VOLUMETRIC SURVEY OF LAKE HOUSTON

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CITY OF HOUSTON

Prepared by:

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INTRODUCTION

Staff of the Hydrographic Survey Program of the Texas Water Development Board (TWDB) conducted a hydrographic survey on Lake Houston in February, 1994. The purpose of the survey was to determine the capacity of the lake at the normal pool elevation and to establish baseline information for future surveys. From this information, future surveys will be able to determine sediment deposition locations and rates 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 noted otherwise. The results will be compared to the information from the latest sedimentation survey performed by Ambursen Engineering (1965). At the normal pool elevation of 44.5 feet, they reported a surface area of 12,240 acres and a capacity of 146,769 acre-feet.

HISTORY AND GENERAL INFORMATION OF THE RESERVOIR

Lake Houston, owned by the City of Houston, is located on the San Jacinto River in Harris County approximately 18 miles northeast of downtown Houston. Dam construction commenced in November, 1951 and was completed in December, 1953. Deliberate impoundment of water began April 9, 1954. Ambursen Engineering Company designed the original structure. The general contractors were Elmer Gardner Construction Company and Swope Brothers. Estimated cost of the facility was $14,850,000. In 1970, Brown and Root engineered modifications for erosion control work immediately downstream of the dam. In the following years, Ebasco Engineering and Construction Company designed the plans for dam reparations and LEM Construction was the contractor for the work performed in 1986 and 1987. The repairs to the structure were estimated at $10.3 million.

Lake Houston's dam consists of a conventional Ambursen type reinforced concrete slab and buttress spillway section that is 3,160 feet in length. The spillway has a crest elevation of 44.5 feet. It has an overflow diffusion grill that discharges water into a stilling pool. The spillway is flanked by two compacted earthfill embankments. The left embankment section is 4,000 feet long while the right embankment is 4,600 feet in length with a maximum height of 48 feet. There are two tainter gates (18 ft. wide by 20.5 ft. high) with a sill elevation of 27.3 feet. Also located just east of the spillway are two flashboard type gates (18 ft. wide by 6 ft. high). The sill elevation for the flashboard-type gates is 38.8 feet. A 36 inch diameter low-flow outlet is located in the spillway structure near the right abutment. The invert elevation for the hand-controlled sluice gate is 21.3 feet. Two 72 inch conduits used to divert water for the City of Houston are connected from the pumping station to the intake structure. The conduits' invert elevation is 23.3 feet.

The reservoir's main body of water (approximately 8.5 miles long by 1.5 miles wide) is located between the dam and confluence of the West and East Forks of the San Jacinto River. Major tributaries are Spring Creek, Luce's Bayou, and Caney Creek. Records indicate the drainage basin is approximately 2,828 square miles.

The State Board of Water Engineers issued Permit No. 1323 (Application No. 1394) dated November 26, 1941 to the City of Houston authorizing the impoundment of 152,000 acre-feet of water and the use of 112,000 acre-feet of water annually for municipal, industrial, recreation, mining and irrigation purposes. Permit No. 1411 (Application No. 1510) dated July 19, 1947 authorized an increase in the impoundment capacity to 160,000 acre-feet of water. It also increased the allocation to 168,000 acre feet of water per annum and allowed irrigation of 1,500 acres of land. There is no Adjudication number assigned to the lake at this time.

HYDROGRAPHIC SURVEYING TECHNOLOGY

The following sections will describe the equipment and methodology used to conduct this hydrographic survey. Some of the theory behind Global Positioning System (GPS) technology and its accuracy are also addressed.

GPS Information

The following is a brief and simple description of Global Positioning System (GPS) technology. GPS is a 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.

GPS technology was developed in the 1960's by the United States Air Force and the defense establishment. After program funding in the eary 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 will be reached when the NAVSTAR (NAVigation System with Time And Ranging) satellite constellation is composed of 24 Block II satellites. At the time of the survey, the system had achieved initial operational capability. A full constellation of 24 satellites, in a combination of Block I (prototype) and Block II satellites, was fully functional.

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) can determine positions of moving objects in real-time or "on-the-fly" and was used during the survey of Lake Houston. 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 a second 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. The large positional errors experienced by a single receiver when S/A is active are greatly reduced by utilizing DGPS. The reference receiver calculates satellite corrections based on its known fixed position, which results in positional accuracies within three meters for the moving receiver. DGPS was used to determine horizontal position only. Vertical information was supplied by the depth sounder.

Equipment

The equipment used in the hydrographic survey of Lake Houston 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, a Motorola Radius radio with an Advanced Electronic Applications, Inc. packet modem, and an on-board computer. The computer was supported by a dot matrix printer and a B-size plotter. Power was provided by a water-cooled generator through an in-line uninterruptible power supply. Reference to brand names does not imply endorsement by the TWDB.

The shore station included a second Trimble 4000SE GPS receiver, Motorola Radius radio and Advanced Electronic Applications, Inc. packet modem, and an omni-directional antenna mounted on a modular aluminum tower to a total height of 40 feet. The combination of this equipment provided a data link with a reported range of 25 miles over level to rolling terrain that does not require that line-of-sight be maintained with the survey vessel in most conditions, thereby reducing the time required to conduct the survey.

As the boat traveled across the lake surface, the depth sounder gathered approximately ten readings of the lake bottom each second. The depth readings were averaged over the one-second interval and stored with the positional data to an on-board computer. After the survey, the average depths were corrected to elevation using the daily lake elevation. The set of data points logged during the survey were used to calculate the lake volume. Accurate estimates of the lake volume can be quickly determined using these methods, to produce an affordable survey. 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 strung 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 strung across the body of water, so surveying instruments were utilized to determine the path of the boat. Monumentation was set for each end point 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 it's 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 in 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 hard to detect after the fact. Large reservoirs required multiple shore stations and a crew to move the shore stations to the next location as the survey progressed. Land surveying was again a major cost.

Another method used mainly prior to construction utilized aerial photography to generate elevation contours which could then be used 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.

Survey Methods

The first task of the Hydrographic Survey field staff after arriving at Lake Houston was to establish a horizontal position reference control point. Figure 3 shows the location of all of the control points established for the survey. The location for the first point, TWDB #9 was chosen due to the close proximity to the reservoir, the unobstructed view of the reservoir, and the security of the area. During the survey, the surrounding pine trees caused some interference in receiving information from the overhead satellites . A second benchmark (TWDB #10) was established in a more open area, away from any tree canopies, to correct this problem.

A static survey using two Trimble 4000SE GPS receivers was performed to obtain coordinates for TWDB #9 on February 7, 1994. Prior to the field survey, staff researched locations of known first-order benchmarks and requested City of Houston employees to physically locate the associated monuments prior to arrival. The monument chosen to provide horizontal control was a Harris Galveston County Subsidance District first-order monument named HGCSD-15, located approximately 100 yards west of the pumping station at the west end of the dam. The coordinates for this monument are published as Latitude 29° 54' 48.56034"N and Longitude 095° 08' 44.76861"W. Staff positioned a GPS receiver over this monument and positioned a second receiver over the TWDB #9 control point. Satellite data, with up to six satellites visible to the receiver, were gathered for approximately one hour at both locations in order to determine the coordinates of TWDB #9.

Once data collection ended, staff returned with the equipment to the boat to process the data on the boat's computer. The data was retrieved and processed from both receivers, using Trimble Trimvec software, to determine coordinates for the shore station benchmark. The NAVSTAR satellites use the World Geodetic System (WGS '84) spherical datum. WGS '84 is essentially identical to NAD '83. The WGS' 84 coordinates for TWDB #9 were determined to be North latitude 30° 00' 11.68", West longitude 095° 06' 51.57", and ellipsoid height of -10.97 meters. The approximate NGVD '29 elevation is 52.35 feet. These coordinates were entered into the shore station receiver located over TWDB #9 to fix its location and allow calculation and broadcasting of corrections through the radio and modem to the roving receiver located on the boat during the survey.

The same procedure was used to establish coordinates for the TWDB #10 benchmark on February 14, 1994. The WGS '84 coordinates for TWDB #10 are North Latitude 30° 00' 12.51", West Longitude 095° 06' 54.24" and ellipsoid height of -13.48 meters. The approximate NGVD '29 elevation height is 44.70 feet.

The reservoir's surface area was determined prior to the survey by digitizing the lake boundary from five USGS quad sheets. The names of the quad sheets are as follows: HARMASTON, 1982; CROSBY, 1982; MOONSHINE HILL, 1961, photo-revised 1980; HUFFMAN, 1960, photo-revised 1980 and MAEDAN, 1982. AutoCad software was used to digitize an estimate of the 44.5 contour based on the North American Datum of 1927 (NAD '27) used for these maps. The graphic boundary was then transformed from NAD '27 to NAD '83 using Environmental Systems Research Institutes's (ESRI) Arc/Info project command with the NADCOM parameters, to get the boundary into a more recent datum compatible with the positions received from the satellites. The area of the boundary shape was the same in both datum. All of the collected data and the calculations performed after the survey were done in the NAD '83 datum, a flat projected representation of the curved earth surface. NAD '27 is also a flat projection, but the two datum have a slightly different point of origin, and distinctly different state plane false northing and false easting coordinate to be able to distinguish coordinate points between the two datum.

After the survey, the resulting shape was modified slightly to insure that all data points gathered were within the boundary. The resulting acreage at the normal pool elevation was thereby estimated to be 11,854 acres, or within 3.15 percent of the recorded 12,240 acres. An aerial topo of the upper four feet of the lake or an aerial photo taken when the lake is at the normal pool elevation would more closely define the present boundary. However, the minimal increase in accuracy does not appear to offset the cost of those services at this time.

The survey layout was pre-planned, using approximately 200 survey lines at a spacing of 500 feet. Innerspace Technology Inc. software was utilized for navigation and to integrate and store positional data along with depths. In areas where vegetation or obstructions prevented the boat from traveling the planned line, random data were collected wherever the boat could maneuver. Additional random data were collected lengthwise in the reservoir. Data points were entered into the data set utilizing the DGPS horizontal position and manually poling the depth in shallow areas where the depth was less than the minimum recordable depth of the depth sounder, which is about 3.5 feet. Figure 2 shows the actual location of the data collection sites. Data were not collected in areas that were inaccessible due to shallow water or obstructions. The data set included approximately 99,951 data points.

TWDB staff verified the horizontal accuracy of the DGPS used in the Lake Houston survey to be within the specified accuracy of three meters prior to the survey. The shore station was set up over a known United States Geological Service (USGS) first order monument and placed in differential mode. The second receiver, directly connected to the boat with its interface computer, was placed over another known USGS first order monument and set to receive and process the corrections. Based on the differentially-corrected coordinates obtained and the published coordinates for both monuments, the resulting positions fell within a three meter radius of the actual known monument position.

During the survey, the GPS receivers were operated in the following DGPS modes. The reference station receiver was set to a horizontal mask of 0°, to acquire information on the rising satellites. A horizontal mask of 10° was used on the roving receiver for better satellite geometry and thus better horizontal positions. A PDOP (Position Dilution of Precision) limit of 7 was set for both receivers. The DGPS positions are known to be within acceptable limits of horizontal accuracy when the PDOP is seven (7) or less. An internal alarm sounds if the PDOP rises above the maximum entered by the user, to advise the field crew that the horizontal position has degraded to an unacceptable level.

The depth sounder measures depth by measuring the time between the transmission of the sound pulse and the reception of its echo. The depth sounder was calibrated with the Innerspace Velocity Profiler typically once per day, unless the maximum depth varied by more than twenty feet. The velocity profiler calculates an average speed of sound through the water column of interest (typically set at a range of two feet below the surface to about ten feet above the maximum encountered depth), and the draft value or distance from the transducer to the surface. The velocity profiler probe is placed in the water to wet the transducers, then raised to the water surface where the depth is zeroed. The probe is then lowered on a cable to just below the maximum depth set for the water column, and then raised to the surface. The unit reads out an average speed of sound for the water column and the draft measurement, which are then entered into the depth sounder. The speed of sound can vary based on temperature, turbidity, density, or other factors. 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 ±0.2 feet, plus an estimated error of ±0.3 feet due to the plane of the boat for a total accuracy of ±0.5 feet for any instantaneous reading. These errors tend to be minimized over the entire survey, since some are plus readings and some are minus readings. Further information on these calculations is presented in Appendix A. Manual poling of depths within shallow areas agreed with the depth obtained by the depth sounder typically within ± 0.3 feet, and since the boat is moving much slower, the plane of the boat has much less effect.

Analog charts were printed for each survey line as the data were collected. The gate mark, which is a known distance above the actual depth that was recorded in the data file, was also printed on the chart. Each analog chart was analyzed, and where the gate mark indicated that the recorded depth was other than the bottom profile, depths in the corresponding data files were modified accordingly. The depth sounder was set to record bad depth readings as 0. During post-processing, all points with a zero depth were deleted.

Each of the resulting data points collected consisted of a latitude, longitude and depth reading. The depths were transformed to elevations with a simple awk Unix command based on the water surface elevation each day, rounded to the nearest tenth of a foot since the depth sounder reads in tenths of a foot. The water surface ranged from 45.12 to 45.76 feet during the field survey. The latitude, longitude data set was converted to decimal degrees and loaded into Arc/Info along with the NAD '83 boundary file using the CREATETIN command. The data points and the boundary file were used to create a Digital Terrain Model (DTM) of the reservoir's bottom surface using the Arc\Info TIN module. 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. Areas that were too shallow for data collection or obstructed by vegetation were estimated by the Arc/Info's TIN product using this method of interpolation.

There were some areas where interpolation could not occur because of a lack of information along the boundary of the reservoir. "Flat triangles" were drawn at these locations. ArcInfo does not use flat triangle areas in the volume or contouring features of the model. These areas were located in the upper reaches of the river and were determined to be insignificant on Lake Houston. Therefore no additional points were required for interpolation and contouring of the entire lake surface. From this three-dimensional triangular plane surface representation, the TIN product calculated the surface area and volume of the entire reservoir at one-tenth of a foot intervals.

The three-dimensional triangular surface was then shaded by a GRIDSHADE command. Colors were assigned to different elevation values of the grid. Using the command COLORRAMP, a set of colors that varied from navy to yellow was created. The lower elevation was assigned the color of navy, and the lake normal pool elevation was assigned the color of yellow. Different intensities of these colors were assigned to the different depths in between. Figure 4 consists of the resulting depth shaded representation of the lake. Figure 5 presents a similar version of the same map, using bands of color for selected contour intervals. The color increases in intensity from the shallow contour bands to the deep water bands.

The DTM was then smoothed and linear smoothing algorithms were applied to the smoothed model to produce smoother contours. The following smoothing options were chosen for this model: Douglas-Peucker option with a 1/1000 tolerance level to eliminate any duplicate points, and Round Corners with a maximum delta of 1/1000 of the model's maximum linear size, in an attempt to smooth some of the angularity of the contours. Contours of the bottom surface at two foot intervals are presented in Figure 6. The map has been split into two maps to increase the definition of the contours.

DATA

The main reservoir of Lake Houston starts at the confluence of the West and East Forks of the San Jacinto River and progresses downstream approximately 8.5 miles to the dam. The topography that bounds the perimeter of the lake has a gentle relief and is covered with foliage consisting of mostly large pine trees. Depth charts made during the survey show the lake bed as being quite irregular. Visual observation noted sparse sediment deposits downstream of the FM 1960 Causeway. Larger amounts of sediment were observed upstream of this point. The largest sediment deposits were observed in the West Fork of the San Jacinto River. The farthest point traveled upstream in the West Fork of the San Jacinto River by the survey vessel was approximately one half of a mile downstream of US Highway 59.

Lake Houston was estimated by this survey to encompass 11,854 acres and to contain a volume of 133,990 acre-feet at the normal pool elevation of 44.5 feet. The lowest elevation encountered during the field survey was -2.28 feet, or 46.78 feet of depth and was found in the old river channel, about 2 miles upstream of the dam. The reservoir volume table is presented in Appendix B and the area table in Appendix C. The one-tenth foot intervals are based on actual calculations from the model. An elevation-area-volume graph is presented in Appendix D. No data points were collected in areas where the depth was shallower than two feet because of the draft limitations of the boat. Straight-line interpolation occurs from the last data points collected to the normal pool elevation lake boundary as digitized. The field data collected corresponded well with the boundary data obtained from the USGS map. The Board does not represent the boundary, as depicted in this report, to be a detailed actual boundary. It is a graphical approximation of the actual boundary that was used solely to compute the volume and area of the lake. This boundary does not represent the true land versus water boundary of the lake.

The storage volume calculated by this survey is approximately 8.7 percent less than the previous record information for the lake. The low flow outlet is at elevation 21.3 feet, resulting in a dead storage of 5,127 acre-feet. Therefore, the conservation storage for the reservoir is calculated to be 128,863 acre-feet.

SUMMARY

Previously, a sedimentation survey performed in 1965 by Ambursen Engineering Corporation found that Lake Houston had lost 11,784 acre-feet, or 7.4 percent of its capacity due to sedimentation in the 11 years that had passed since completion of the reservoir. This equates to an estimated loss of 1071.3 acre-feet per year during the 11 year period.

Twenty-nine years later, a second survey was performed by the Texas Water Development Board's Hydrographic Survey Program. The purpose of the survey was to determine the current storage volume of Lake Houston utilizing a technologically advanced surveying system consisting of satellite surveying and digital depth sounding equipment, and digital terrain modeling software. Results from the survey indicate that the lake's capacity at the normal pool elevation of 44.5 feet was 133,990 acre-feet. The conservation storage capacity was calculated to be 128,863 acre-feet. The estimated reduction in storage capacity, compared to the 1965 survey, was 11,637 acre-feet, or 8.3 percent. This equates to an estimated loss of 401.3 acre-feet per year during the last 29 years. The loss since the reservoir was built can be estimated at 585.5 acre-ft per year if results from this survey are compared to the original information on record for the reservoir.

It is assumed that the reduction in estimated storage capacity is due to both a combination of sedimentation, and improved data and calculation methods. Repeating this survey with the same calculation methodology in five to ten years or after major flood events should remove any noticeable error due to improved calculation techniques and will help isolate the storage loss due to sedimentation.

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):

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

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 May 20 1994

RESERVOIR VOLUME TABLE

LAKE HOUSTON FEBRUARY 1994 SURVEY

VOLUME IN ACRE-FEET ELEVATION INCREMENT IS ONE TENTH FOOT

ELEV. FEET	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
				1	1	1	1	1	1	1
1	1	1	1	1	2	2	2	2	2	2
2	3	3	3	3	4	4	4	5	5	5
3	6	6	6	7	7	7	8	8	9	9
4	10	11	11	12	13	14	14	15	16	17
5	18	19	20	22	23	24	25	27	28	30
6	32	33	35	37	39	41	43	45	48	50
7	53	55	58	61	64	68	71	74	78	82
8	86	90	95	99	104	109	114	119	125	131
9	137	143	149	156	163	170	178	186	194	202
10	211	220	229	239	249	259	270	281	292	304
11	316	328	341	355	368	383	397	412	427	443
12	459	476	493	511	528	547	566	585	605	625
13	646	668	690	712	735	758	783	807	832	858
14	884	911	939	967	996	1025	1055	1086	1117	1149
15	1182	1216	1250	1285	1320	1356	1393	1431	1469	1508
16	1548	1589	1630	1672	1715	1759	1803	1849	1895	1942
17	1990	2038	2088	2138	2189	2241	2294	2348	2403	2459
18	2516	2574	2633	2693	2754	2816	2880	2944	3010	3077
19	3145	3214	3285	3357	3430	3505	3581	3659	3738	3818
20	3900	3983	4067	4154	4242	4332	4424	4518	4615	4713
21	4813	4916	5021	5127	5236	5348	5461	5576	5694	5814
22	5936	6061	6187	6316	6446	6579	6714	6851	6990	7131
23	7275	7421	7570	7721	7875	8032	8192	8354	8520	8689
24	8860	9035	9214	9395	9580	9768	9960	10156	10355	10558
25	10765	10976	11190	11409	11632	11859	12089	12324	12563	12805
26	13051	13302	13556	13814	14076	14342	14613	14888	15168	15452
27	15740	16033	16330	16631	16937	17247	17561	17880	18204	18532
28	18865	19203	19545	19893	20245	20602	20964	21330	21701	22077
29	22456	22840	23229	23621	24018	24419	24823	25232	25645	26062
30	26483	26908	27338	27771	28209	28651	29097	29547	30002	30461
31	30925	31393	31865	32342	32823	33308	33797	34291	34788	35289
32	35795	36304	36818	37336	37859	38385	38916	39452	39993	40538
33	41087	41640	42199	42761	43328	43900	44476	45056	45641	46231
34	46825	47424	48028	48637	49250	49868	50491	51118	51751	52389
35	53032	53680	54333	54991	55654	56321	56993	57670	58352	59038
36	59729	60424	61124	61829	62538	63251	63968	64690	65416	66147
37	66882	67622	68366	69114	69866	70621	71381	72145	72912	73683
38	74459	75238	76020	76807	77598	78392	79190	79992	80798	81608
39	82422	83240	84061	84887	85716	86549	87387	88228	89074	89924
40	90779	91638	92501	93368	94240	95117	95997	96881	97770	98662
41	99559	100460	101360	102270	103190	104100	105020	105950	106880	107820
42	108760	109710	110660	111620	112590	113560	114530	115510	116490	117480
43	118480	119480	120480	121490	122510	123530	124550	125580	126610	127650
44	128700	129740	130800	131850	132920	133990				

TEXAS WATER DEVELOPMENT BOARD
RESERVOIR AREA TABLE

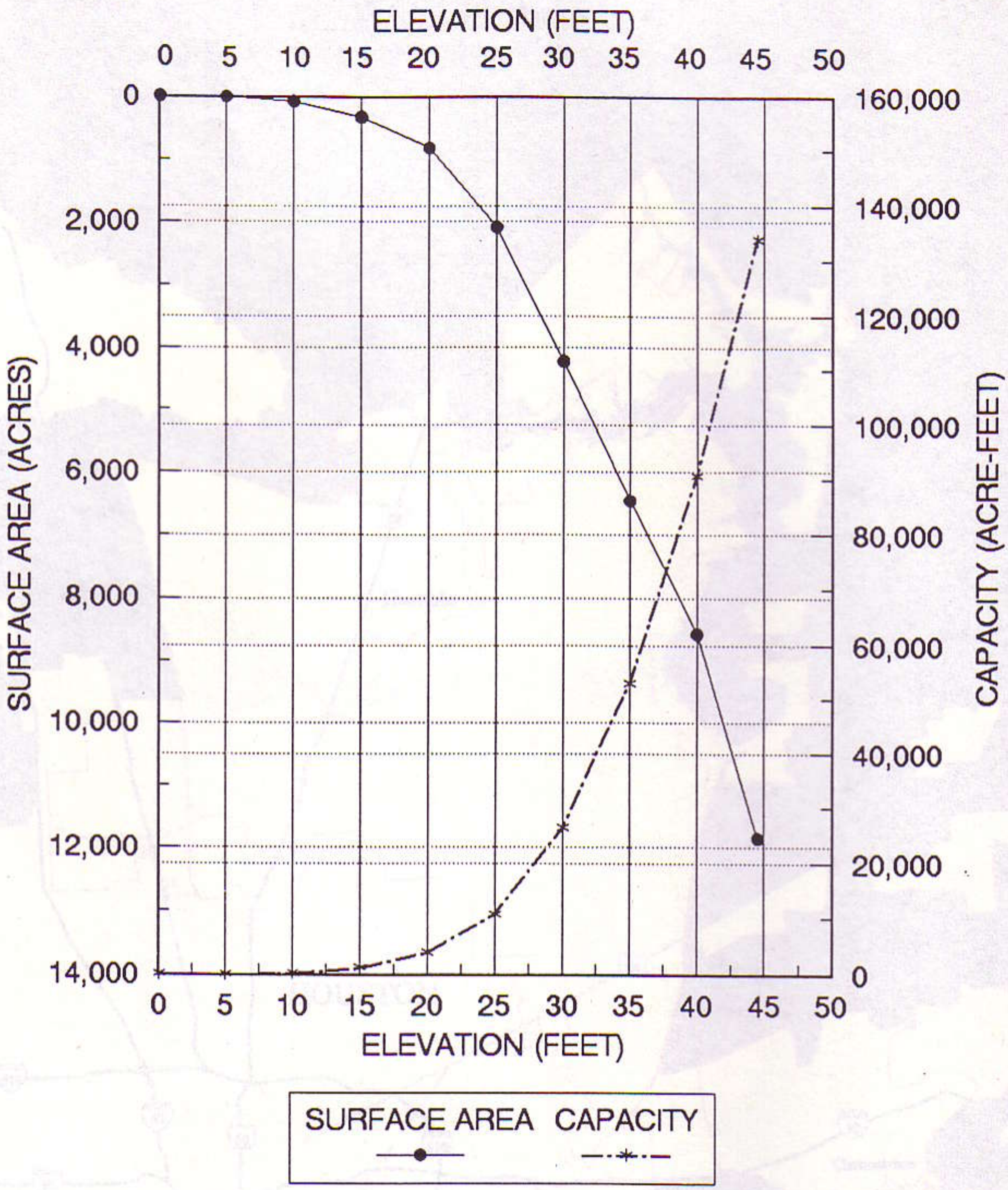
May 20 1994

LAKE HOUSTON FEBRUARY 1994 SURVEY

AREA IN ACRES

ELEVATION INCREMENT IS ONE TENTH FOOT

ELEV. FEET	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
			1	1	1	1	1	1	1	1
1	1	1	1	1	1	2	2	2	2	2
2	2	2	2	3	3	3	3	3	3	3
3	4	4	4	4	4	4	5	5	5	6
4	6	6	7	7	8	8	8	9	9	10
5	10	11	12	12	13	13	14	15	15	16
6	17	18	18	19	20	21	22	23	24	25
7	26	28	29	30	32	33	35	36	38	39
8	41	43	44	46	48	50	52	55	57	59
9	61	64	66	69	71	74	77	79	82	85
10	88	91	95	98	101	105	108	112	116	119
11	123	127	131	135	139	143	147	152	156	160
12	164	168	173	177	182	187	191	196	201	206
13	211	216	222	227	232	238	243	249	254	260
14	266	272	278	285	291	298	304	311	317	324
15	331	338	345	352	359	366	373	380	387	395
16	402	409	417	425	433	442	449	457	465	473
17	482	490	499	508	517	526	535	545	555	565
18	575	585	595	605	616	627	639	651	663	675
19	688	700	713	727	741	754	768	782	796	810
20	825	840	855	874	892	911	930	950	972	994
21	1015	1036	1058	1079	1101	1123	1145	1167	1189	1211
22	1232	1253	1275	1296	1317	1338	1359	1381	1402	1425
23	1449	1474	1500	1527	1554	1583	1612	1641	1671	1702
24	1734	1765	1798	1830	1866	1903	1938	1975	2011	2049
25	2088	2128	2167	2208	2248	2287	2326	2365	2405	2445
26	2484	2522	2560	2600	2642	2686	2731	2776	2819	2861
27	2904	2947	2990	3035	3079	3123	3168	3212	3259	3305
28	3352	3401	3451	3499	3546	3595	3642	3687	3732	3775
29	3818	3861	3903	3946	3988	4029	4069	4109	4149	4189
30	4231	4272	4314	4356	4397	4440	4483	4527	4571	4615
31	4658	4702	4745	4788	4830	4872	4913	4953	4994	5034
32	5075	5116	5159	5202	5245	5289	5334	5381	5427	5471
33	5515	5559	5604	5648	5693	5738	5783	5829	5874	5920
34	5966	6013	6061	6110	6157	6204	6252	6300	6351	6403
35	6456	6507	6556	6604	6652	6698	6745	6792	6839	6885
36	6932	6978	7022	7066	7109	7153	7197	7242	7286	7330
37	7375	7418	7459	7499	7539	7578	7616	7654	7693	7732
38	7771	7809	7847	7885	7924	7963	8003	8042	8080	8119
39	8158	8196	8234	8273	8313	8354	8395	8436	8479	8522
40	8567	8611	8654	8698	8741	8783	8824	8864	8904	8944
41	8984	9024	9065	9107	9151	9197	9244	9294	9346	9402
42	9454	9507	9558	9610	9662	9718	9772	9824	9875	9924
43	9973	10021	10069	10118	10167	10215	10264	10313	10361	10410
44	10459	10508	10557	10606	10655	11854				



LAKE HOUSTON

FEBRUARY 1994 SURVEY

Prepared by: TWDB May 1994

FIGURE 1

LAKE HOUSTON

Location Map

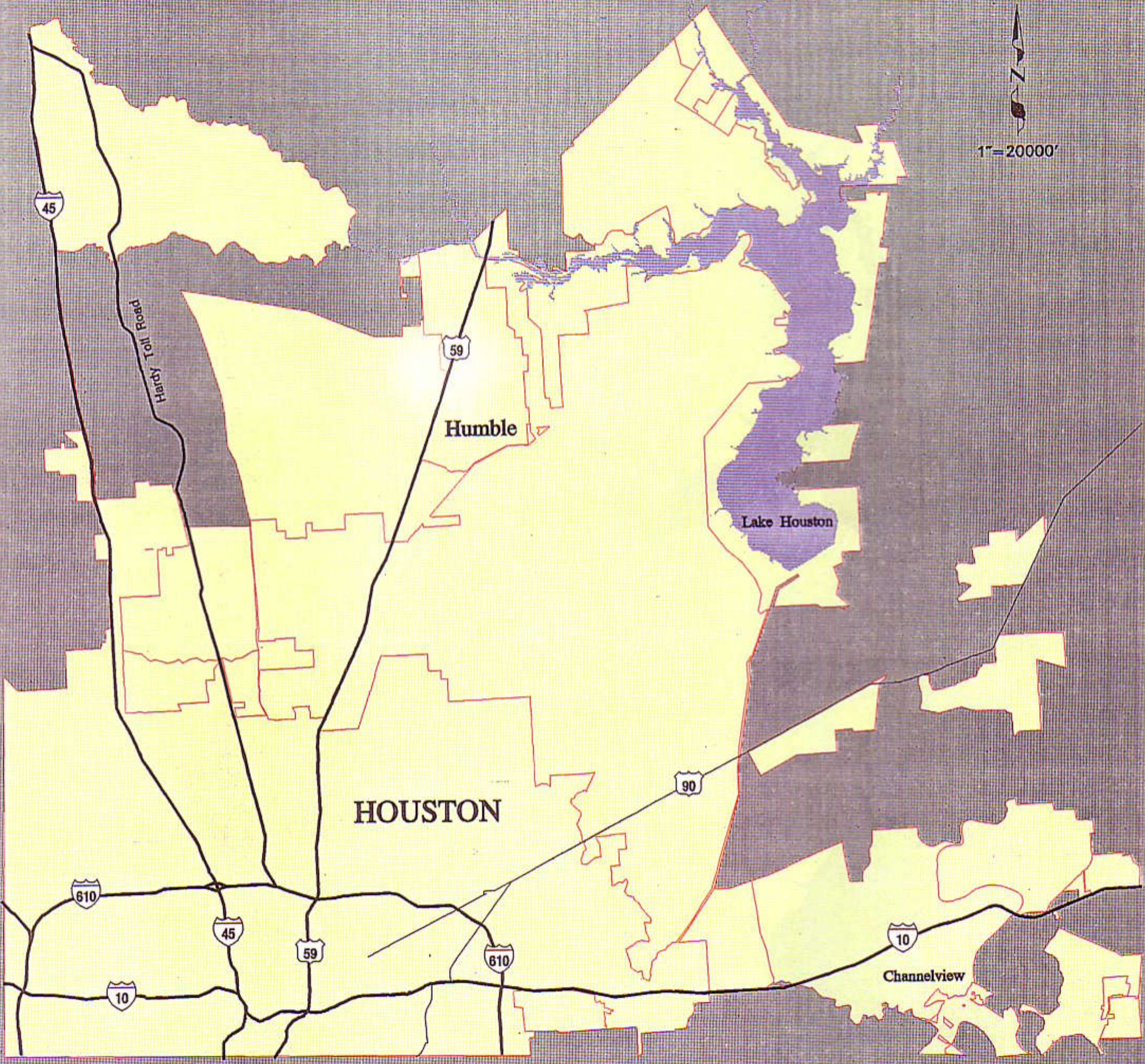
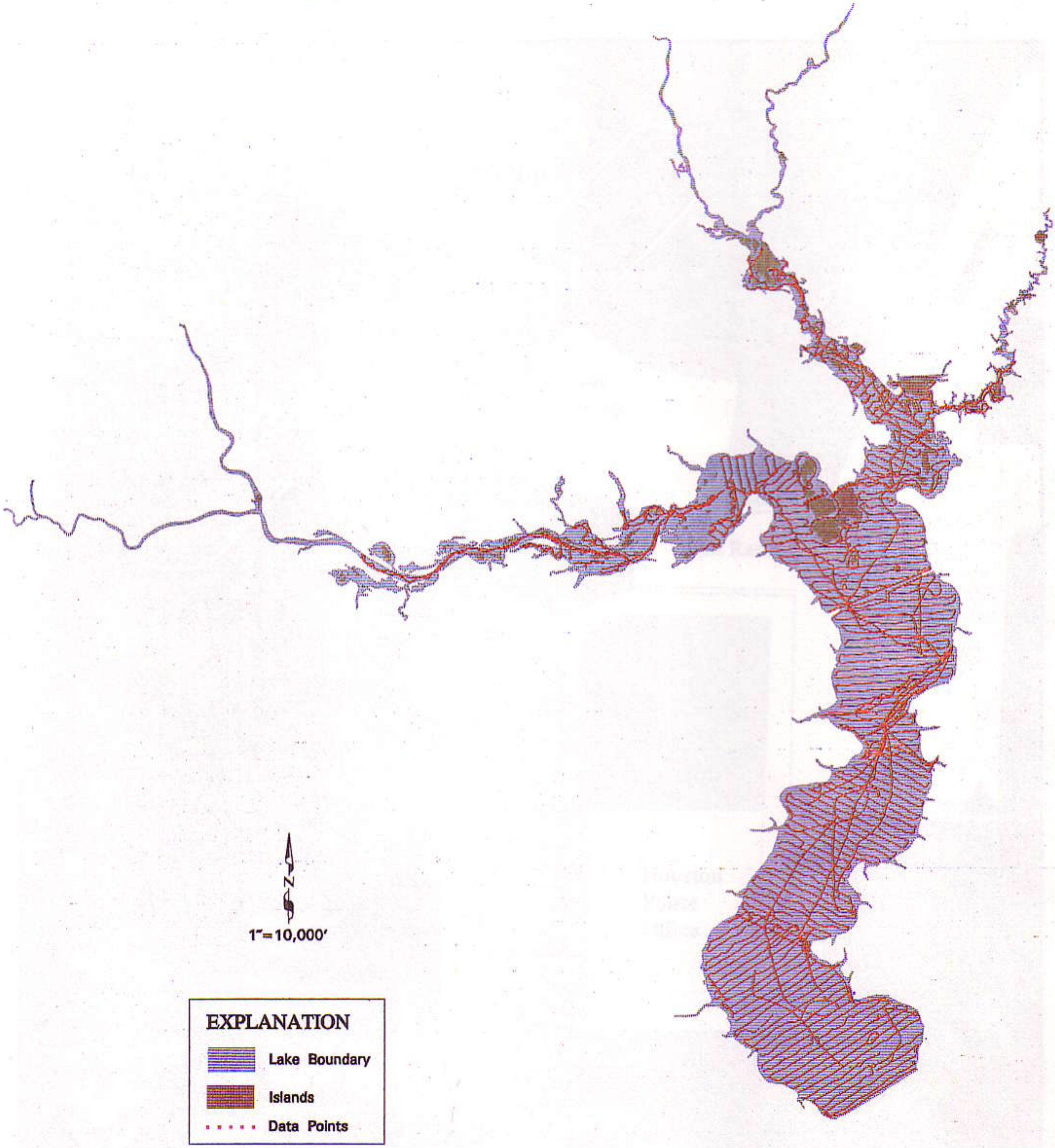


FIGURE 2

LAKE HOUSTON

Location of Survey Data



PREPARED BY: TWDB MAY 1994

FIGURE 3

LAKE HOUSTON

Location of control points # 009 and # 010.

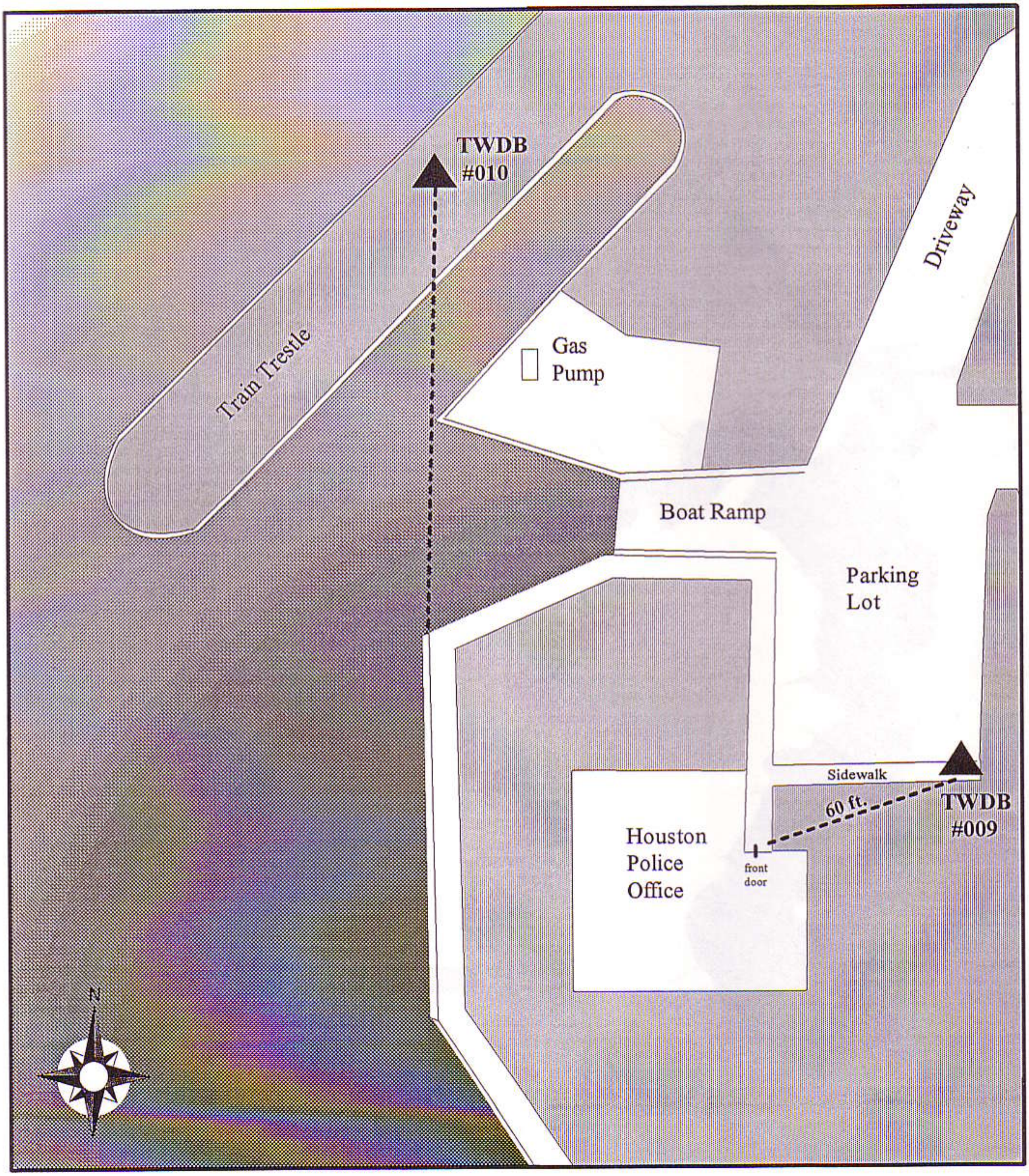
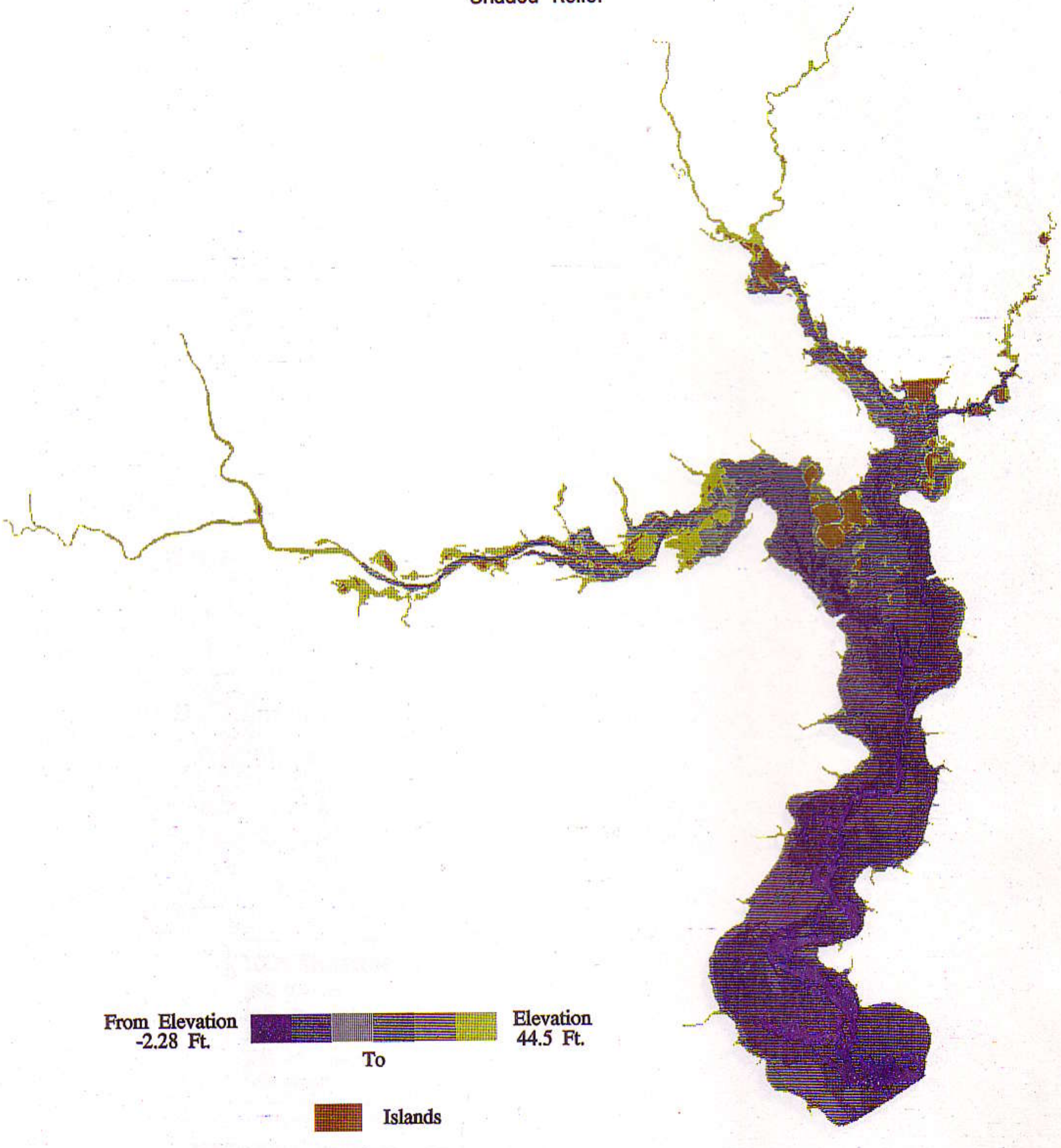


FIGURE 4

LAKE HOUSTON

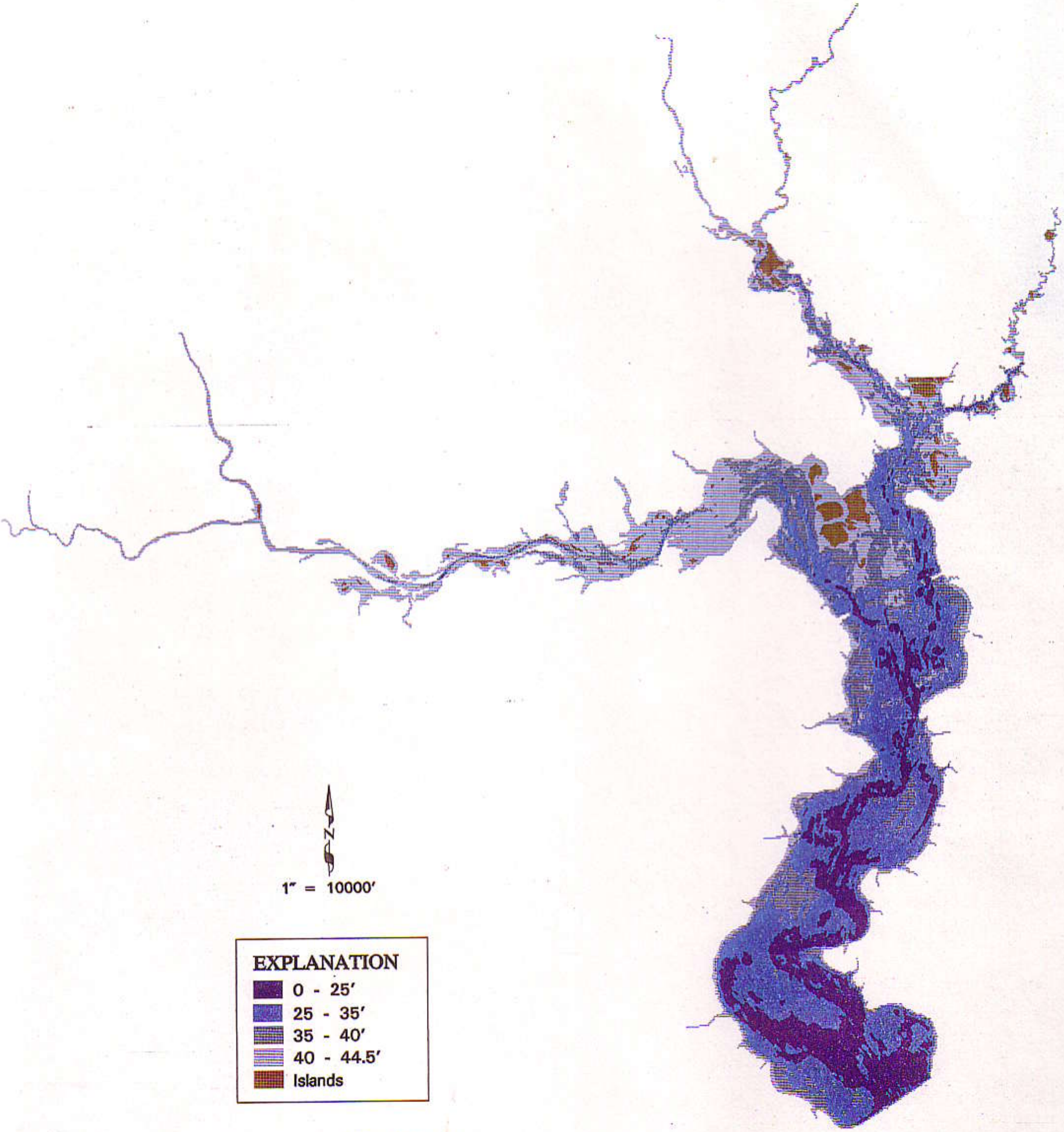
Shaded Relief



PREPARED BY: TWDB MAY 1994

FIGURE 5

LAKE HOUSTON
Depth Ranges



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