
702	119266	119740	120216	120693	121172	121651	122133	122615	123099	123585
703	124072	124560	125049	125540	126033	126527	127022	127518	128016	128516
704	129016	129519	130022	130527	131034	131541	132050	132561	133073	133586
705	134101	134617	135135	135654	136174	136696	137219	137743	138269	138796
706	139325	139855	140387	140920	141454	141989	142526	143065	143605	144146
707	144689	145233	145778	146325	146873	147423	147974	148526	149080	149635
708	150192	150750	151309	151870	152432	152996	153560	154127	154694	155264
709	155834	156406	156979	157554	158130	158708	159287	159867	160449	161032
710	161616	162202	162787	163373	163960	164549	165138	165728	166320	166912
711	167505	168100	168695	169292	169889	170488	171087	171688	172290	172892
712	173496	174101	174706	175313	175921	176530	177140	177751	178363	178976
713	179590	180205	180821	181438	182056	182676	183296	183917	184540	185163
714	185787	186413	187039	187667	188295	188925	189555	190187	190820	191453
715	192088	192724	193361	193999	194637	195277	195918	196560	197203	197847
716	198492	199138	199786	200434	201083	201733	202384	203037	203690	204345
717	205000	205656	206314	206972	207632	208293	208954	209617	210281	210945
718	211611	212278	212946	213614	214284	214955	215627	216300	216974	217649
719	218326	219003	219681	220360	221040	221722	222404	223087	223772	224457
720	225143	225831	226522	227215	227909	228605	229303	230001	230702	231404
721	232107	232812	233518	234226	234936	235647	236359	237073	237789	238506
722	239224	239944	240666	241389	242113	242839	243567	244296	245026	245758
723	246492	247227	247963	248702	249441	250182	250925	251669	252414	253162
724	253910									

RESERVOIR AREA TABLE

BENBROOK LAKE January 1998 Survey

AREA IN ACRES ELEVATION INCREMENT IS ONE TENTH FOOT

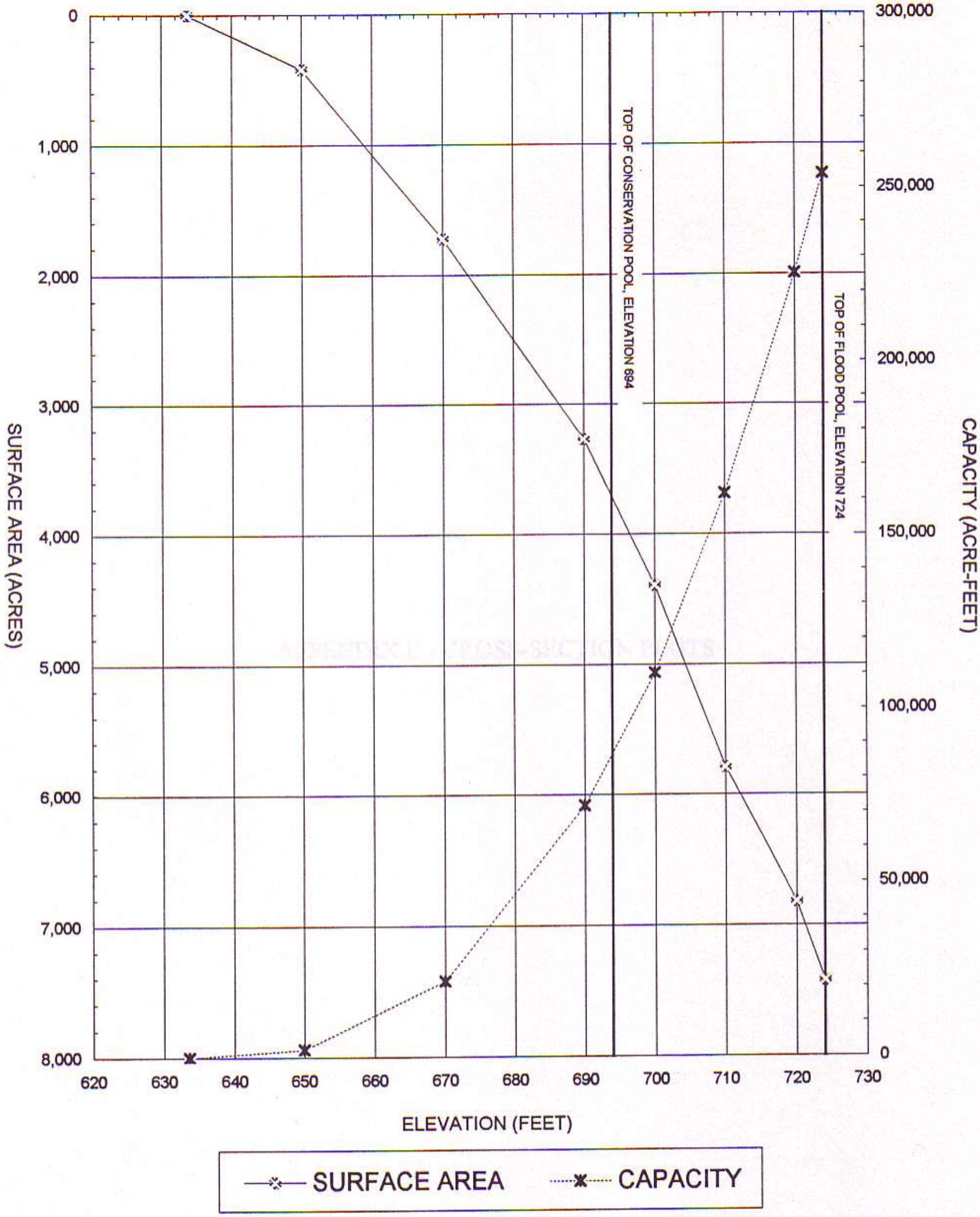
ELEV. FEET	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
634				1	1	1	1	1	1	1
635	2	2	2	2	2	2	3	3	3	3
636	3	4	4	4	5	5	5	6	6	6
637	7	7	8	9	10	11	13	15	17	19
638	21	23	25	27	29	31	33	36	38	40
639	43	45	47	50	52	54	56	58	60	62
640	64	66	68	70	72	74	76	78	80	81
641	83	85	86	88	90	91	93	95	97	99
642	101	103	105	108	112	116	121	125	131	137
643	143	149	154	158	163	167	171	174	178	182
644	185	188	191	194	198	201	204	207	209	212
645	215	217	220	223	225	228	231	233	236	239
646	242	245	248	251	255	260	265	271	280	285
647	291	296	302	308	313	318	323	328	332	337
648	342	346	351	355	360	364	368	372	376	380
649	384	388	392	396	400	403	407	410	413	416
650	419	423	427	431	435	439	444	448	453	457
651	463	468	473	477	483	488	493	497	501	506
652	510	515	520	524	529	533	538	542	547	551
653	555	560	565	570	575	580	585	590	595	600
654	605	610	616	621	627	632	637	642	647	652
655	656	661	666	671	676	682	687	693	699	705
656	711	717	723	728	733	738	742	747	751	756
657	760	765	769	774	780	786	791	796	801	807
658	812	817	822	826	831	836	840	845	850	855
659	859	864	869	873	878	884	889	895	901	907
660	913	919	926	933	940	946	953	960	967	973
661	979	985	991	997	1004	1011	1018	1024	1031	1038
662	1045	1051	1058	1065	1071	1077	1083	1090	1096	1103
663	1109	1116	1122	1129	1135	1142	1148	1154	1160	1166
664	1172	1178	1185	1191	1198	1206	1214	1222	1230	1238
665	1246	1256	1265	1274	1283	1294	1304	1313	1321	1329
666	1336	1345	1353	1361	1369	1376	1384	1393	1401	1409
667	1417	1426	1434	1442	1451	1460	1469	1479	1489	1499
668	1510	1521	1532	1542	1553	1564	1575	1586	1597	1609
669	1619	1630	1641	1651	1663	1674	1684	1695	1705	1715
670	1726	1736	1746	1756	1766	1776	1787	1797	1808	1818
671	1828	1838	1847	1856	1865	1873	1881	1890	1898	1907
672	1916	1925	1934	1942	1952	1963	1973	1983	1993	2003
673	2013	2022	2031	2040	2049	2057	2066	2075	2083	2091
674	2099	2107	2114	2121	2129	2136	2144	2151	2158	2164
675	2171	2177	2184	2190	2196	2203	2210	2218	2226	2232
676	2239	2245	2252	2258	2264	2270	2276	2282	2288	2294
677	2300	2307	2313	2319	2325	2331	2336	2342	2347	2353
678	2359	2365	2371	2377	2384	2390	2396	2402	2408	2415
679	2421	2427	2434	2440	2447	2454	2461	2468	2475	2482
680	2490	2497	2504	2512	2519	2526	2533	2541	2548	2555
681	2562	2569	2577	2584	2591	2598	2606	2613	2620	2627
682	2635	2642	2650	2657	2664	2672	2680	2687	2695	2703

BENBROOK LAKE January 1998 Survey

AREA IN ACRES

ELEVATION INCREMENT IS ONE TENTH FOOT

ELEV. FEET	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
683	2711	2718	2726	2734	2741	2748	2756	2764	2771	2780
684	2788	2796	2805	2814	2823	2831	2838	2846	2853	2860
685	2867	2874	2880	2887	2894	2901	2909	2916	2923	2930
686	2937	2944	2951	2958	2966	2973	2980	2987	2994	3001
687	3008	3016	3023	3031	3038	3046	3053	3061	3069	3077
688	3086	3094	3102	3111	3120	3129	3138	3147	3156	3164
689	3173	3182	3191	3200	3209	3219	3230	3242	3253	3263
690	3274	3284	3295	3305	3316	3327	3338	3348	3359	3369
691	3380	3389	3399	3409	3418	3427	3435	3443	3451	3459
692	3467	3475	3483	3490	3498	3505	3513	3520	3528	3535
693	3542	3549	3557	3565	3575	3585	3595	3605	3615	3625
694	3635	3647	3660	3673	3685	3698	3711	3723	3736	3748
695	3761	3774	3786	3799	3812	3824	3837	3850	3862	3875
696	3888	3900	3913	3926	3938	3951	3964	3976	3989	4002
697	4014	4027	4040	4052	4065	4078	4090	4103	4116	4128
698	4141	4154	4166	4179	4192	4204	4217	4230	4242	4255
699	4267	4280	4293	4305	4318	4331	4343	4356	4369	4381
700	4394	4408	4422	4436	4450	4464	4478	4492	4506	4520
701	4534	4548	4561	4575	4589	4603	4617	4631	4645	4659
702	4673	4687	4701	4715	4729	4743	4757	4771	4785	4799
703	4813	4826	4840	4854	4868	4882	4896	4910	4924	4938
704	4952	4966	4980	4994	5008	5022	5036	5050	5064	5078
705	5092	5105	5119	5133	5147	5161	5175	5189	5203	5217
706	5231	5245	5259	5273	5287	5301	5315	5329	5343	5357
707	5371	5384	5398	5412	5426	5440	5454	5468	5482	5496
708	5510	5524	5538	5552	5566	5580	5594	5608	5622	5636
709	5650	5663	5677	5691	5705	5719	5733	5747	5761	5775
710	5789	5799	5810	5820	5830	5841	5851	5861	5872	5882
711	5892	5903	5913	5923	5934	5944	5954	5965	5975	5986
712	5996	6006	6017	6027	6037	6048	6058	6068	6079	6089
713	6099	6110	6120	6130	6141	6151	6161	6172	6182	6192
714	6203	6213	6223	6234	6244	6254	6265	6275	6285	6296
715	6306	6316	6327	6337	6347	6358	6368	6378	6389	6399
716	6409	6420	6430	6440	6451	6461	6471	6482	6492	6503
717	6513	6523	6534	6544	6554	6565	6575	6585	6596	6606
718	6616	6627	6637	6647	6658	6668	6678	6689	6699	6709
719	6720	6730	6740	6751	6761	6771	6782	6792	6802	6813
720	6823	6838	6853	6868	6883	6898	6914	6929	6944	6959
721	6974	6989	7004	7019	7034	7049	7064	7079	7094	7109
722	7125	7140	7155	7170	7185	7200	7215	7230	7245	7260
723	7275	7290	7305	7321	7336	7351	7366	7381	7396	7411
724	7426									

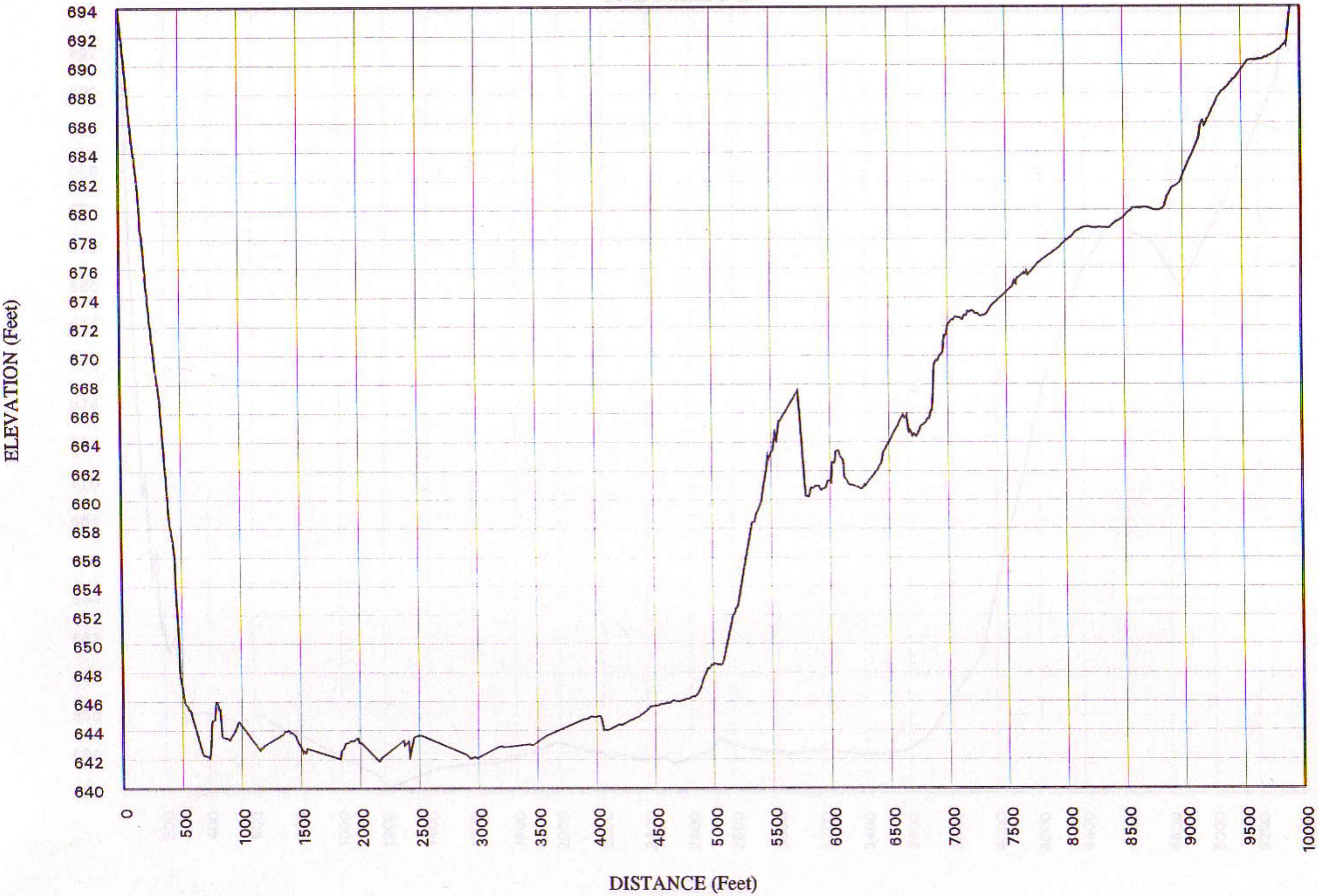


BENBROOK LAKE

January 1998 Survey

Prepared by: TWDB March 1998

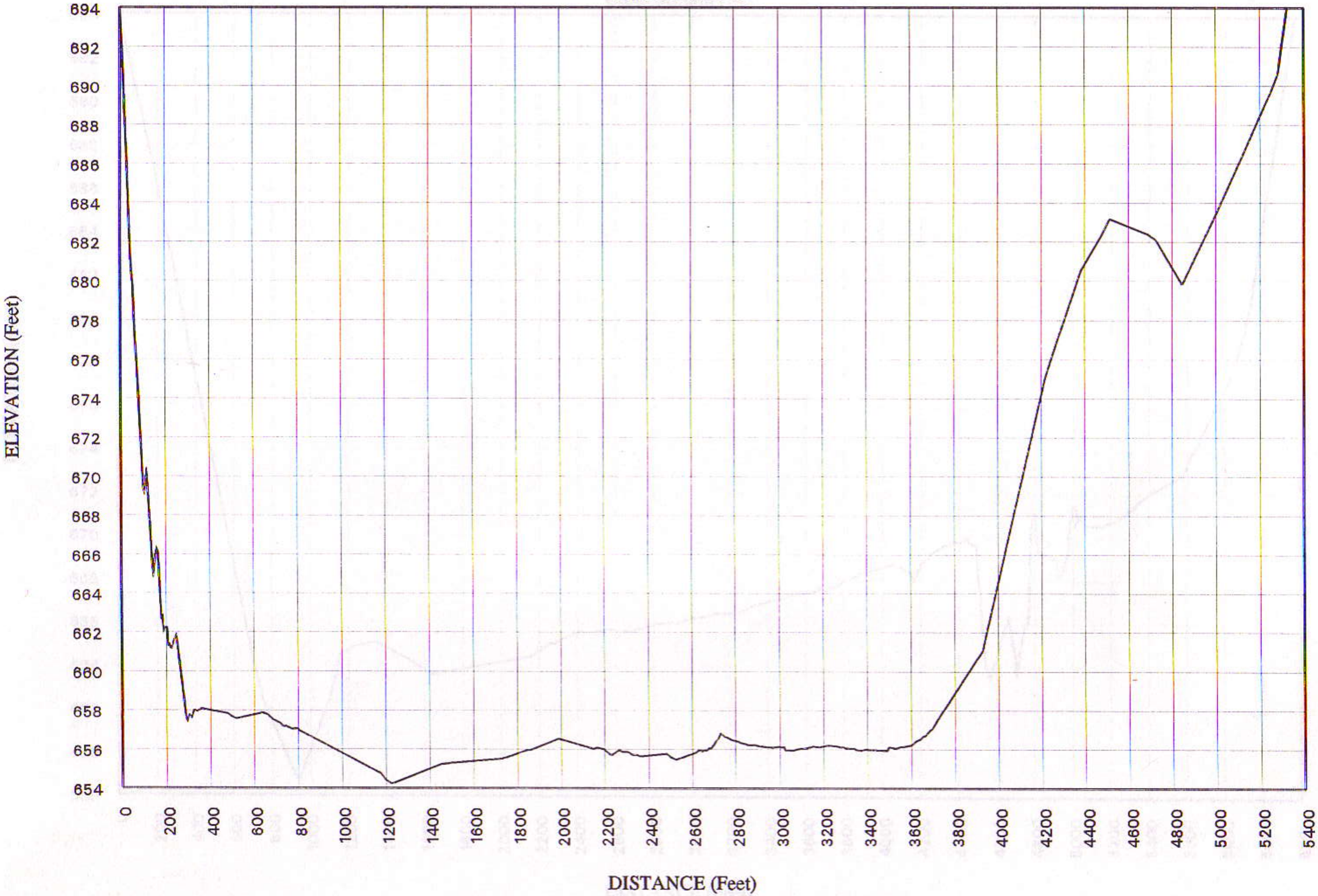
BENBROOK LAKE
Cross Section A-A′



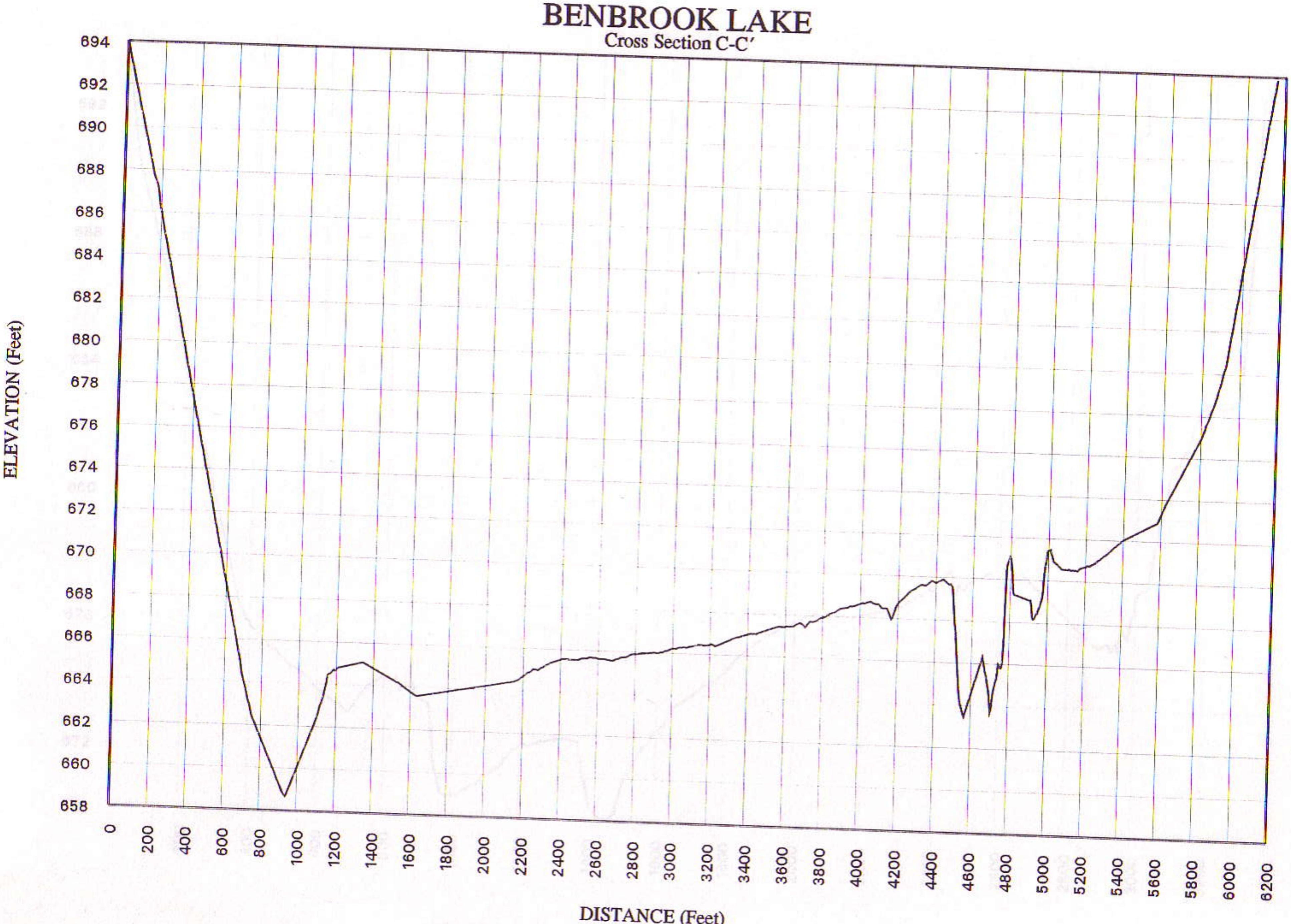
PREPARED BY: TWDB MARCH 1998

BENBROOK LAKE

Cross Section B-B'

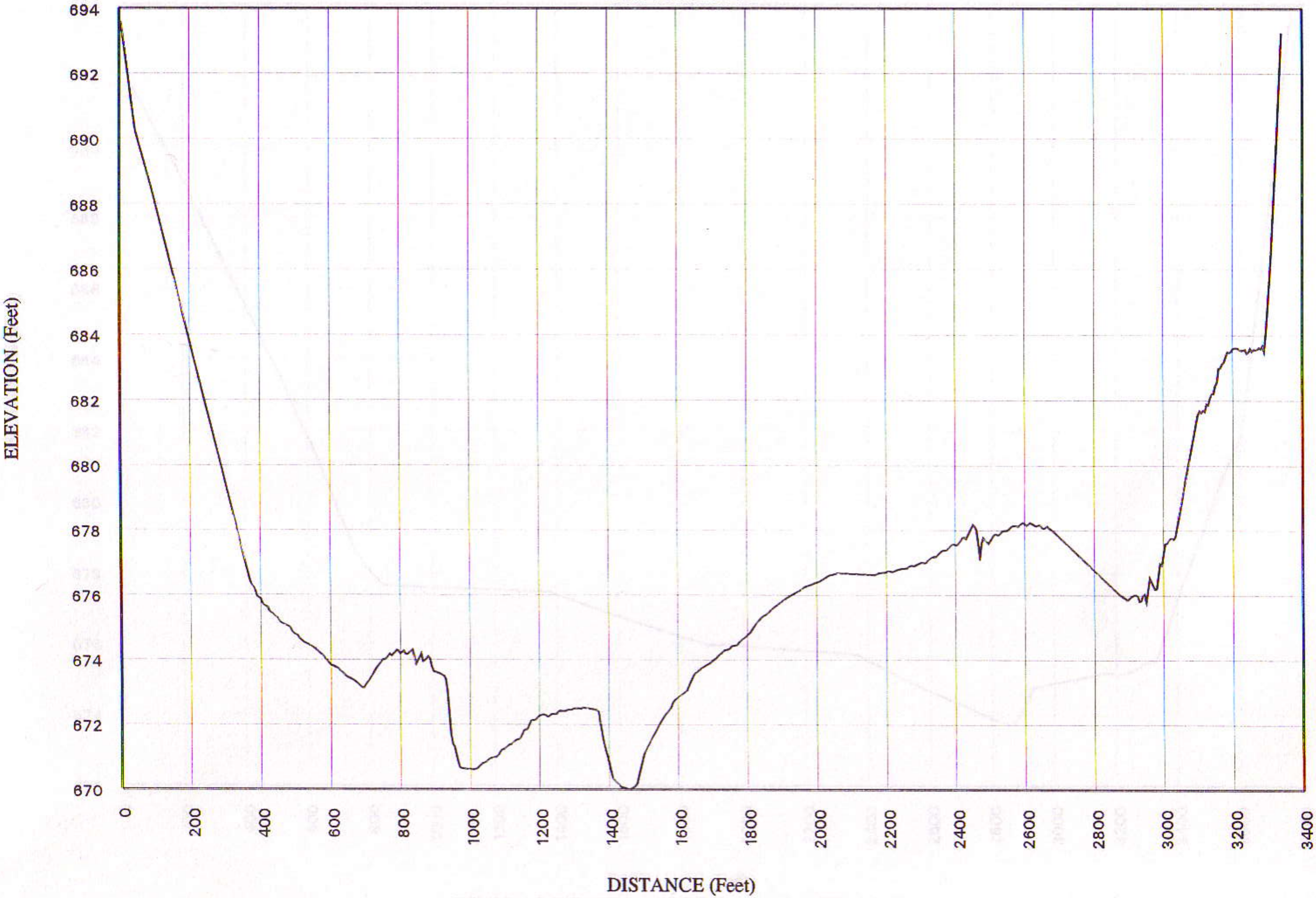


PREPARED BY: TWDB MARCH 1998



PREPARED BY: TWDB MARCH 1998

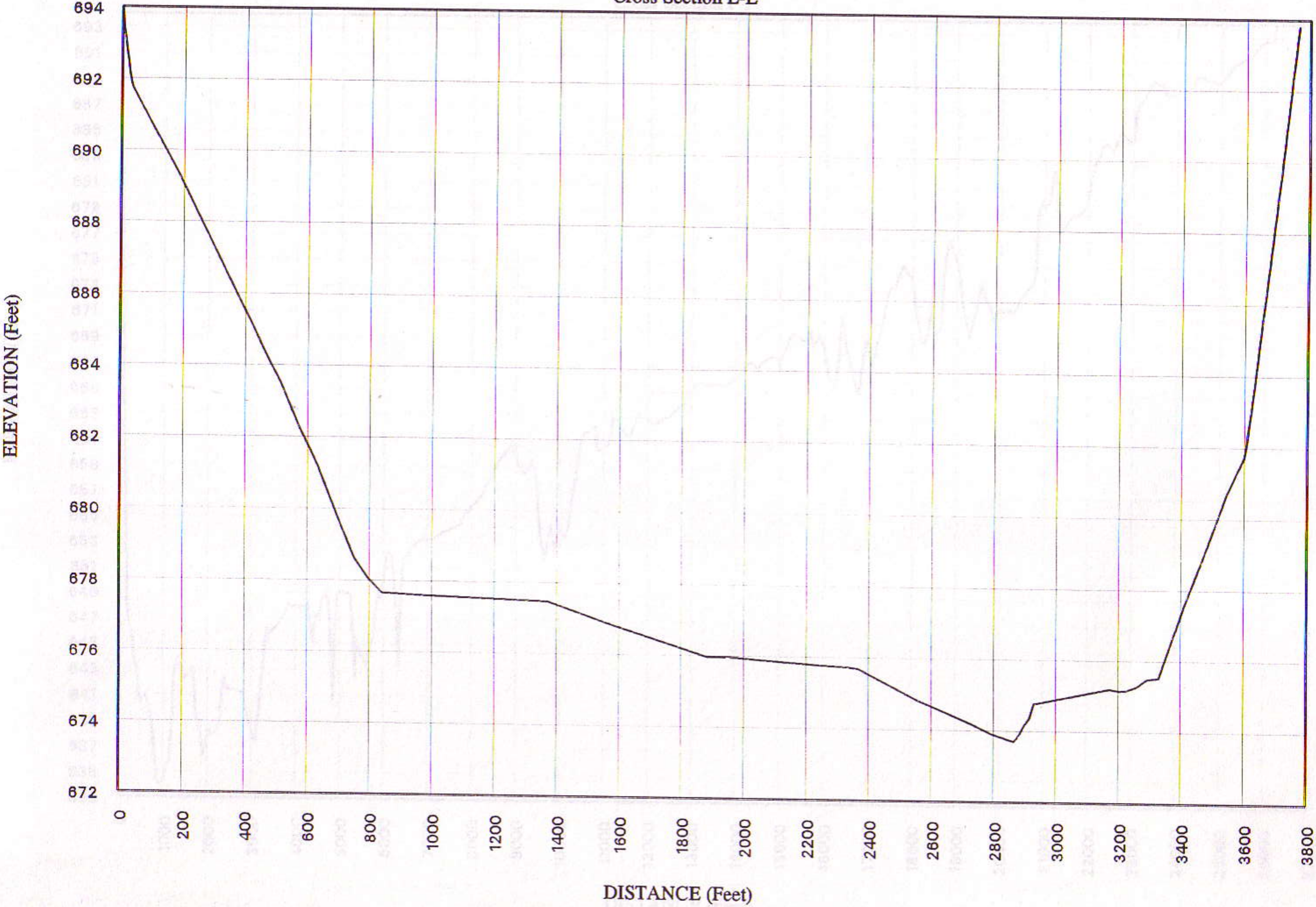
BENBROOK LAKE
Cross Section D-D′



PREPARED BY: TWDB MARCH 1998

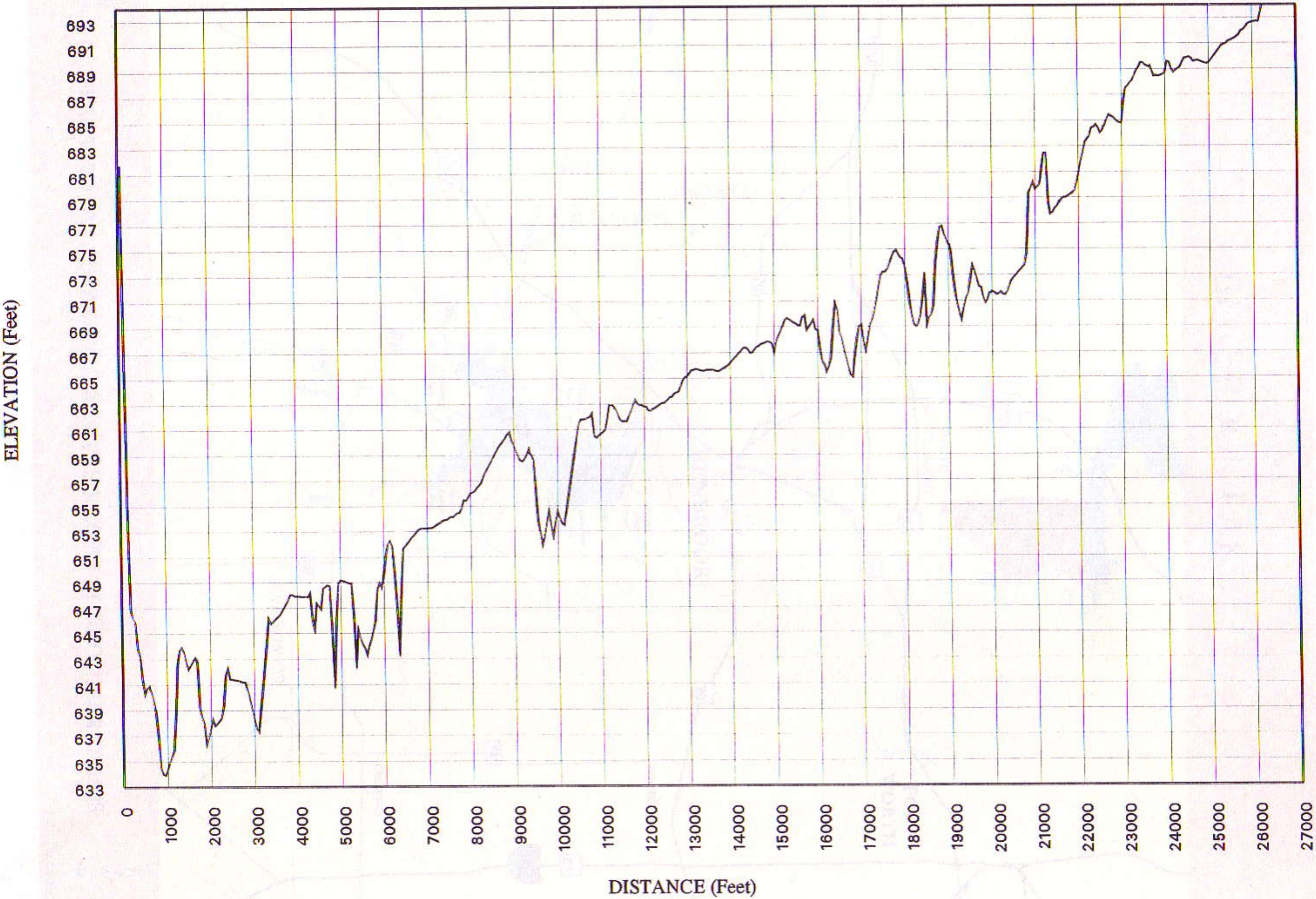
BENBROOK LAKE

Cross Section E-E′



PREPARED BY: TWDB MARCH 1998

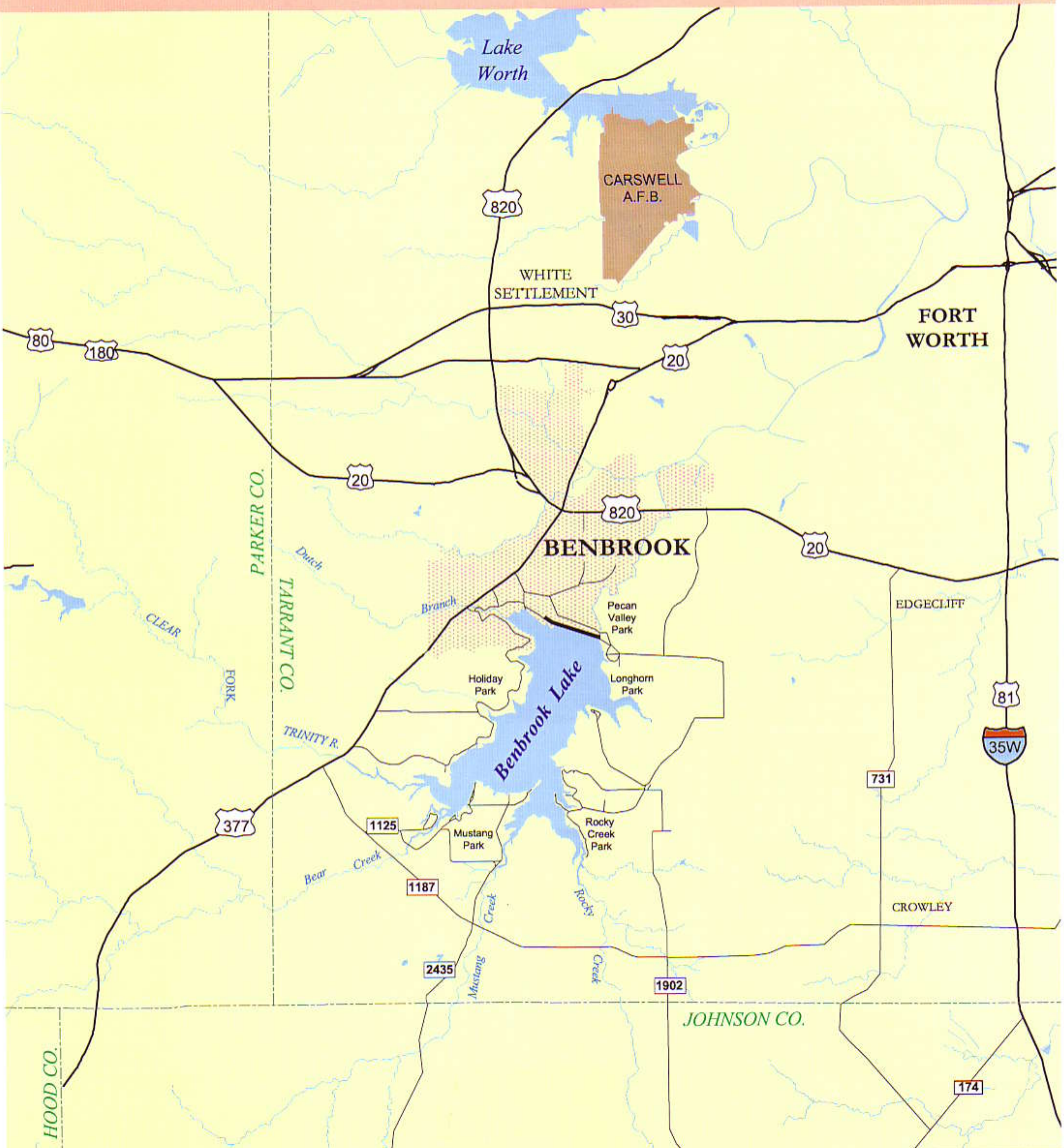
BENBROOK LAKE
Cross Section F-F′



PREPARED BY: TWDB MARCH 1998

FIGURE 1

BENBROOK LAKE



PREPARED BY: TEXAS WATER DEVELOPMENT BOARD MARCH 1998

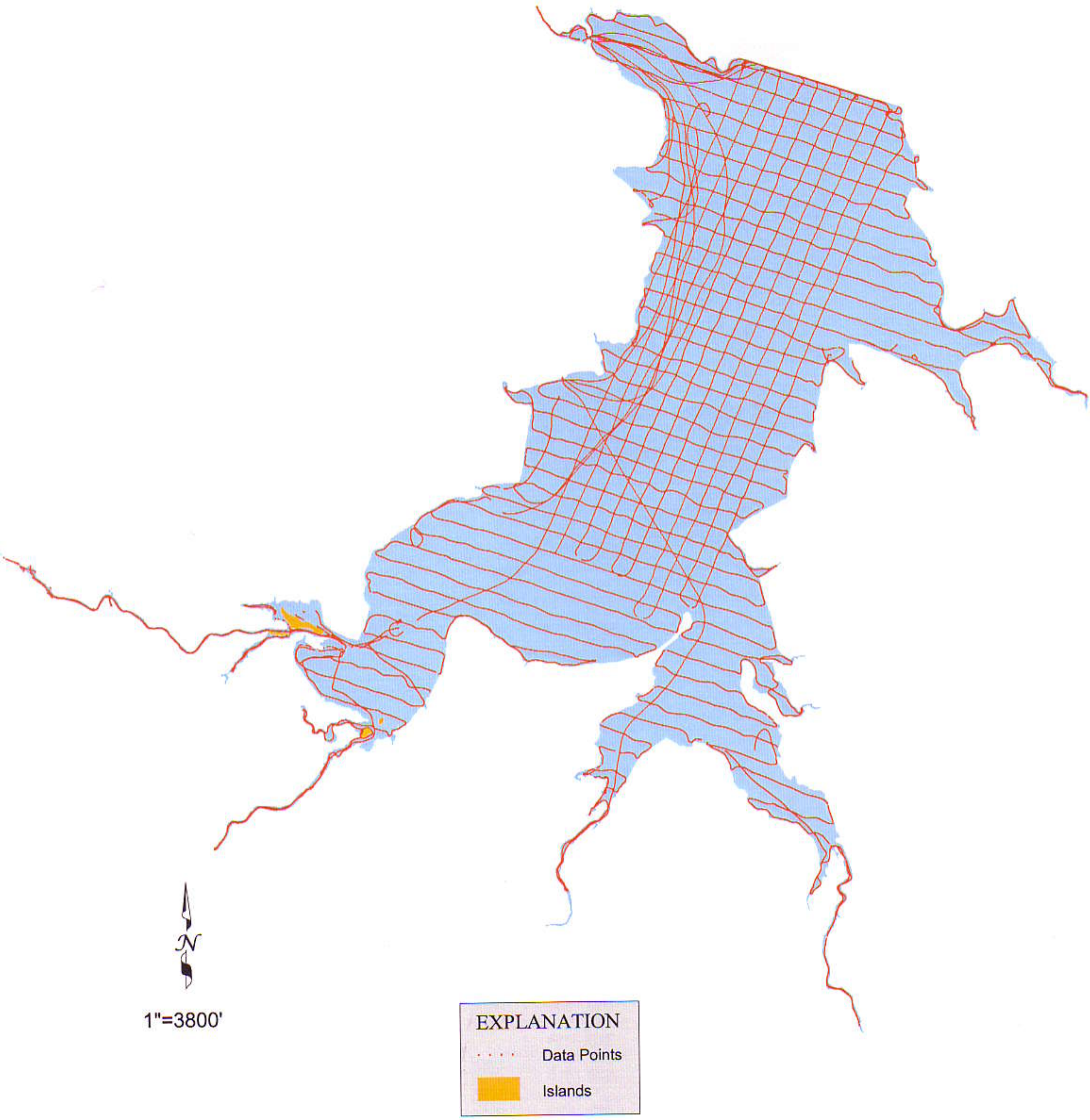
N

1"=14000'

FIGURE 2

BENBROOK LAKE

Location of Survey Data

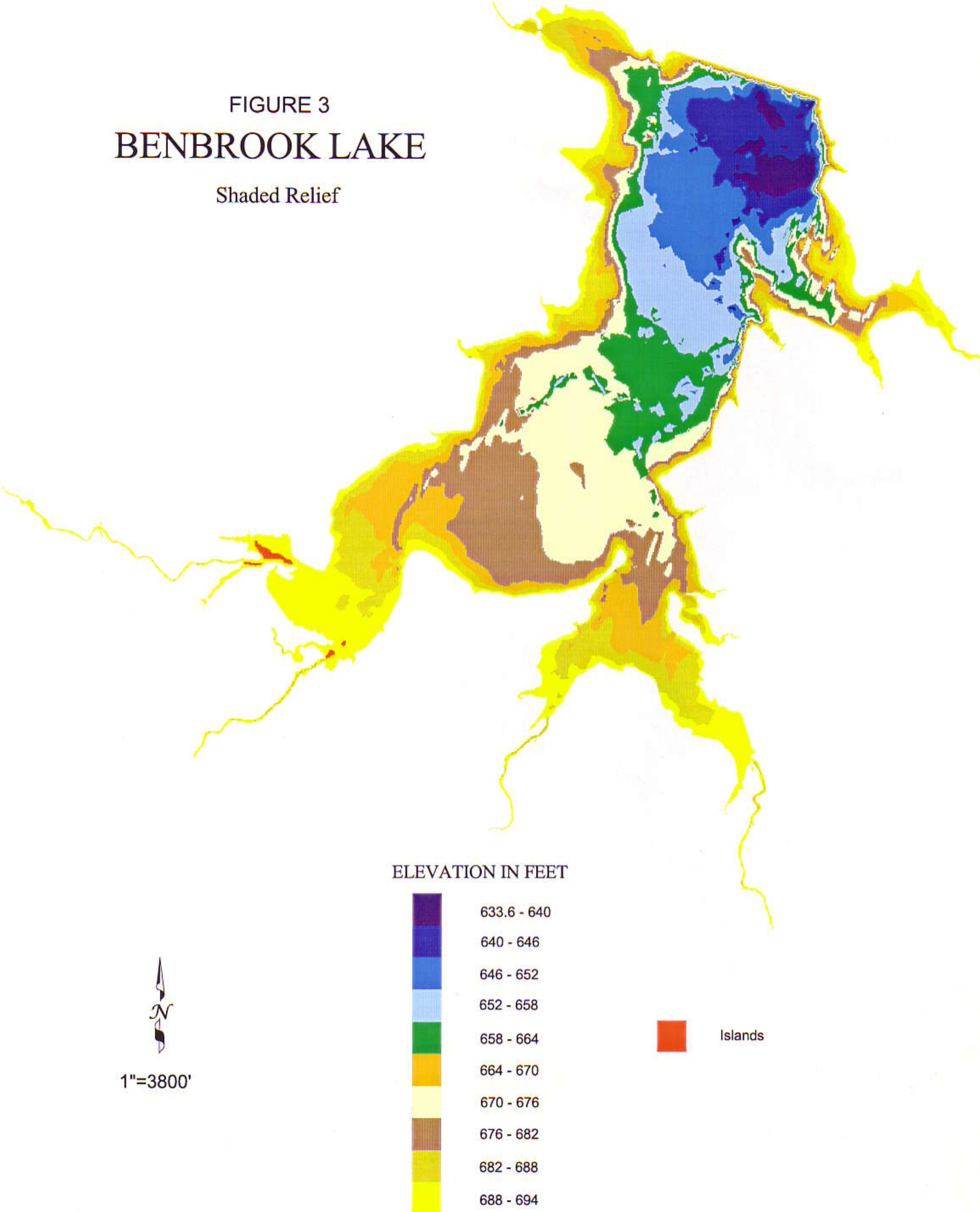


PREPARED BY: TWDB MARCH 1998

FIGURE 3

BENBROOK LAKE

Shaded Relief

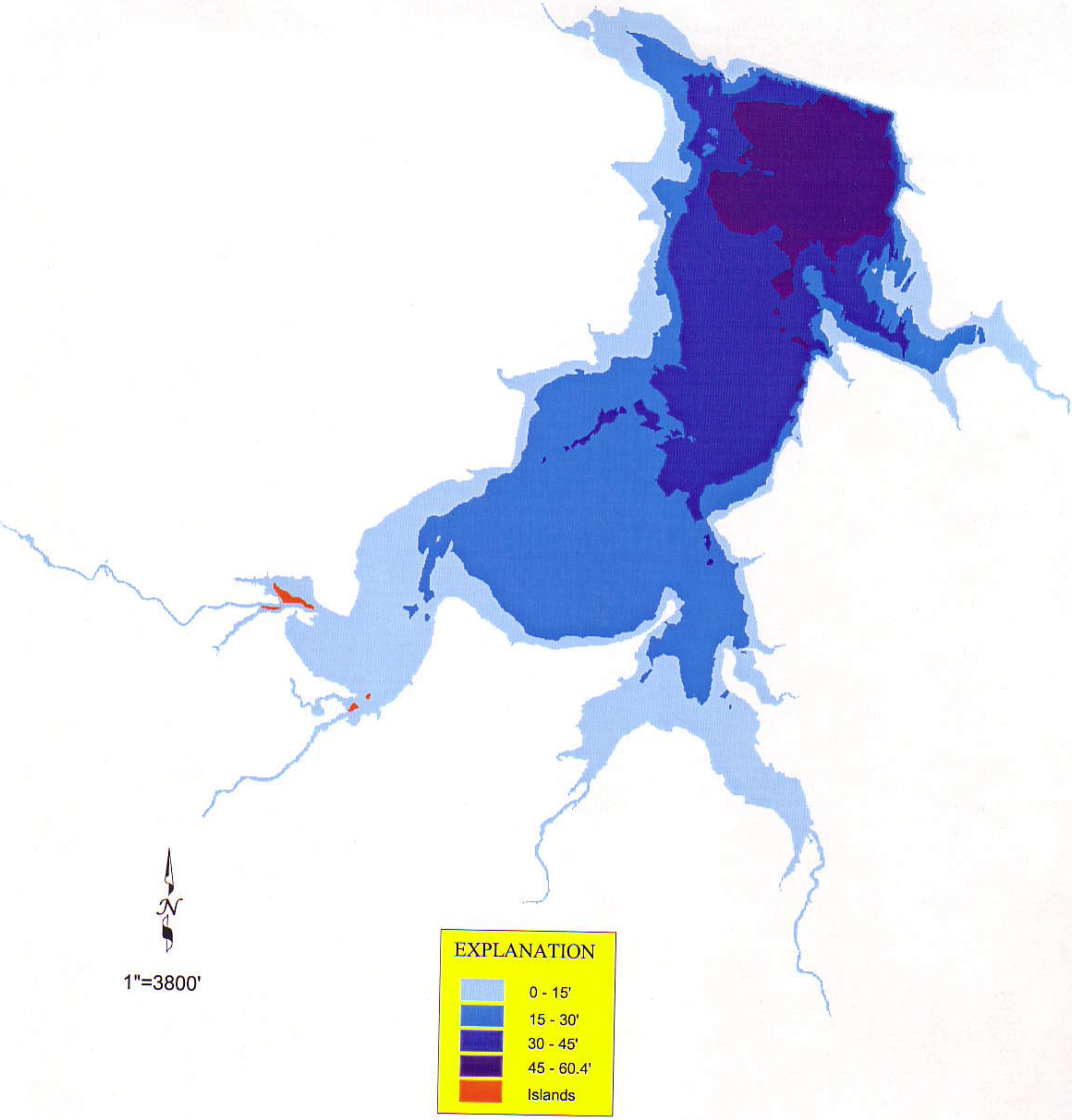


PREPARED BY: TWDB MARCH 1998

FIGURE 4

BENBROOK LAKE

Depth Ranges



PREPARED BY: TWDB MARCH 1998