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Managing Water in the West

Technical Report No. SRH-2014-15

Pueblo Reservoir 2012 Bathymetric Survey



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

March 2015

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Reclamation Report

This report was produced by the Bureau of Reclamation's Sedimentation and River Hydraulics Group (Mail Code 86-68240), PO Box 25007, Denver, Colorado 80225-0007, www.usbr.gov/pmts/sediment/.

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Pueblo Reservoir 2012 Bathymetric Survey

prepared by

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U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Water and Environmental Resources Division
Sedimentation and River Hydraulics Group
Denver, Colorado

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14. ABSTRACT Reclamation surveyed Pueblo Reservoir in May 2012 to develop updated reservoir topography and compute present storage-elevation relationships (area-capacity tables). The bathymetric survey, conducted near water surface elevation 4,873 feet, was tied to the water surface gage vertical datum that this survey measured around 3.2 feet lower than the North American Vertical Datum of 1988 (NAVD88) (GEIOD12A). This study assumed the reservoir has been operated on the project vertical datum since dam closure in January of 1974. The survey crew used sonic depth recording equipment interfaced with a real-time kinematic (RTK) global positioning system (GPS) that provided sounding positions throughout the underwater portion of the reservoir covered by the survey vessel. The above-water topography was developed from high altitude aerial photography and bare earth data called Interferometric Synthetic Aperture Radar (IFSAR) collected in 2007 near water surface elevation 4,855 (NAVD88). For this study, the developed reservoir topography was tied to NAVD88 (GEOID12A) in US Survey Feet (feet) and resulting elevation versus area and capacity values were shifted down 3.2 feet to the project vertical datum. As of May 2012, at active conservation use elevation 4,880.49, the reservoir surface area was 4,453 acres with a capacity of 245,862 acre-feet. Since dam closure in January 1974 a total capacity change of 19,001 acre-feet below conservation elevation 4,880.49 was measured, resulting in a 7.17 percent loss in reservoir capacity. The capacity change is primarily due to sediment deposition and partially due to methodology differences between this survey and previous surveys.					
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Technical Report No. SRH-2014-15

**Pueblo Reservoir 2012
Bathymetric Survey**

**Pueblo Dam
Colorado**


Prepared: Ronald L. Ferrari

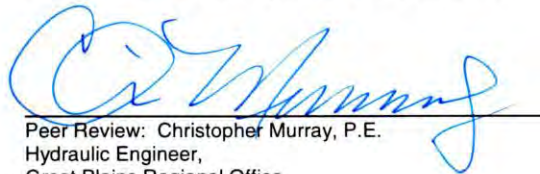
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Introduction

Pueblo Reservoir and Dam, located on the Arkansas River in Pueblo County, are 6 miles west of the city of Pueblo in south-central Colorado. Pueblo Reservoir is one of the major storage features of the Fryingpan-Arkansas Project (Fry-Ark). Fry-Ark is a multipurpose transmountain development that diverts water from the Fryingpan River and tributaries on the western slope of the Rocky Mountains to the Arkansas River on the eastern slope. Additional reservoirs within the project include Ruedi on the western slope along with Turquoise Lake, Mt. Elbert Forebay and Twin Lake Reservoirs on the eastern slope. Pueblo Reservoir is the largest and terminal storage feature of the Fry-Ark (Figure 1).



Figure 1 - Reclamation Reservoirs on the Fryingpan–Arkansas Project.

Pueblo Dam construction began in 1970, was completed in August 1975, and initial water storage began on January 9, 1974. The design of the dam and features are tied to a project vertical datum that could not be determined by this study. The current and assumed original capacity values were tied to a vertical datum that this survey determined to be 3.2 feet lower than NAVD88/GEOID12A (NAVD88) in US Survey Feet (feet). This shift was determined by measuring the reservoir water surface elevation and comparing with the reservoir water surface gage readings. For this 2012 study the elevation computations were tied to the current gage vertical datum. The developed topography was tied to NAVD88 and surface area computations shifted down 3.2 feet to match the vertical datum used for dam operations.

Pueblo Dam is Reclamation’s first and only massive-head buttress dam (Figure 2). The dam has composite earthfill embankments and a concrete midsection with a total crest length of 10,230 feet. The concrete dam consists of 23 massive-head buttresses with a central 550-foot overflow spillway section. The dam has the following dimensions in feet (design elevations in project vertical datum):

Concrete Section:

Structural height ¹	250	Hydraulic height	191
Crest length	1,750	Crest elevation ²	4,921.0
Top width	30	Parapet wall	4,925.25

Earthfill Embankment Section:

Crest length	8,480	Top width	30
Crest elevation	2,925		



Figure 2 - Downstream view of Pueblo Dam and spillway.

¹ Values for concrete dam section. The definition of such terms as “top width,” “structural height,” etc. may be found in manuals such as Reclamation’s *Design of Small Dams* and *Guide for Preparation of Standing Operating Procedures for Dams and Reservoirs*, or ASCE’s *Nomenclature for Hydraulics*.

² Elevations in feet. Unless noted, all elevations based on the operation vertical datum that this study determined was 3.2 feet lower than NAVD88 (GEOID12A). The 2012 reservoir topography was tied to NAVD88 in US Survey Feet (feet). The elevation versus surface area and capacity values from the topography were shifted down 3.2 feet for operational purposes.

The spillway, located within center of the dam's concrete section, is an uncontrolled overflow spillway with crest elevation 4,898.7 (Figure 3). The spillway consists of a concrete ogee crest, training walls, flip bucket, stilling basin, and outlet channel. The spillway capacity at design maximum reservoir elevation 4,919.0 is 191,500 cubic feet per second (cfs).



Figure 3 - Pueblo Dam uncontrolled spillway in center portion of dam's concrete section.

There are five separate outlets that operate at Pueblo Dam. The Bessemer Ditch, located in the right embankment, is controlled by four high-pressure gates with a maximum discharge of 393 cfs. The river outlet, located in the buttress over the streambed, is controlled by two gates with a maximum discharge of 1,120 cfs. The spillway outlets, located under the spillway, consist of three gated conduits with a maximum combined discharge of 8,190 cfs. The fish hatchery outlet, located in the buttress with multilevel gated intakes, controls water quality to the downstream fish hatchery with a maximum discharge rate of 30 cfs. The south outlet, located in a buttress with gated intakes, releases a maximum discharge of 345 cfs for municipal and industrial use.

Description of Basin

The Arkansas River originates in central Colorado, flows southerly to above Salida, Colorado, then east to Pueblo Reservoir. The total drainage area above Pueblo Dam is 4,669 square miles with a net sediment contributing area of 4,170 square miles. The net sediment contributing area is calculated as the total drainage area less areas of the watershed that trap sediment inflow, such as areas above dams. The upper Arkansas River is a steep mountain stream and the headwaters area contains about 25 mountain peaks above 14,000 feet. The river emerges from the mountainous headwaters through the Royal Gorge where the valley gradually widens through the foothills and the plains around Pueblo, Colorado.

The vegetative cover is diverse, varying with topography and the wide range of annual precipitation throughout the basin. In the mountainous regions the precipitation varies widely over relatively short distances with much occurring as snow. In the plains most precipitation is from rainfall. Violent cloudbursts with short-duration flash floods occur frequently in this area. Annual precipitation within the watershed varies from 9 to 19 inches. Due to elevation variation, mean annual temperatures range from 37 to 54 °F with extremes from -54 to 105 °F.

Previous Surveys

Original

The original surface areas for Pueblo Reservoir were determined by planimeter of the topographic maps of the reservoir area developed prior to inundation. The topographic maps had a scale of 1 inch equals 400 feet and 5-foot contour intervals. Prior to inundation, Reclamation established 31 range lines upstream of Pueblo Dam to monitor future changes due to sedimentation.

1993 Survey

The spring 1993 survey was the first since Pueblo Dam closure in January 1974 (Reclamation, 1994). The bathymetric survey, conducted near water surface elevation 4,859, collected data along the 31 range lines established prior to inundation of the reservoir. The small boat system consisted of a sonic depth recorder and a reflector prism mounted on the boat. The distances along the range lines from a known point (usually one of the range end markers) to the small boat were determined by an electronic distance measuring instrument. The topographic survey of the range lines, above the water line, was conducted using standard land surveying techniques

The 1993 reservoir surface areas were computed by the width adjustment method that entails computing new segmental contour areas between the range lines by applying an adjustment factor to the original segmented contour areas. The computed adjustment factor for each segment is the ratio of the new average width to the original average width for the ranges lines that outline the segment at each specified contour elevation. The input data included the original and 1993 range line data along with the original segmental area for each contour elevation. Additional information on collection and analysis procedures is outlined in Chapter 9 of the *Erosion and Sedimentation Manual* (Ferrari and Collins, 2006).

Control Survey Data Information

The 2012 survey established a temporary control point that overlooked the reservoir just downstream of the outer edge of the right abutment, as shown in Figures 4 and 5. The contour point was marked with a yellow plastic cap, labeled “BOR Sediment,” mounted on rebar driven into the ground. The point is considered temporary because it is located in an area that could be easily disturbed. The Online Positioning User Service (OPUS) was used to establish horizontal and vertical control on the temporary point that was occupied for the entire 2012 survey. OPUS is operated by the National Geodetic Survey (NGS) and allows users to submit GPS data files that are processed with known point data to determine positions relative to the national control network. The horizontal control was established in Colorado state plane south coordinates, NAD83, in feet, and elevations were referenced to NAVD88 (GEOID09) in feet (US Survey feet).

The 2012 OPUS generated coordinates were used to measure the horizontal position and the vertical difference between NAVD88 (GEOID09), the recorded water surface elevations during the 2012 survey, and Reclamation monuments located downstream of the dam. The water surface measurements were collected during very calm conditions with no wind or wave action from boat activities on May 13 and 14, 2012 with recorded gage readings between 4,873.09 and 4,873.19. The measured Reclamation monuments included brass caps labeled “Art,” “Blake,” and “Burt.” These monuments were previously surveyed in 2003 by Reclamation’s Western Colorado Area Office with the coordinates and elevations referenced to the “Reclamation vertical datum.”

From the 2012 survey, it appeared the 2003 monument elevations were near the national geodetic vertical datum of 1929 (NGVD29). The 2012 survey did not include any measurements on project structures such as the top of the dam. The RTK GPS topo measurements, tied to NAVD88 (GEOID09), were determined to be 3.2 to 3.3 feet higher than the recorded water surface measurements and 3.0 feet higher than the “Reclamation” datum elevations of the brass monuments. This discrepancy between recorded reservoir water surface and published

Reclamation monument elevations raised concerns about the true project vertical datum to be used for developing the 2012 area and capacity values for reservoir operation. No vertical datum consensus was reached during discussions between the Sedimentation Group and Great Plains Regional personnel. Those involved in past surveys have since retired from Federal service and existing documentation that was located did not provide information to resolve this issue.

In August 2013 RTK GPS measurements were taken to inform the decision of which vertical datum the 2012 survey data (and resulting area and capacity tables) would be referenced to. The temporary point "BOR Sediment" was located and used as the base for the survey. The reservoir water surface elevation recorded at the gage at the time of this survey was 4,846.31; around 25 feet lower than the 2012 survey. The 2013 survey obtained GPS observation control measurements on brass monuments "Blake" and "Burt," and RTK GPS topo measurements of the reservoir water surface, elevation markers used to adjust the reservoir water surface gage, and points along the right abutment of the concrete and earthen portions of the dam as shown in Figures 6 through 11.

The OPUS generated coordinates developed in May 2012 were used to start the survey in NAD83 and NAVD88 (GEOID09). As part of the 2013 survey, the new base information was submitted for OPUS processing. The processed coordinates were tied to NAD83 (2011) and NAVD88 (GEOID12A) that became the control datums for the study. There was a minimal difference between the 2012 and 2013 OPUS solutions. Table one provides a portion of the 2013 measured points and the computed differences from the published project features and recorded water surfaces at time of measurements. As indicated on Figure 6 and Figure 8, the Reclamation monuments were established in 1997, more than 20 years after the construction of Pueblo Dam. The 2003 survey labeled the monument elevations as tied to the USBR datum that the 2012 and 2013 surveys show is near NGVD29. For the Pueblo Reservoir area, the NGS computed difference between NAVD88 and NGVD29 is around 2.9 feet. The difference between the 2012 and 2013 surveys, tied to NAVD88, and the 2003 survey elevations at the two monuments was around 3.0 feet. No information was located to confirm monument elevations were referenced to the vertical datum used during construction of the dam. The two monuments are set in highly stable solid rock and can be used as future survey control around the reservoir.

The 2013 survey visited the right abutment of the earthen and concrete portion of the dam where no monuments were located. GPS measurements were taken on different points of the concrete dam (design elevation 4,921.0) and top of the parapet wall (design elevation 4,925.25). Measurements were also taken on top of the earthen portion of the embankment dam (design elevation 4,925). On average, the measured difference between NAVD88 (GEOID12A) and design elevation drawings of these features were around 2.2 feet.

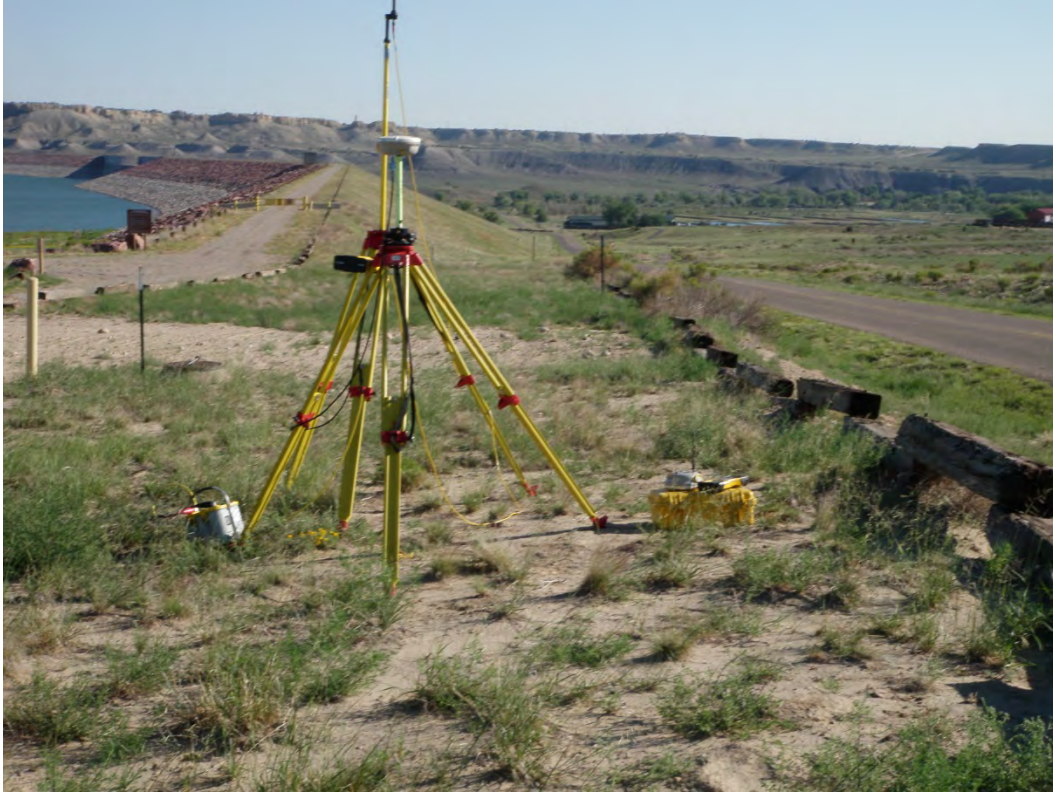


Figure 4 - Temporary control point used as base for the 2012 hydrographic survey.



Figure 5 - Temporary monument labeled "BOR Sediment" established in May 2012.

The 2013 survey included measuring points at the southern boat ramp located near the dam. This included the water surface during very calm conditions and rebar along the eastern curb of the paved boat ramp with labeled elevations between 4,846.0 and 4,883.0. No information was located documenting who set the rebar or what techniques were used, but they are currently used for confirming and adjusting reservoir gage elevation measurements as necessary. As seen on Table 1, the differences between NAVD88 (GEOID12A) and the labeled pins and recorded gage water surface measurements varied between 3.2 and 3.3 feet.

The 2013 survey confirmed the feature elevation differences computed from the 2012 survey data. The 2013 measurements at the base station and on the brass monuments located downstream of the dam were long term observation measurements using a fixed tripod while the measurements on top of the dam, water surface, and elevation pins along the boat ramp were RTK GPS topo measurements using a level survey rod. The level survey rod was also used to obtain topographic measurements on the two brass monuments downstream of the dam. Comparison of the topographic and observation class measurements revealed an average elevation difference of around 0.04 feet between methods.

The 2012 and 2013 survey data was used to determine the vertical datum to reference the 2012 analysis. The 2012 study assumed the same vertical datum has been used to measure the water surface and setting the elevation points along the boat ramp. The 2012 RTK GPS survey conducted near elevation 4,873 measured a 3.2 foot shift between the gage measurements and NAVD88 (GEOID09). The 2013 RTK GPS survey measured a shift between 3.2 and 3.3 feet from the water surface gage (near elevation 4,446) and the marked pins at the boat ramp to NAVD88 (GEOID12A). The average shift for both surveys, around 3.2 feet, was applied to the 2012 study to match the current reservoir operation elevations. Future measurements on other features, such as the spillway crest, may assist in determining the vertical datum used during construction and how the current operational vertical datum compares to the spillway crest elevation.



Figure 6 - Reclamation brass monument "Burt" located on right bank downstream of dam.



Figure 7 - Reclamation monument "Burt" located in solid rock, looking north.



Figure 8 - Reclamation brass monument "Blake" located on right bank downstream of dam.



Figure 9 - Reclamation monument "Blake" in solid rock, looking northwest.

Pueblo Reservoir RTK GPS Survey August 20 of 2013					
Base set on "BOR Sediment" point established in 2012					
2013 OPUS solution tied to NAD83 (2011) and NAVD88					
<u>East</u>	<u>North</u>	<u>Elevation</u>	<u>Description</u>	<u>Elevations</u>	<u>Differences</u>
				<u>Gage and Publications</u>	
3,221,552.517	1,578,425.065	4,938.957	Base, OPUS 2013		
3,223,101.850	1,584,003.785	4,760.779	Blake 1997	4757.81	2.969
3,223,502.218	1,584,522.100	4,755.558	Burt 1997	4752.58	2.978
3,218,528.427	1,578,895.980	4,849.57	ws 8.20.13 810am	4846.3	3.27
3,218,527.849	1,578,892.397	4,850.27	4847 nail	4847	3.27
3,218,531.351	1,578,885.452	4,851.25	4848 nail	4848	3.25
3,218,535.149	1,578,878.254	4,852.30	4849 nail	4849	3.30
3,218,529.159	1,578,897.926	4,849.64	ws 820am	4846.3	3.34
3,218,538.883	1,578,870.992	4,853.27	4850 nail	4850	3.27
3,218,546.687	1,578,856.747	4,855.31	4852 nail	4852	3.31
3,218,550.440	1,578,849.840	4,856.25	4853 nail	4853	3.25
3,218,554.147	1,578,843.010	4,857.25	4854 nail	4854	3.25
3,218,558.171	1,578,835.818	4,858.20	4855 nail	4855	3.20
3,218,562.035	1,578,829.017	4,859.27	4856 nail	4856	3.27
3,218,565.886	1,578,821.866	4,860.25	4857 screw	4857	3.24
3,218,569.776	1,578,815.253	4,861.26	4858 nail	4858	3.26
3,218,573.967	1,578,808.245	4,862.19	4859 nail	4859	3.19
3,218,577.961	1,578,801.467	4,863.19	4860 nail	4860	3.19
3,218,582.908	1,578,793.268	4,864.17	4861 nail	4861	3.17
3,218,587.976	1,578,784.994	4,865.12	4862 nail	4862	3.12
3,218,593.211	1,578,776.485	4,866.16	4863 scew	4863	3.16
3,218,598.532	1,578,768.066	4,867.21	4864 nail	4864	3.21
3,218,609.249	1,578,751.384	4,869.26	4866 nail	4866	3.26
3,218,620.222	1,578,734.733	4,871.16	4868 nail	4868	3.16
3,218,631.530	1,578,718.322	4,873.18	4870 nail	4870	3.18
3,218,649.226	1,578,694.526	4,876.18	4873 nail	4873	3.18
3,218,661.173	1,578,679.218	4,878.19	4875 nail	4875	3.19
3,218,667.610	1,578,671.419	4,879.23	4876 nail	4876	3.23
3,218,680.493	1,578,656.001	4,881.18	4878 nail	4878	3.18
3,218,694.469	1,578,640.287	4,883.27	4880 nail	4880	3.27
3,218,710.358	1,578,622.987	4,885.21	4882 screw	4882	3.21
3,218,738.836	1,578,593.126	4,888.17	4885 pin in road	4885	3.17
3,218,719.613	1,578,613.354	4,886.11	4883 scew	4883	3.11
3,218,459.362	1,578,860.289	4,849.62	ws 845am	4846.3	3.32
3,218,524.389	1,578,899.032	4,849.31	4846 nail in water	4846	3.31

Table 1 - 2013 RTK GPS control survey, NAVD88 (GEOID12A).

Pueblo Reservoir RTK GPS Survey August 20 of 2013						
Base set on "BOR Sediment" point established in 2012						
2013 OPUS, NAD83 (2011) and NAVD88 (GEOID12A)						
<u>East</u>	<u>North</u>	<u>Elevation</u>	<u>Description</u>	<u>Elevations</u>	<u>Differences</u>	
				<u>Gage and Publications</u>		
3,221,552.517	1,578,425.065	4,938.957	Base, OPUS 2013			
3,222,411.58	1,583,964.62	4,923.40	cl concrete dam	4921		2.40
3,222,405.10	1,583,964.59	4,927.63	top wall	4925.25		2.38
3,222,407.01	1,583,965.57	4,927.64	top wall	4925.25		2.39
3,222,416.09	1,583,965.14	4,927.63	top wall	4925.25		2.38
3,222,410.86	1,583,952.50	4,923.31	cl concrete	4921		2.31
3,222,409.94	1,583,928.84	4,923.20	cl concrete	4921		2.20
3,222,409.08	1,583,902.33	4,923.21	cl concrete	4921		2.21
3,222,406.93	1,583,862.85	4,923.08	cl concrete	4921		2.08
3,222,405.29	1,583,819.26	4,923.15	cl concrete	4921		2.15
3,222,403.21	1,583,772.49	4,922.94	cl concrete	4921		1.94
3,222,401.54	1,583,740.43	4,923.02	cl concrete	4921		2.02
3,222,399.74	1,583,704.50	4,922.79	cl concrete	4921		1.79
3,222,398.10	1,583,665.74	4,922.88	cl concrete	4921		1.88
3,222,396.51	1,583,623.26	4,922.70	cl concrete	4921		1.70
3,222,394.88	1,583,586.37	4,922.78	cl concrete	4921		1.78
3,222,393.05	1,583,554.49	4,922.62	cl concrete	4921		1.62
3,222,391.85	1,583,525.01	4,922.65	cl concrete	4921		1.65
3,222,390.98	1,583,506.18	4,923.16	cl concrete	4921		2.16
3,222,387.90	1,583,440.55	4,926.60	cl concrete edge	4925.25		1.35
3,222,385.72	1,583,535.91	4,926.98	wall	4925.25		1.73
3,222,386.94	1,583,555.16	4,927.04	wall	4925.25		1.79
3,222,386.83	1,583,555.20	4,927.06	wall cl disk	4925.25		1.81
3,222,391.60	1,583,428.63	4,926.93	cl earthen dam	4925		1.93
3,222,393.40	1,583,412.57	4,927.30	cl earthen dam	4925		2.30
3,222,395.57	1,583,392.21	4,927.57	cl earthen dam	4925		2.57
3,222,392.12	1,583,366.04	4,927.71	cl earthen dam	4925		2.71
3,222,390.90	1,583,314.48	4,927.45	cl earthen dam	4925		2.45
3,222,389.70	1,583,281.22	4,927.45	cl earthen dam	4925		2.45
3,222,388.23	1,583,256.75	4,927.44	cl earthen dam	4925		2.44

Table 1 - 2013 RTK GPS control survey, NAVD88 (GEOID12A).



Figure 10 - 2013 survey point locations around Pueblo Dam.

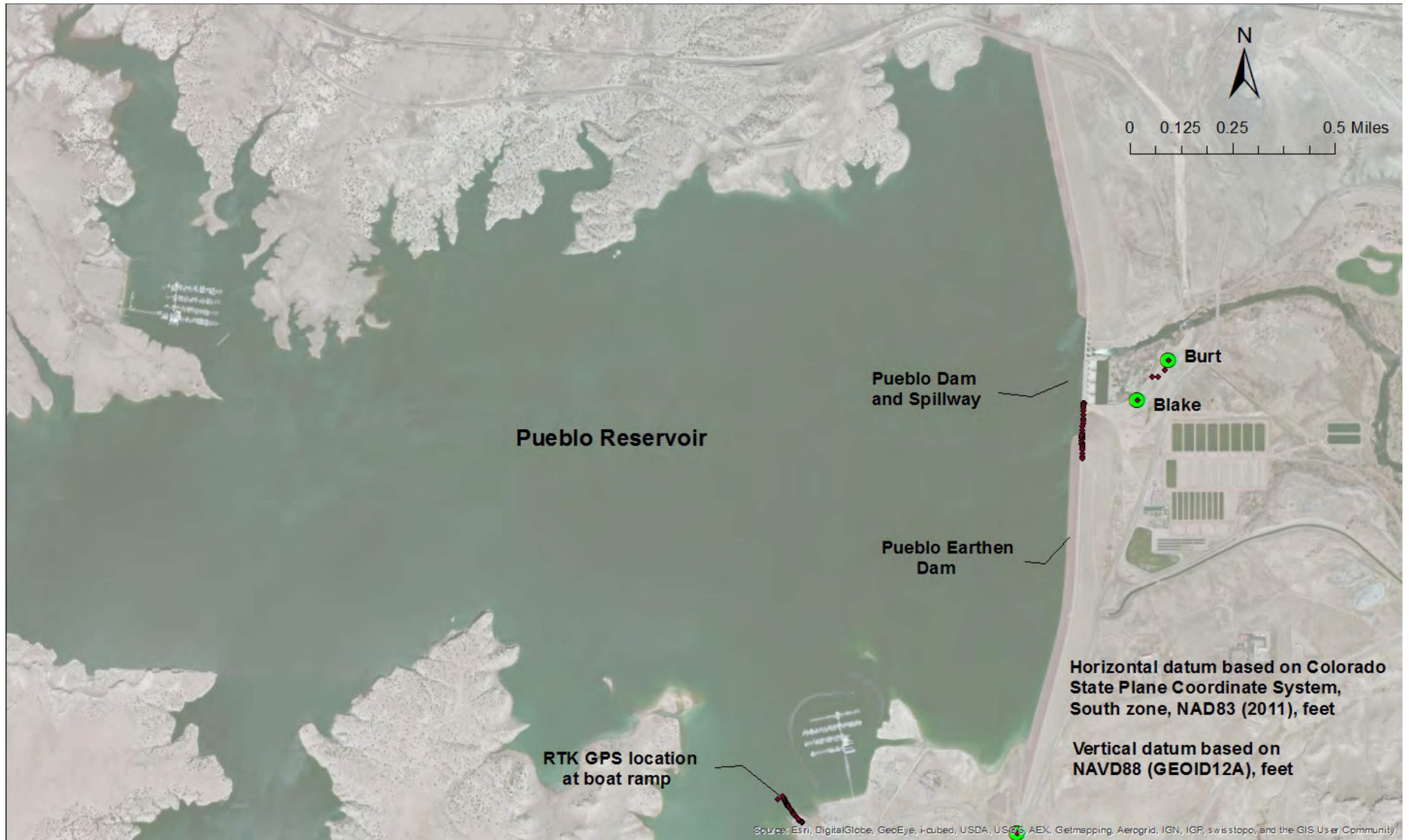


Figure 11 - 2013 survey point locations.

Reservoir Operations

Pueblo Reservoir is the terminal storage facility for the Fry-Ark project and is a multiuse facility providing irrigation and municipal water, flood control storage space, and wildlife and recreation benefits. A 1994 sediment distribution study included 94,939 acre-feet allowance for 81 years of sediment deposition between the streambed and elevation 4,898.7. Of the 94,939 acre-feet, 71,473 are above inactive storage elevation 4,796.7.

The 2012 area and capacity tables were developed using the 2012 bathymetric data combined with IFSAR above water data that covered the entire reservoir area and digitized water surfaces from aerial photography collected over multiple years between reservoir elevation 4,837 and 4,885 (NAVD88). The IFSAR data was collected in 2007 near reservoir elevation 4,855 (NAVD88) and was the latest available information for the above water area. The IFSAR developed contours compared well with the 2012 bathymetry and other data sets in the flat and open areas of the reservoir. Many banks along the Pueblo Reservoir shoreline are steep, approaching vertical in some areas. The IFSAR data did not represent the reservoir shoreline topography well in the steep-bank areas and could not be used for developing reservoir surface area and reservoir capacity above the 2012 bathymetric data set. In these areas the IFSAR data was removed and contours digitized from aerial photographs were used. The upper most aerial contour used was at elevation 4,885 (NAVD88). Consequently, the 2012 study assumed no change in surface area since the 1993 survey from reservoir elevation 4,890.0 and above. The 2012 reservoir topography elevations were tied to NAVD88 and the computed results were shifted downward 3.2 feet to match the operational vertical datum of the reservoir water surface gage. The 2012 total capacity at maximum design operation elevation 4,919.0 was 469,878 acre-feet. Following values are from the May 2012 capacity table (elevations tied to operational vertical datum):

- 131,504 acre-feet of surcharge between elevation 4,898.7 and 4,919.0.
- 26,990 acre-feet of flood control between elevation 4,893.8 and 4,898.7.
- 65,522 acre-feet of joint use between elevation 4,880.49 and 4,893.8.
- 220,261 acre-feet of active conservation between elevation 4,796.7 and 4,880.49
- 23,706 acre-feet of inactive storage between elevation 4,764.0 and 4,796.7.
- 1,895 acre-feet of dead storage below elevation 4,764.0.

Surface area information from the 1993 study allowed the 2012 tables to be extended to elevation 4,925.0 with a computed total capacity of 516,061 acre-feet. Pueblo Reservoir inflow and end-of-month stage records in Table 2 show the annual fluctuation for water years 1974 through May 2012. The average reservoir water inflow during this period was 589,890 acre-feet. Since the initial year of operation, 1974, the levels have ranged from maximum elevation 4,888.4 in 1996

to minimum elevation 4,819.9 in 2004. The spillway is an uncontrolled overflow with crest elevation 4,898.7 that has never been used.

Hydrographic Survey, Equipment, and Method of Collection

Bathymetric Survey Equipment

Bathymetric survey equipment was mounted on two aluminum vessels for the 2012 survey. An 18-foot flat-bottom aluminum boat had a single beam transducer mounted over the side for surveying shallower areas (Figure 12). A multibeam bathymetric survey system with transducer mounted to the bow of a 24-foot trihull aluminum vessel was for mapping in deeper water as shown in Figure 13. The hydrographic systems for each vessel included a GPS receiver with built-in radio, a multibeam or single beam depth sounder, helmsman display for navigation, computer, and hydrographic system software for collecting the underwater data. Batteries powered the collection system on the smaller boat while an on-board generator supplied power to the large boat equipment. The shore equipment included a GPS receiver with an external radio. The GPS receiver and antenna, powered with a 12-volt battery, were mounted on a survey tripod over a known datum point.

The Sedimentation Group uses RTK GPS with the major benefit being precise elevations measured in real time to monitor water surface elevation changes and to determine the vertical datum of the study. Similarly to differential GPS, the RTK GPS system employs two receivers that track the same satellites simultaneously. The basic outputs from a RTK receiver are precise 3-D coordinates in latitude, longitude, and elevation with accuracies on the order of 2 centimeters horizontally and 3 centimeters vertically. The RTK output is on the GPS WGS-84 datum that the hydrographic collection software converted into Colorado's state plane south coordinates, NAD83 (2011), and elevations tied to NAVD88 in US Survey Feet (feet).

The Pueblo Reservoir bathymetric survey was conducted between water surface elevations 4,872.9 and 4,873.3 from May 11 through May 15, 2012. The bathymetric survey used multibeam and single beam sonic depth recording equipment interfaced with RTK GPS that measured the sounding locations in the reservoir area traversed by the survey vessel. Before the survey field work was initiated, grid lines were established throughout the reservoir with the survey system software and used as a guide during the field collection. The survey system software continuously recorded reservoir depths and horizontal coordinates as the survey boat moved along these grid lines. Shoreline data was



Figure 12 - Survey vessel for reservoir mapping with mounted single beam transducer on side (Lake Sumner-New Mexico, March 2013).



Figure 13 - Large survey vessel with mounted instrumentation for mapping upstream of Grand Coulee Dam on Franklin D. Roosevelt Reservoir, Washington.

collected as the vessel traversed to each grid line and as it returned to port each day. The survey vessel's guidance system provided directions to the boat operator to assist in maintaining a course along the predetermined grid lines. As each line was traversed, the depth and position data were recorded on the laptop computer hard drive for subsequent processing, resulting in point data at one second intervals for the single beam data, and 5-foot grids for the multibeam data sets. The water surface elevations at the dam from Reclamation gage records and RTK GPS measurements were used to convert the sonic depth measurements to lake-bottom elevations. The reservoir mapping was tied to NAVD88 and resulting surface areas were shifted downward 3.2 feet to match the vertical datum of the current reservoir water surface gage measurements.

Single Beam System

Portions of the underwater data were collected using a single beam depth sounder at a 200 kHz frequency calibrated by adjusting for the speed of sound through the water column which varies with density, salinity, temperature, turbidity, and other conditions. The data was digitally transmitted to the computer collection system through a RS-232 serial port. The single beam produced digital charts of the measured bed and when the charted depths indicated a difference from the computer recorded bottom depths, the computer data files were modified during the analysis to match the chart.

Multibeam Survey

In 2001, the Sedimentation Group began using an integrated multibeam hydrographic survey system. The system consists of a single transducer mounted on the center bow of the boat. From the single transducer, a fan array of narrow beams generates detailed bathymetry as the survey vessel passes over the areas mapped. The system transmits 80 separate 1-1/2-degree slant beams resulting in a 120-degree swath from the transducer. The 200 kHz frequency, high-resolution multibeam echo sounder system measures the relative water depth across a wide swath perpendicular to the vessel's track that is about 3.5 times as wide as the water depth below the transducer (in 100 feet of water depth the bottom swath width would be approximately 350 feet).

The multibeam system is composed of several instruments all in constant communication with a central on-board laptop computer. The components include the RTK GPS for positioning; a motion reference unit to measure the heave, pitch, and roll of the survey vessel; a gyro compass to measure the yaw or vessel attitude; and a velocity meter to measure the speed of sound through the vertical profile of the reservoir water. The multibeam sounder was calibrated by lowering the velocity meter that measured the sound velocity through the reservoir water column. The individual depth soundings were adjusted by the measured speed of sound which can vary with density, salinity, temperature, turbidity, and other conditions. With proper calibration, the data processing software uses all the incoming information to provide an accurate detailed xyz

data set of the lake bottom. The multibeam survey system software continuously recorded reservoir depths and horizontal coordinates as the survey vessel moved along closely-spaced grid lines. Most transects (grid lines) were run parallel to the reservoir alignment with the multibeam swaths overlapping in the deeper areas to provide full bottom coverage of these surveyed areas. In the shallower areas of the reservoir the multibeam swaths did not overlap, but the additional beams did provide more reservoir bottom detail than would have been possible using the single beam system only.

Bathymetric Data Sets

Figures 14 and 15 shows the areas of the reservoir surveyed by the two bathymetric collection systems, single and multibeam. The bathymetric data was processed using the hydrographic system software. During processing, all corrections such as vessel location, roll, pitch, and yaw effects were applied. Other corrections included applying the sound velocity through the reservoir water column and converting all depth data points to elevations using the measured water surface elevation at the time of collection with all tied to NAVD88. To reduce the time required for topographic map processing, without compromising survey accuracy, the massive amount of the multibeam data was filtered into 5-foot cells or grids. For the single beam data, it was filtered to 1-second intervals retaining the maximum depths during the collection. The combination of multibeam and single beam soundings resulted in a detailed data set of around 3,132,000 xyz points that represents the reservoir bed elevations below the water surface at the time of the collection. Additional information on general bathymetric data collection and analysis procedures can be found in *Engineering and Design: Hydrographic Surveying* (Corps of Engineers, January 2002) and *Reservoir Survey and Data Analysis* (Ferrari and Collins, 2006).

Aerial Photographs

During analysis, orthographic aerial images collected over several years (2005-2011) between water surface elevations 4,837 and 4,885 (NAVD88) were downloaded from the USDA data web site (USDA, 2010). The aerial photos with the highest water surface elevation and clearest imagery were collected in 2010. Reservoir contours were developed by digitizing the water's edge from the 2010 aerial images and used in areas not included in the 2012 bathymetric data and along the steep banks where the IFSAR data was unreliable. Figures 16 and 17 provide images of the upper sediment delta of the reservoir at different water levels. In 2010 the reservoir was at elevation 4,884.9 (NAVD88) and aerial photos in the upper end show a relatively straight shoreline with the river flowing through the southern portion of the delta (Figure 16). The 2011 aerial image was collected at reservoir elevation 4,873.3 (NAVD88) showing more of the sediment delta and the river, once again, in the southern portion of the sediment delta which is much more exposed due to the lower water surface (Figure 17). The aerial images indicate sediment deposition in the upper reservoir elevations, but did not

provide sufficient data to develop the topography accurately to represent the 2012 reservoir conditions in that area. IFSAR data was collected in 2007 and had limitations along the steep reservoir banks, allowing it to be used for reservoir topography development, but not for accurate surface area computations.

IFSAR Data Set

Development of the topography for areas of the reservoir not covered by the 2012 bathymetric survey required additional information. Interferometric Synthetic Aperture Radar (IFSAR) digital data was obtained as a bare earth raster collected in 2007, tied to Colorado's state plane south zone, with vertical elevations tied to NAVD88. IFSAR airborne technology enables mapping of large areas quickly and efficiently, resulting in detailed information at a much lower cost than other technologies such as aerial photogrammetry and LiDAR. The IFSAR data was collected when the reservoir was drawn down to around elevation 4,855 (NAVD88), allowing data in areas not covered by the 2012 bathymetric survey to be used for developing the reservoir topography. The IFSAR reported accuracies are 2 meters or better horizontally and 1 meter or better vertically for areas of unobstructed flat ground (Intermap, 2011). Along with the aerial photography, the IFSAR data was the best available information to merge with the 2012 bathymetric data for developing continuous topography of Pueblo Reservoir.

During analysis all data sources were overlaid, revealing issues with the IFSAR data in the steep areas along the reservoir shoreline. In the flat open areas with limited vegetation, the IFSAR data compared very well with overlapping 2012 bathymetric data and aerial images. During processing of the various data sets, areas that overlapped the 2012 bathymetry were clipped out along with data in questionable areas, such as the IFSAR data on the steep slopes. In these near-shore areas, the digitized water surfaces from aerial photographs were used to represent the shoreline, leaving gaps in the contours. The contours in these blank spaces along the shoreline were interpolated using a GIS program that developed the 2012 reservoir topography between the digitized water surface contours and the upper elevations of the IFSAR data. This interpolation technique smoothed contours above the 2010 USDA elevation 4,884.9 contour, creating topography that is not a true representation of the shoreline geometry in that area. Breaklines were not created to improve contour development since computed surface areas would represent interpolated contours, not actual topography, in these areas. To avoid interpolated contour and surface area problems the 2012 study assumed no change in the reservoir surface area, since the 1993 study, from elevation 4,890.0 and above.

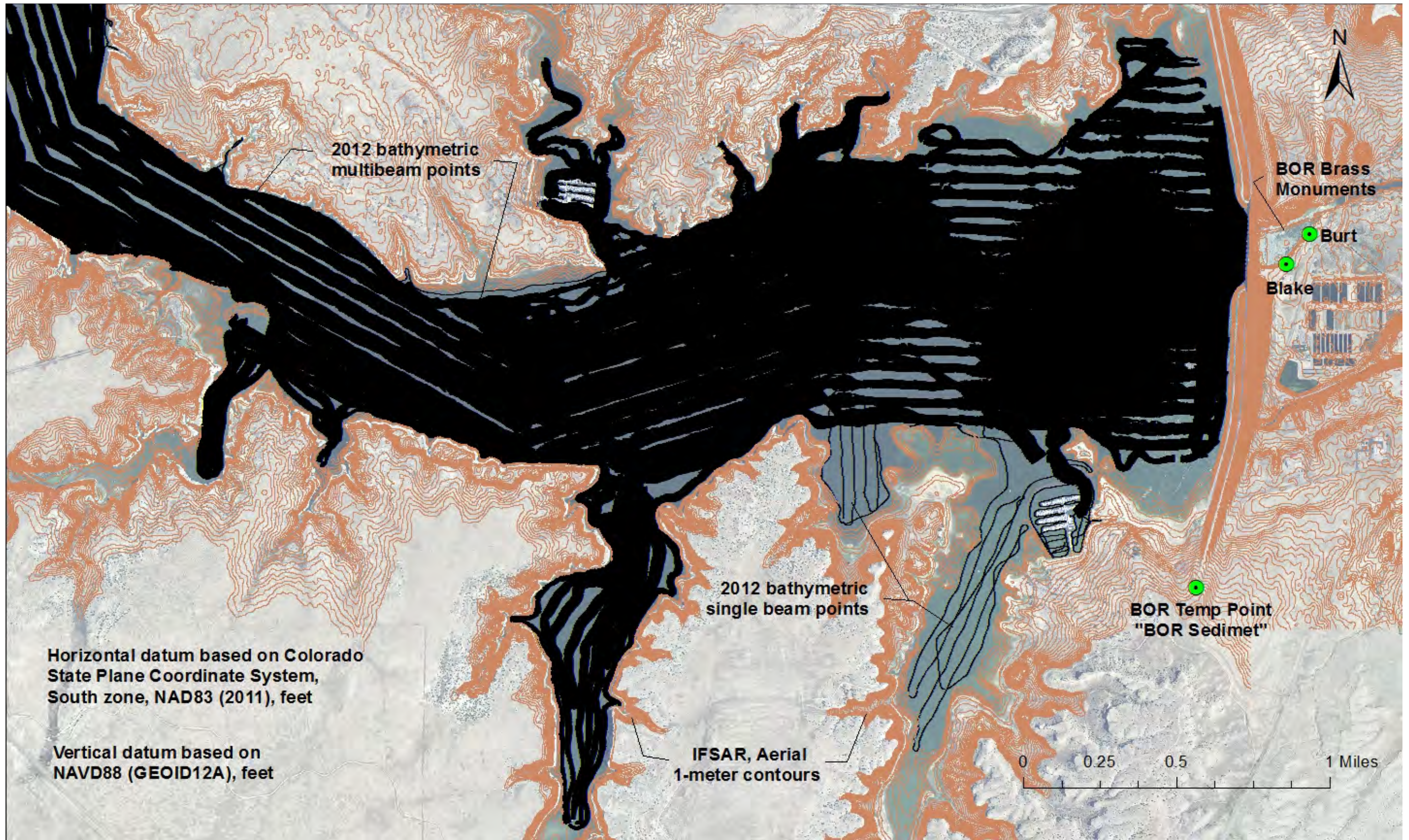


Figure 14 - Pueblo Reservoir 2012 data sets, NAVD88 (GEOID12A).

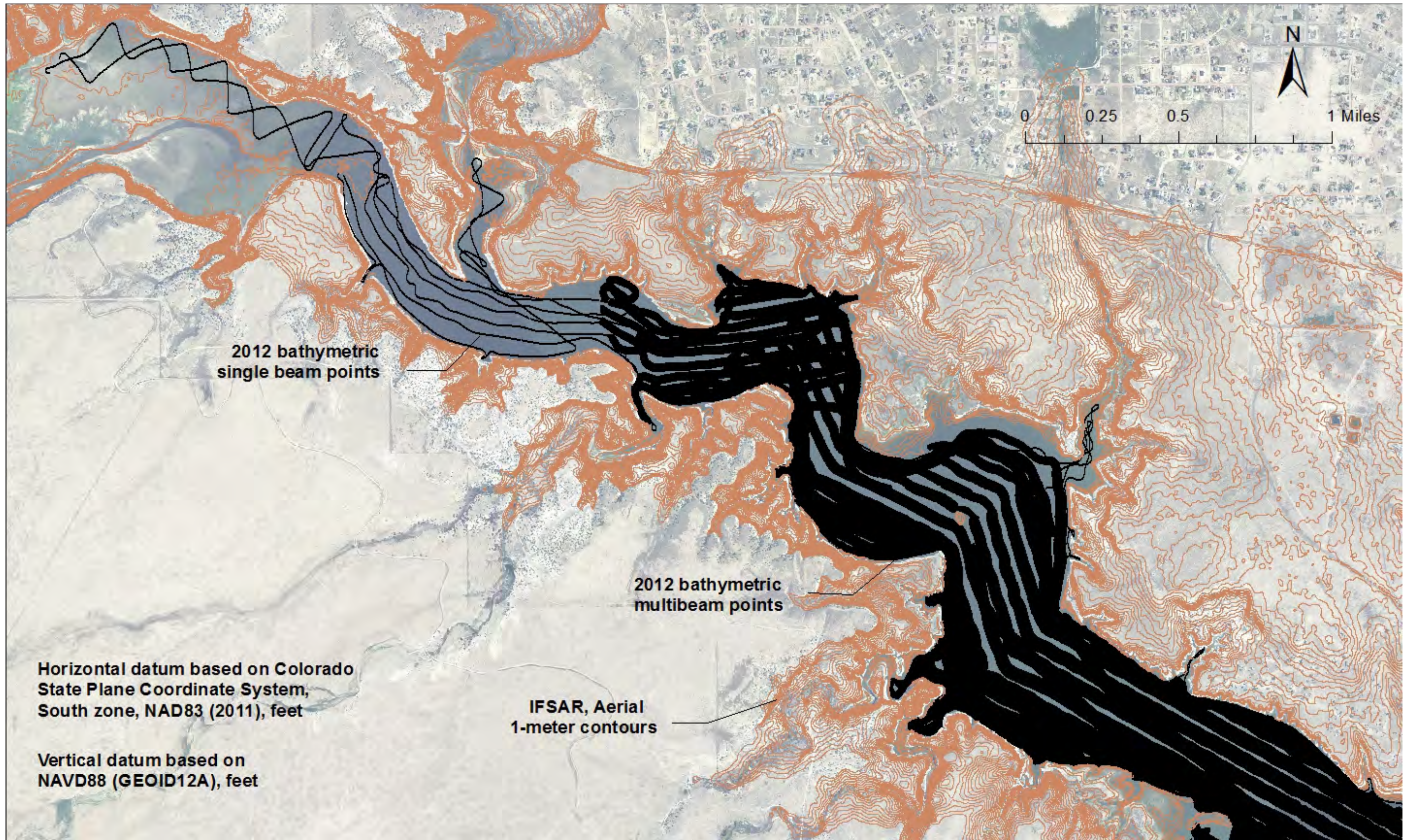


Figure 15 - Pueblo Reservoir 2012 data sets, NAVD88 (GEOID12A).



Figure 16 - Pueblo Reservoir, upper reservoir 2010 aerial photography, water surface reservoir elevation 4,884.9 (NAVD88)(GEOID12A).

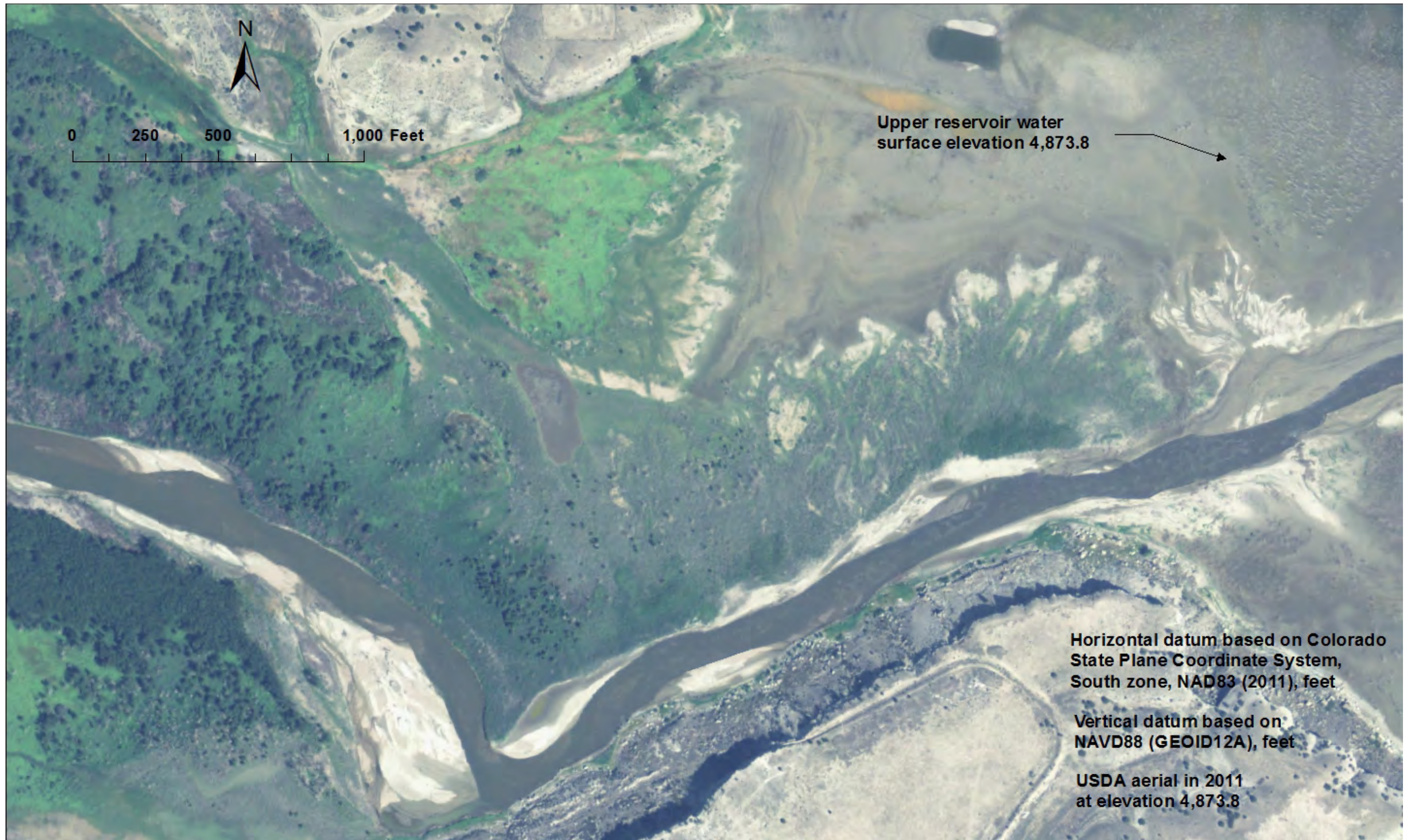


Figure 17 - Pueblo Reservoir, upper reservoir 2011 aerial photography, water surface reservoir elevation 4,873.3 (NAVD88)(GEOID12A).

Reservoir Area and Capacity

Topography Development

The 2012 Pueblo Reservoir topographic contours were generated from several data sources including the 2012 bathymetric survey, digitized reservoir water edges from USDA aerial photographs, and IFSAR data collected in 2007. The 2012 Pueblo Reservoir topography was tied to NAVD88 (GEOID12A) in feet. The areas of the data sets covered by the 2012 bathymetric data points were removed or erased using ArcGIS tools. For the majority of the reservoir area with no 2012 bathymetric data, the 2007 IFSAR data set was the best available source for continuous topography development, primarily above the upper USDA developed contour elevation 4,884.9 (NAVD88).

The data coverages were processed into a triangulated irregular network (TIN) that was used to develop 2-foot contours, surface areas, and volumes referenced to NAVD88 (GEOID12A), as shown in Figures 18 and 19. In preparation for developing the TIN, a polygon (hardclip) was created to enclose the data sets allowing contour development for computations of the reservoir surface areas and resulting volumes within the study area. Hardclip is an ArcGIS term that represents the polygon that encloses or clips the data used to develop the topography of the study area. This polygon, not assigned an elevation, was used as a hard boundary preventing development of the 2012 TIN and contours outside of the hardclip.

Contours for Pueblo Reservoir were developed from the TIN generated within ArcGIS. A TIN is a set of adjacent non-overlapping triangles computed from irregularly spaced points with x,y coordinates and z elevation values. A TIN is designed to deal with continuous data such as elevations. ArcGIS uses a method known as Delaunay's criteria for triangulation where triangles are formed among all data points within the polygon clip. The method requires that a circle drawn through the three nodes of a triangle will contain no other point, meaning that all the data points are connected to their nearest neighbors to form triangles, preserving all the data points. The TIN method is described in more detail in the ArcGIS user's documentation (ESRI, 2012).

The linear interpolation option of the ArcGIS *TIN* and *CONTOUR* commands were used to interpolate contours from the Pueblo Reservoir TIN. The surface areas of the enclosed contour polygons at 2-foot increments were computed for elevation 4,746.0 and above. The reservoir contour topography at 2-foot intervals is presented in Figures 20 through 52 from elevations 4,746.0 through 4,950.0.

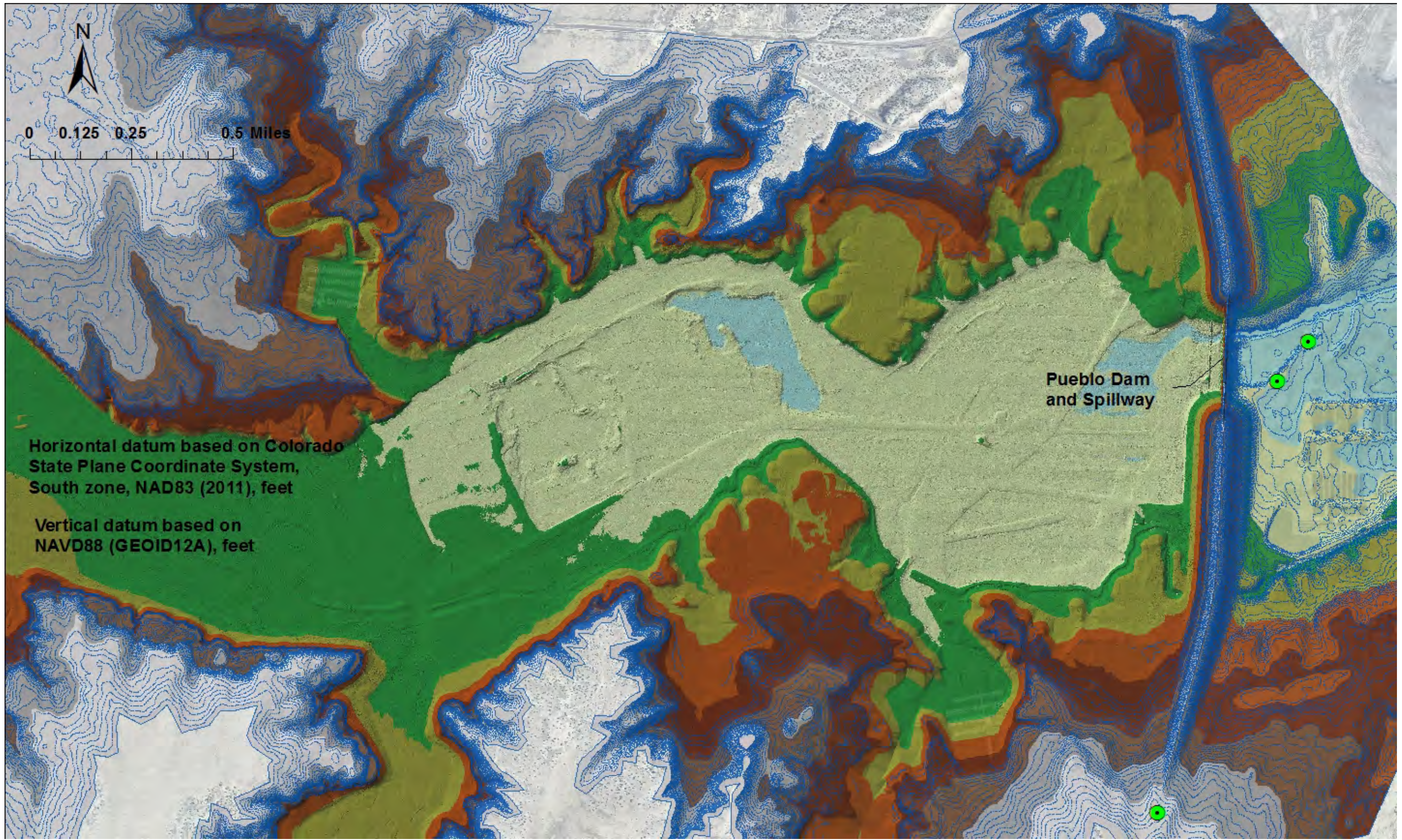


Figure 18 - Pueblo Dam and Reservoir developed TIN (NAVD88).

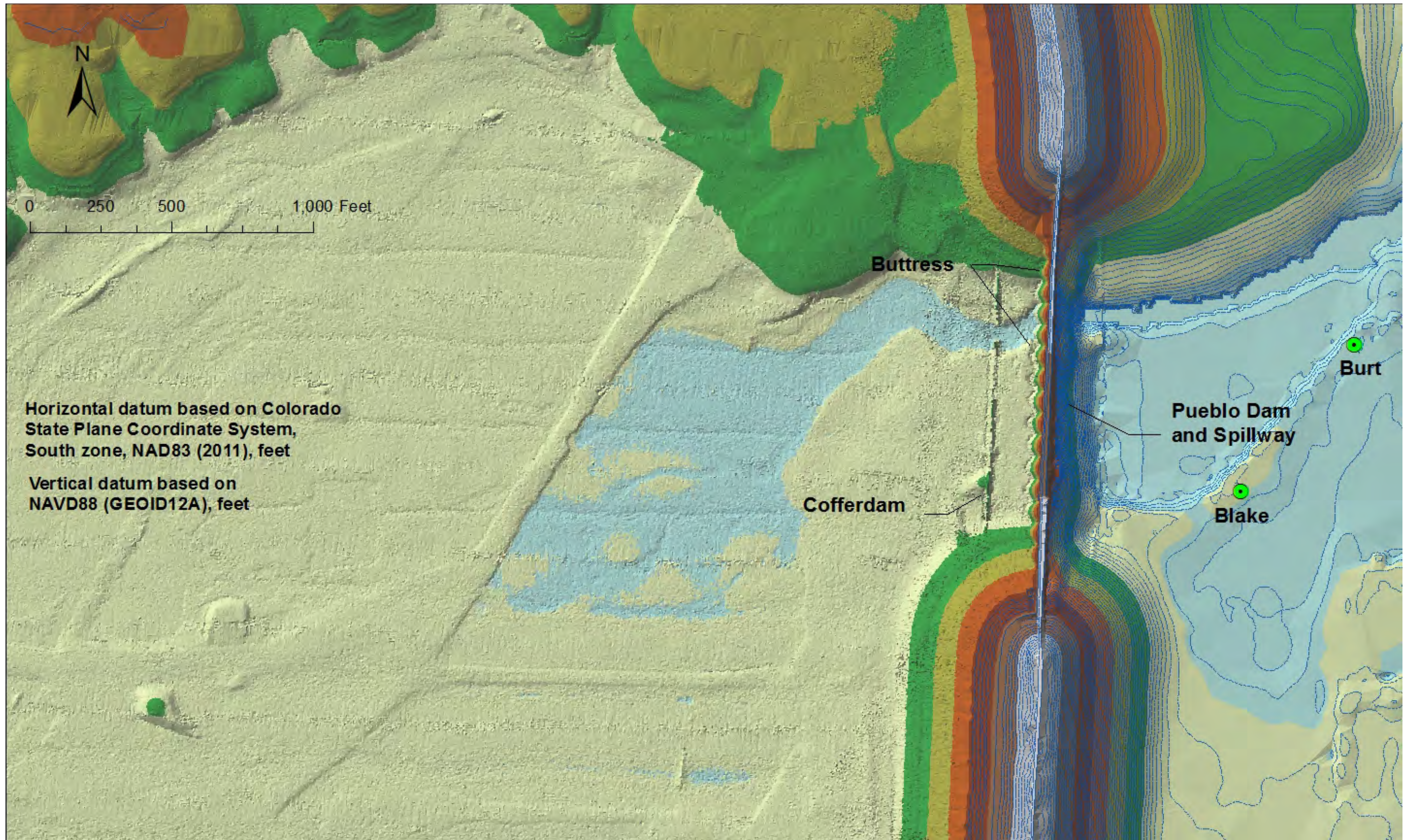


Figure 19 - Pueblo Reservoir 2012 developed TIN (NAVD88).

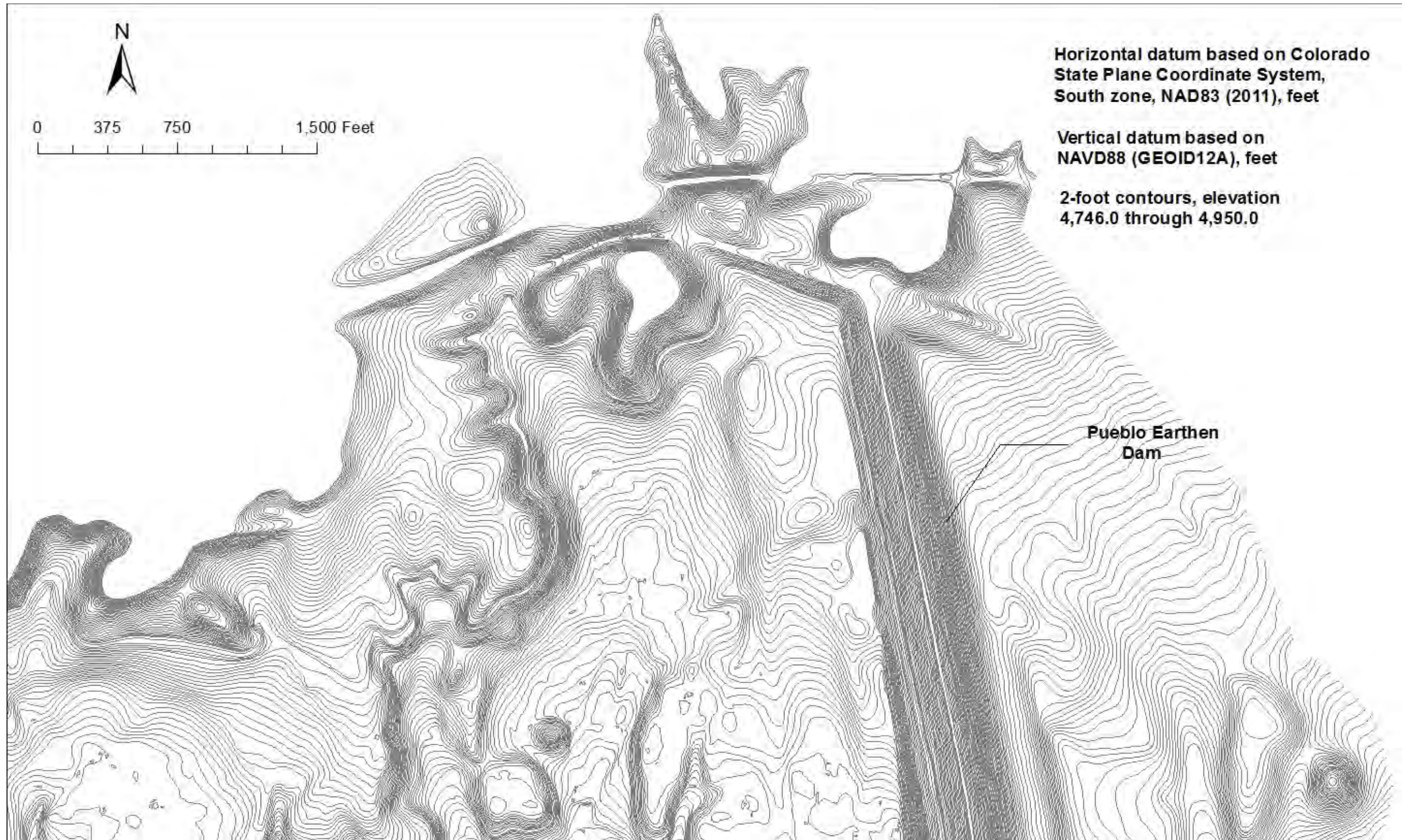


Figure 20 - 2012 Pueblo Reservoir 2-foot contours, 1 of 33 (NAVD88).

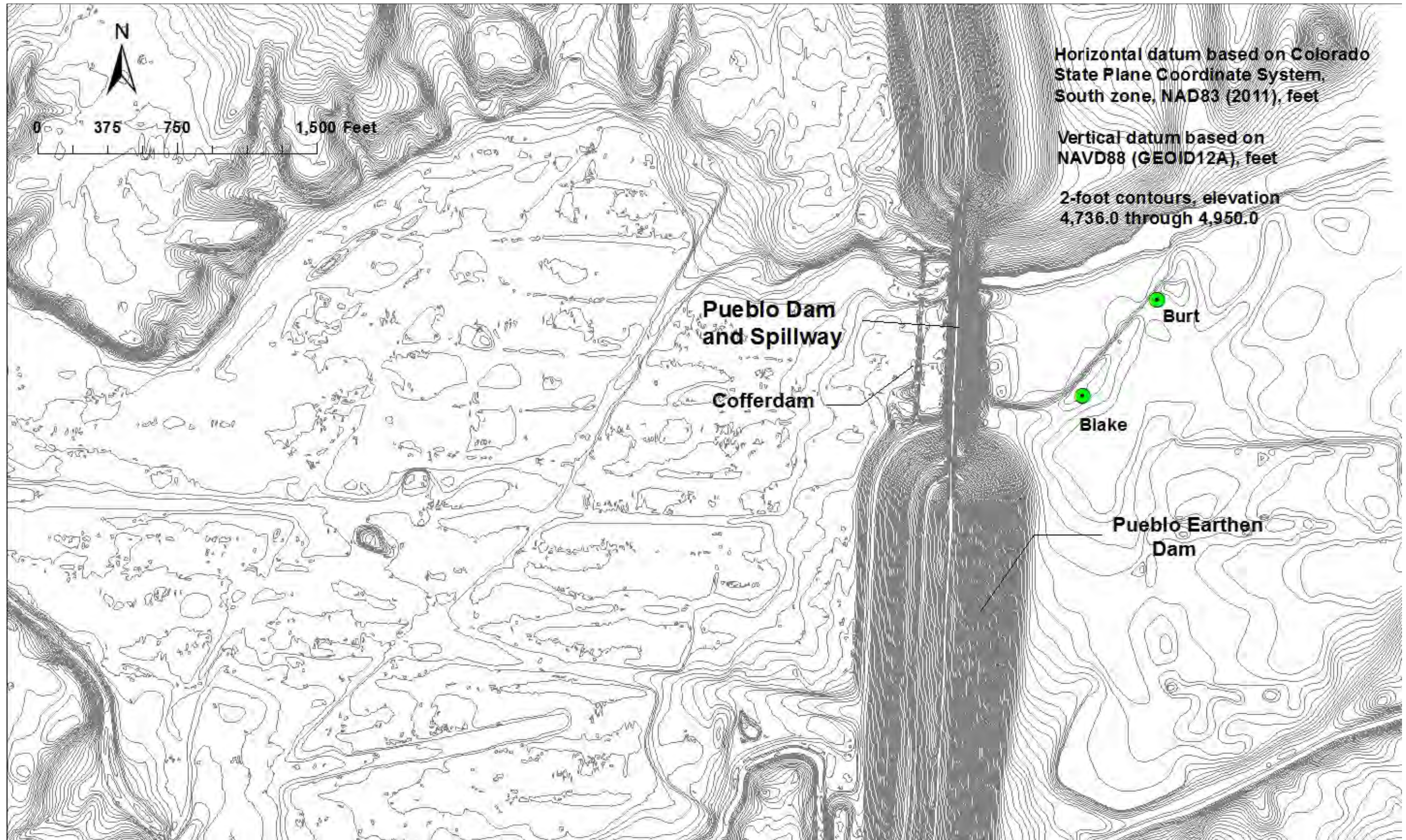


Figure 21 - 2012 Pueblo Reservoir 2-foot contours, 2 of 33 (NAVD88).

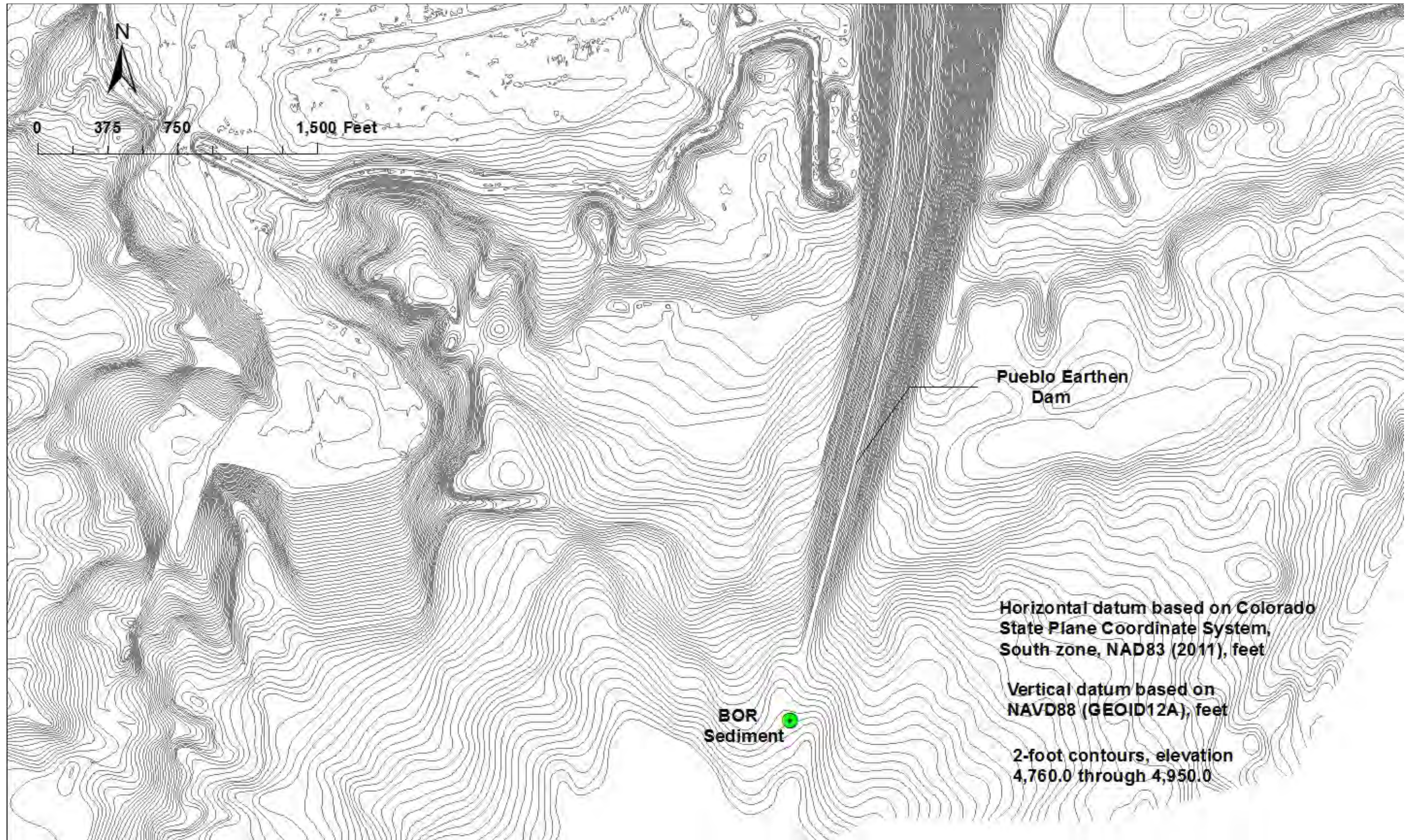


Figure 22 - 2012 Pueblo Reservoir 2-foot contours, 3 of 33 (NAVD88).

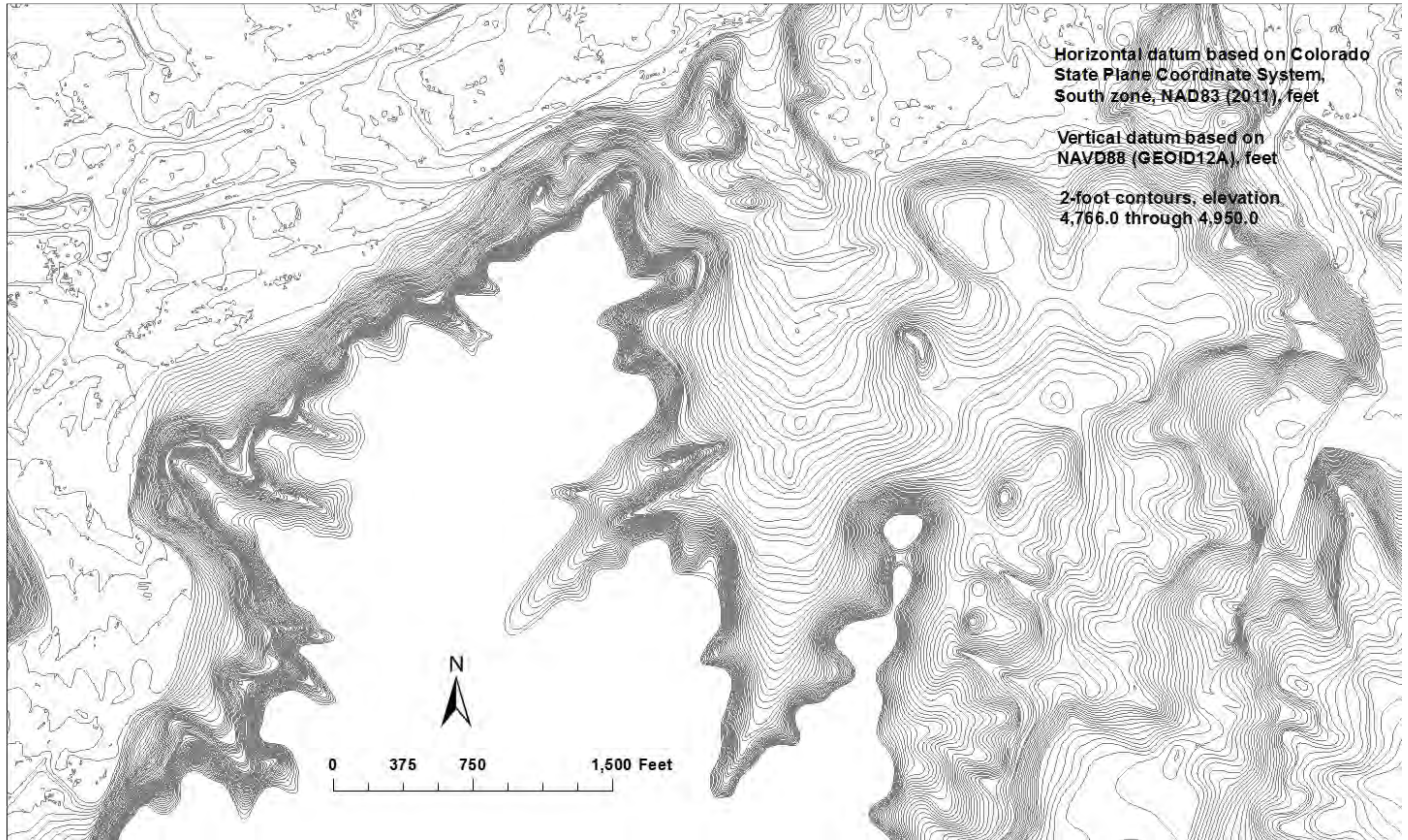


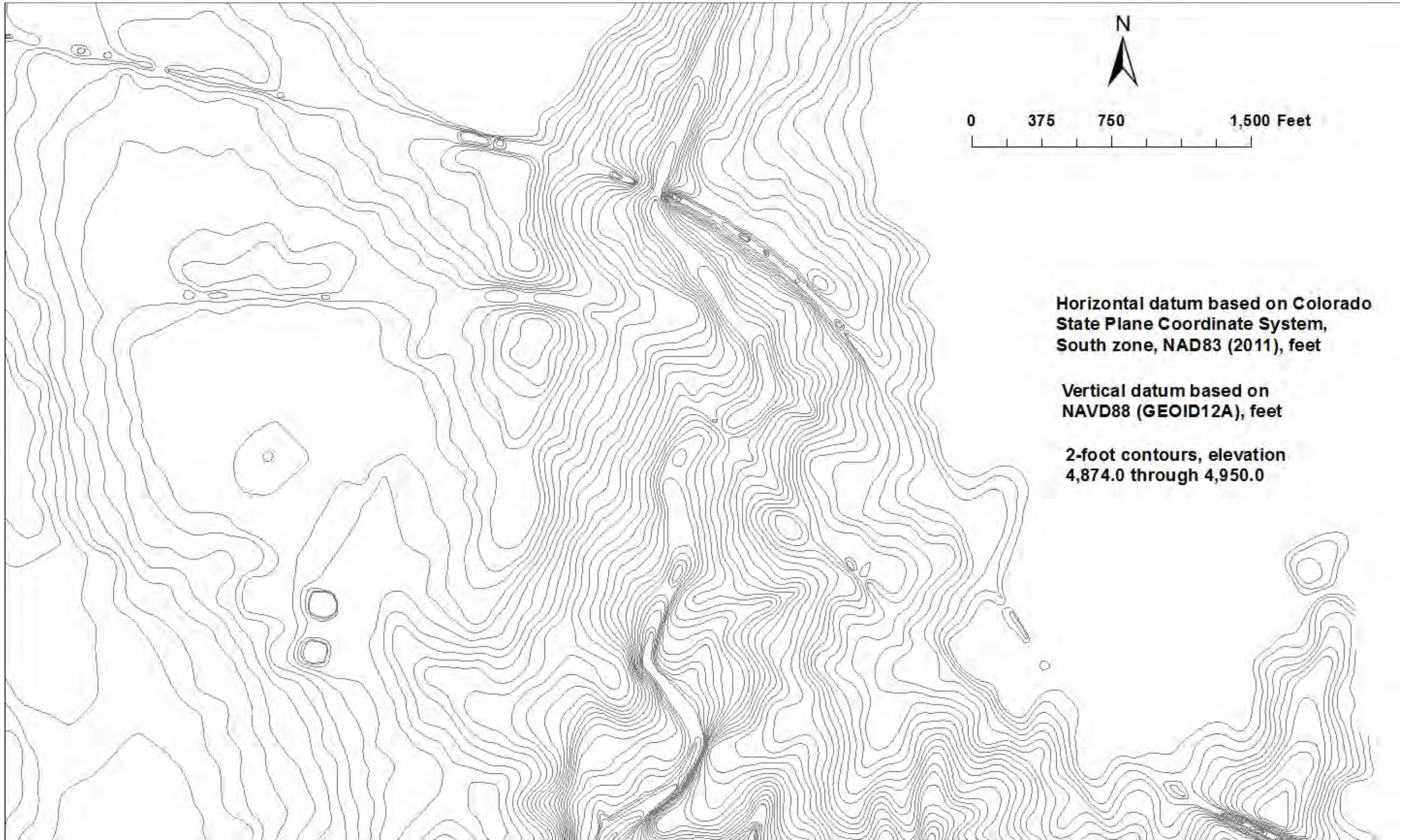
Figure 23 - 2012 Pueblo Reservoir 2-foot contours, 4 of 33 (NAVD88).



Figure 24 - 2012 Pueblo Reservoir 2-foot contours, 5 of 33 (NAVD88).



Figure 25 - 2012 Pueblo Reservoir 2-foot contours, 6 of 33 (NAVD88).



Horizontal datum based on Colorado State Plane Coordinate System, South zone, NAD83 (2011), feet

Vertical datum based on NAVD88 (GEOID12A), feet

2-foot contours, elevation 4,874.0 through 4,950.0

Figure 26 - 2012 Pueblo Reservoir 2-foot contours, 7 of 33 (NAVD88).

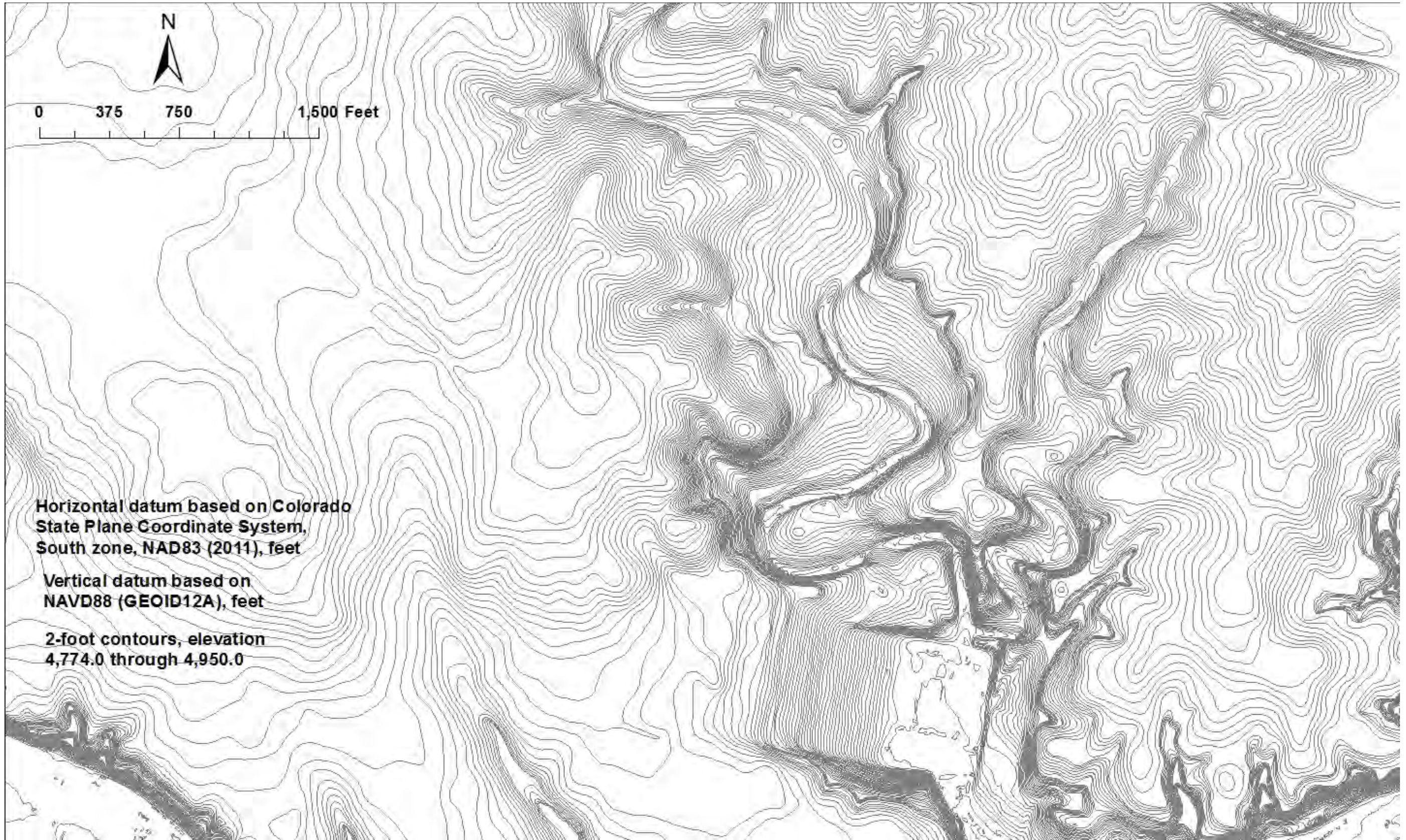


Figure 27 - 2012 Pueblo Reservoir 2-foot contours, 8 of 33 (NAVD88).

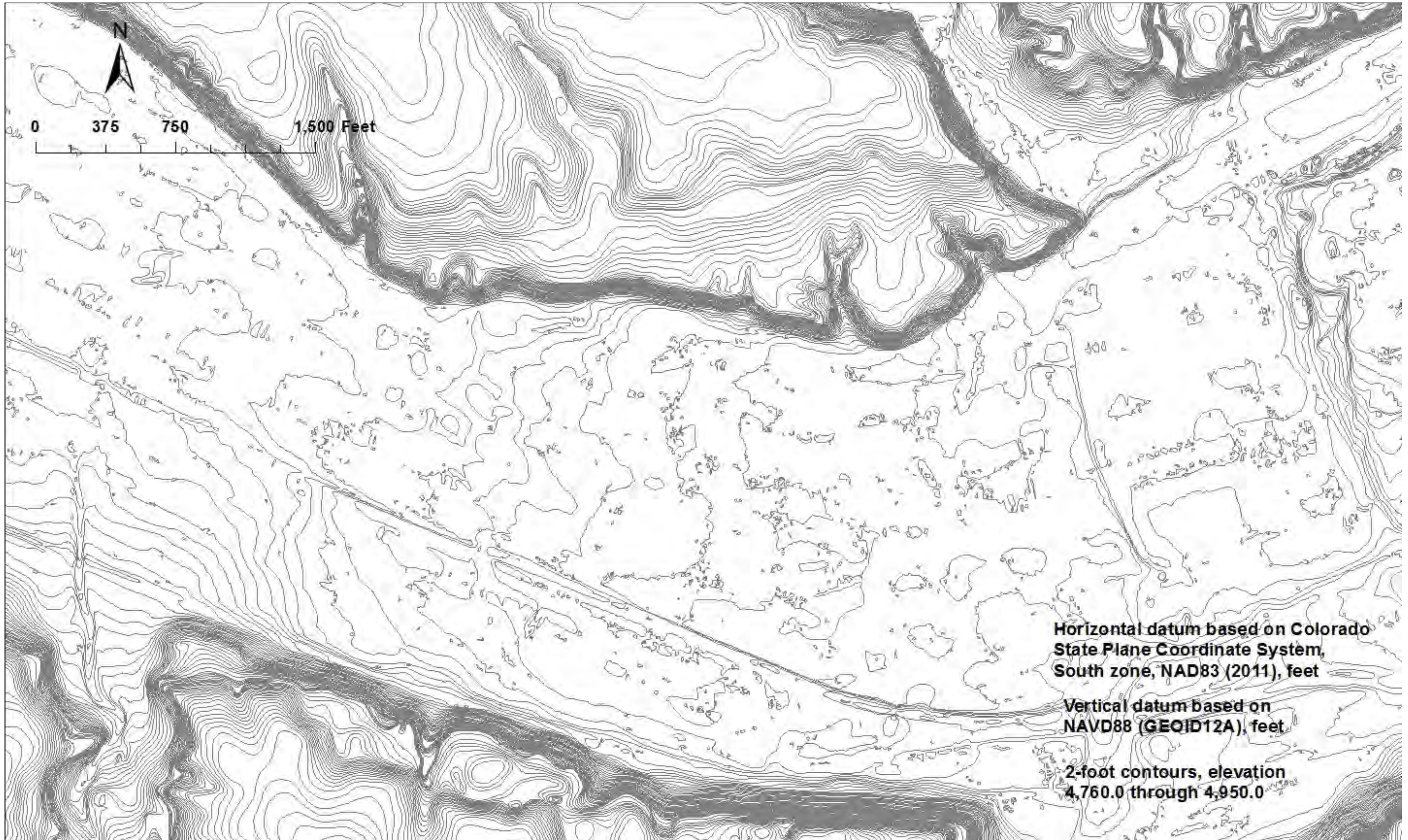


Figure 28 - 2012 Pueblo Reservoir 2-foot contours, 9 of 33 (NAVD88).

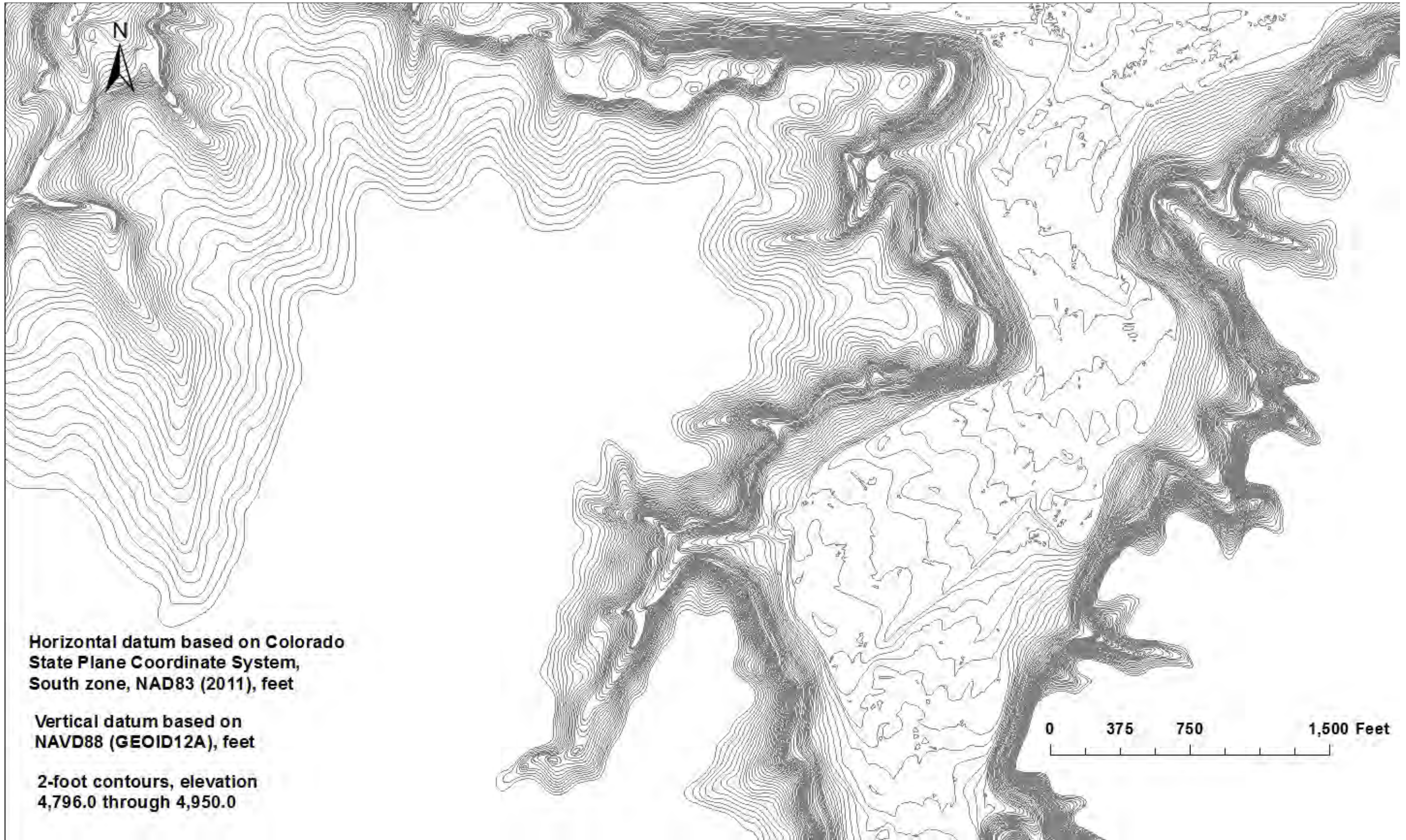


Figure 29 - 2012 Pueblo Reservoir 2-foot contours, 10 of 33 (NAVD88).

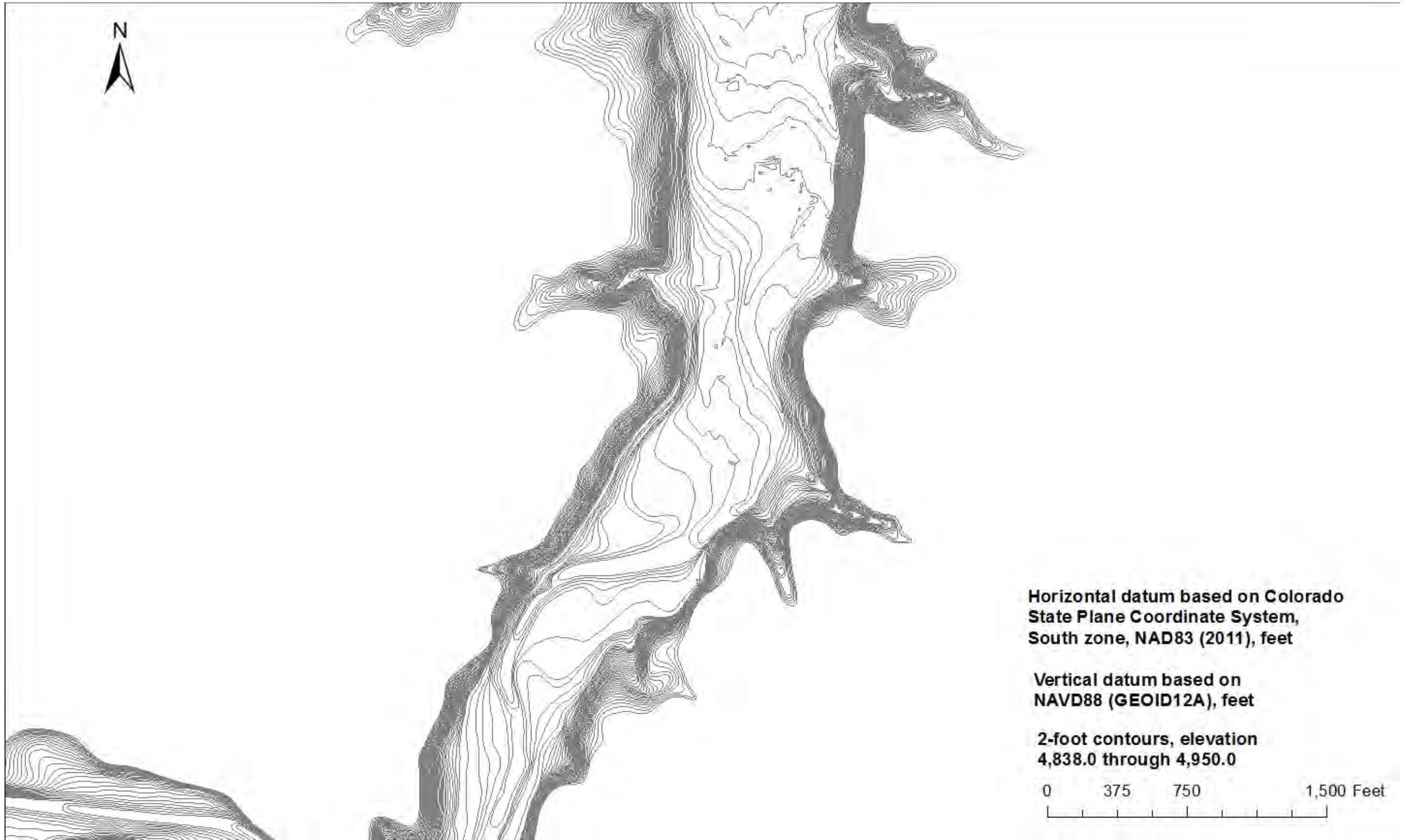


Figure 30 - 2012 Pueblo Reservoir 2-foot contours, 11 of 33 (NAVD88).

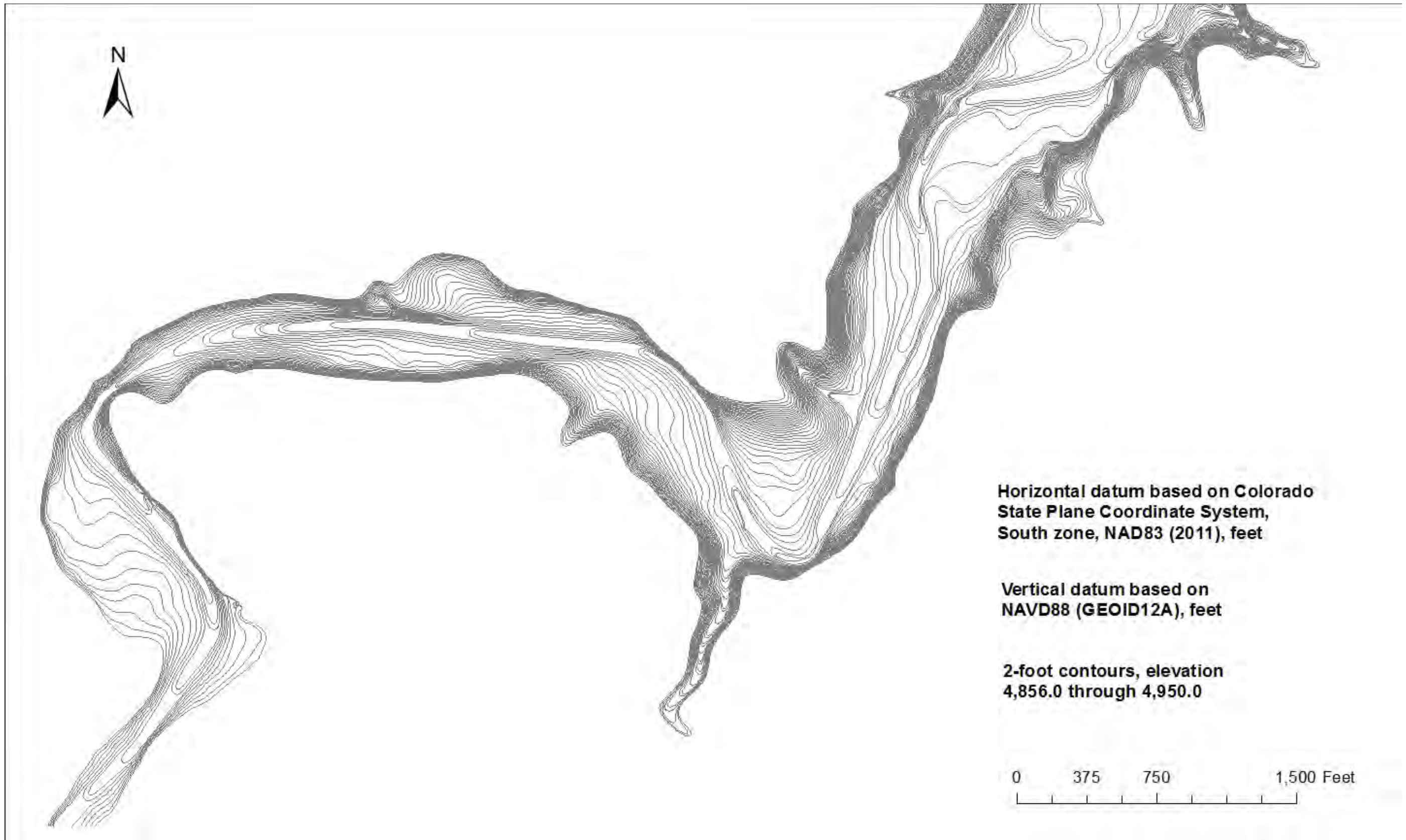


Figure 31 - 2012 Pueblo Reservoir 2-foot contours, 12 of 33 (NAVD88).

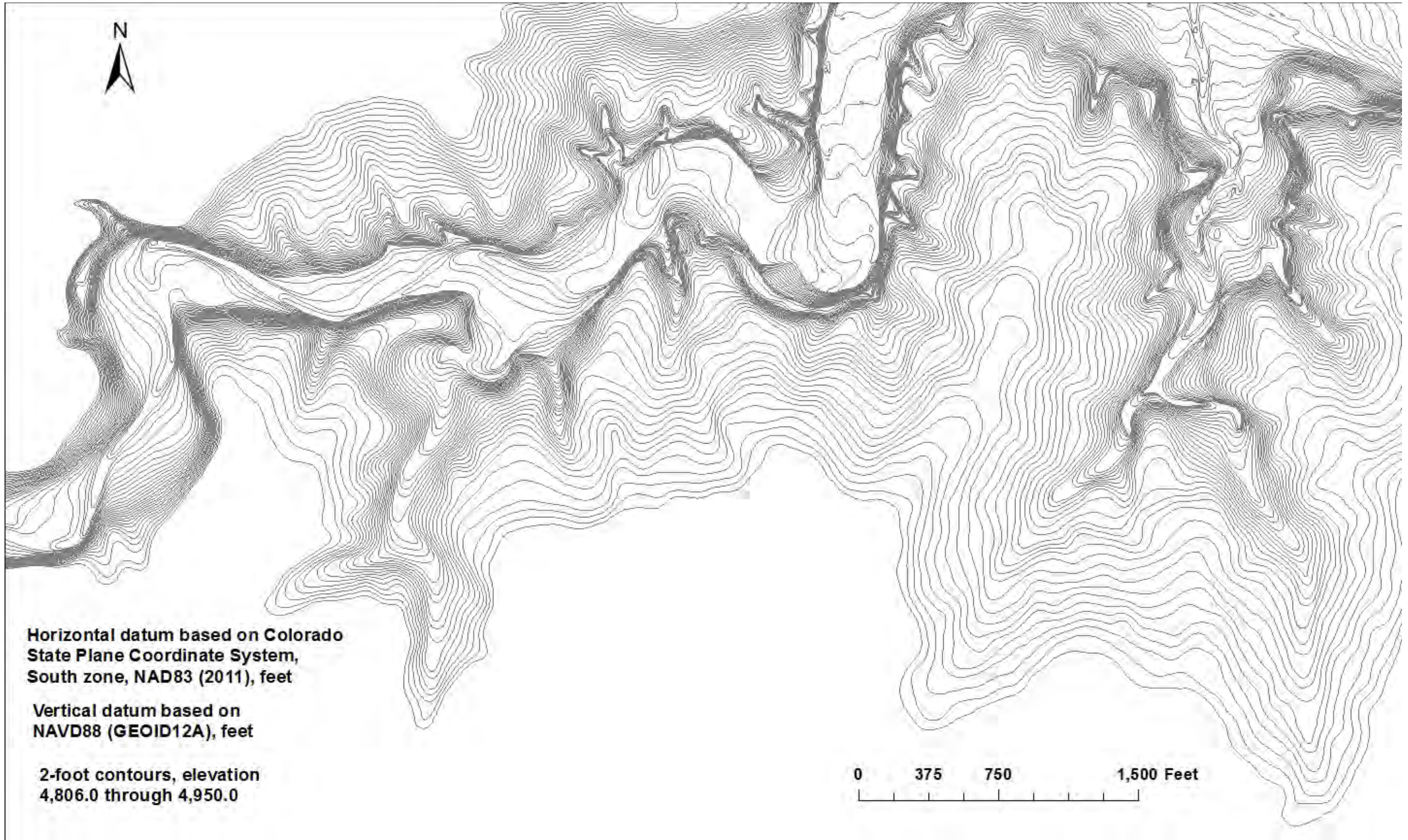


Figure 32 - 2012 Pueblo Reservoir 2-foot contours, 13 of 33 (NAVD88).

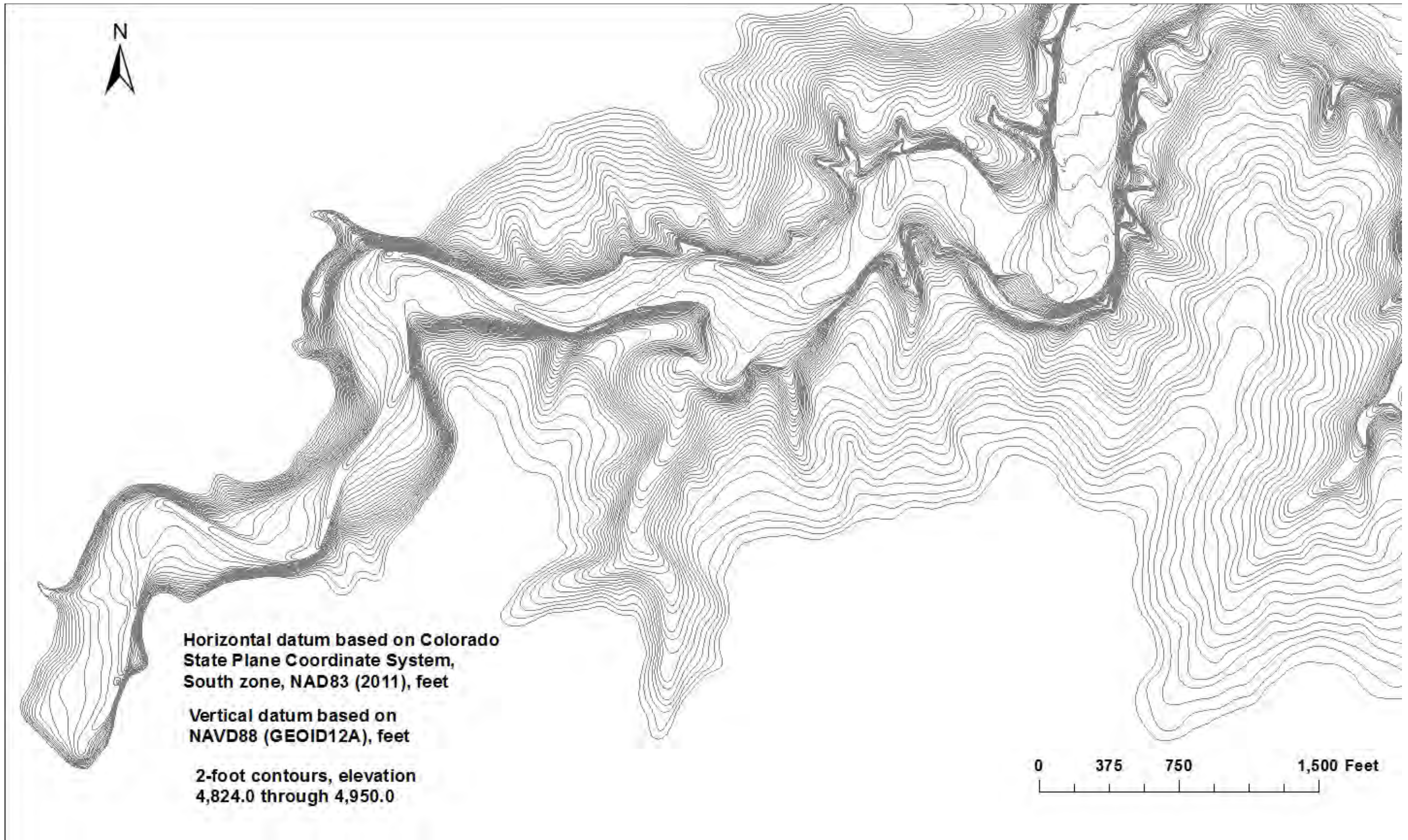


Figure 33 - 2012 Pueblo Reservoir 2-foot contours, 14 of 33 (NAVD88).

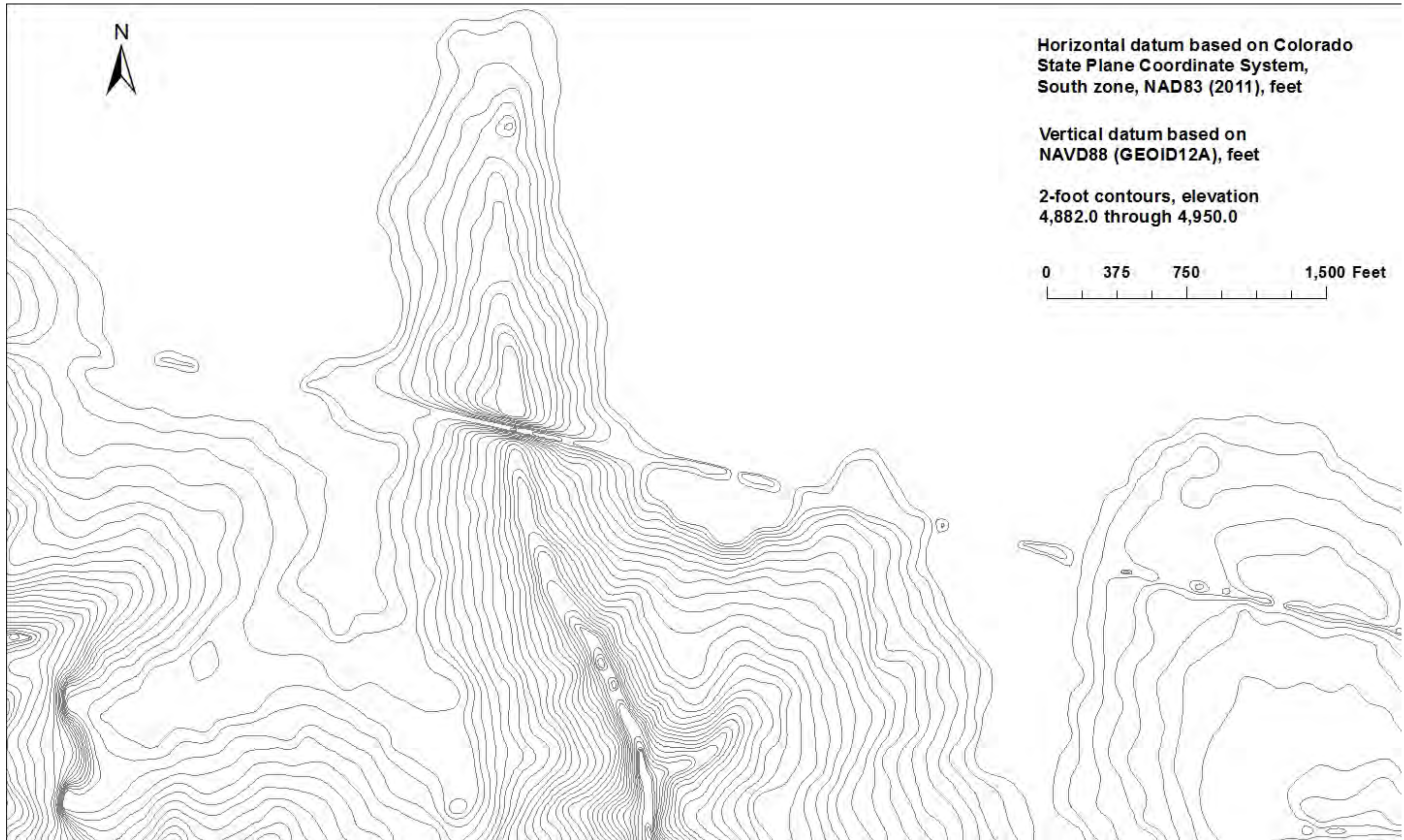


Figure 34 - 2012 Pueblo Reservoir 2-foot contours, 15 of 33(NAVD88).

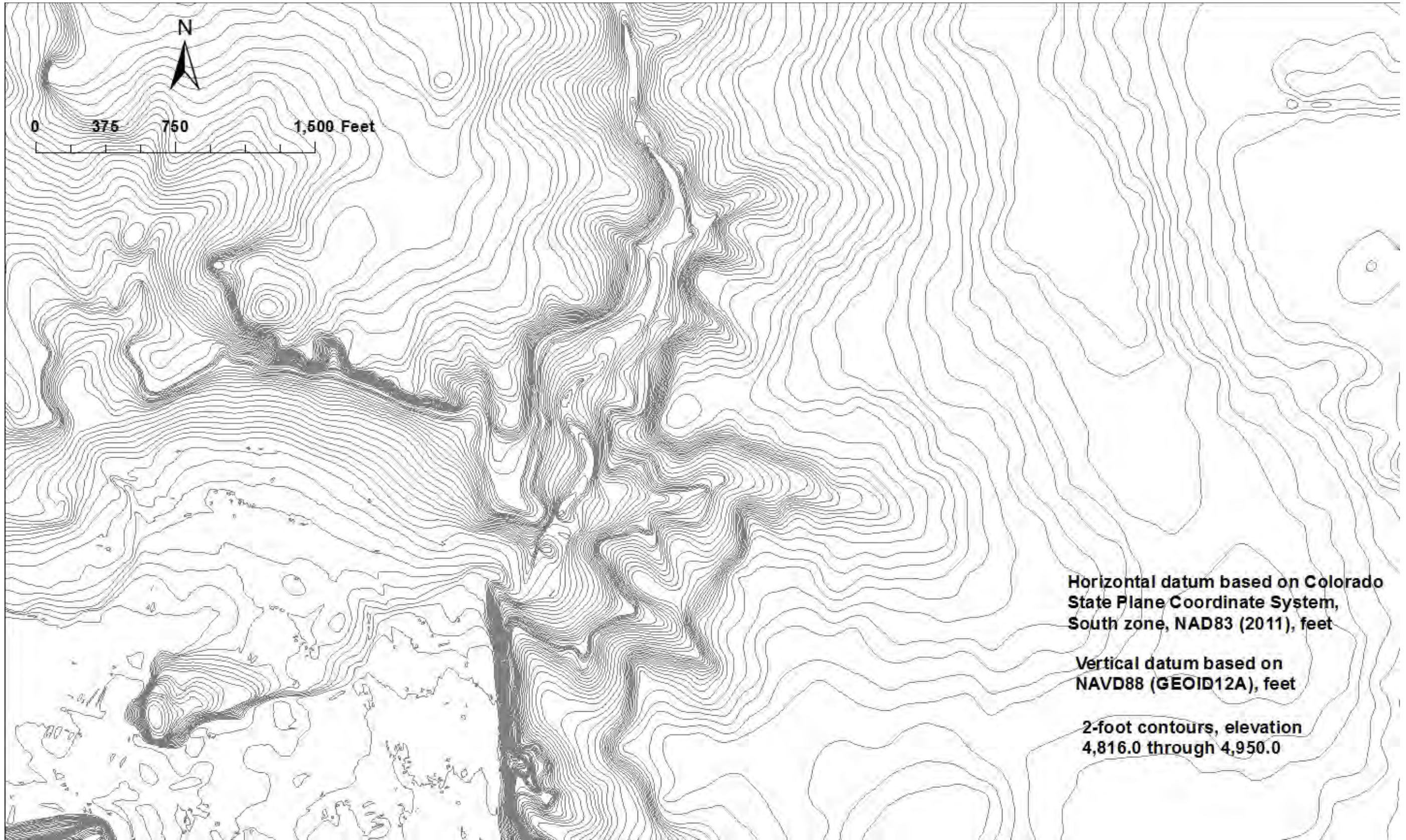


Figure 35 - 2012 Pueblo Reservoir 2-foot contours, 16 of 33 (NAVD88).

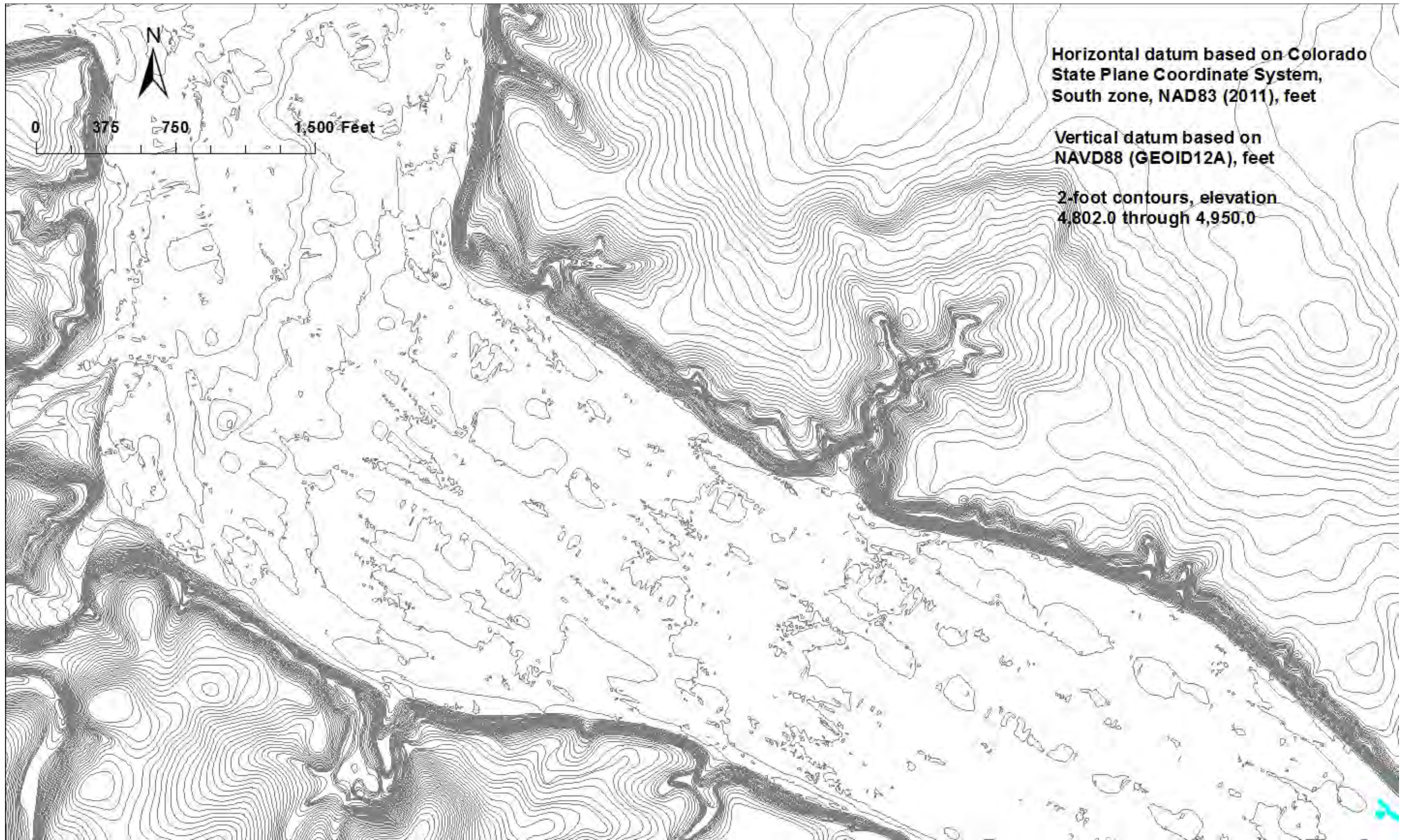


Figure 36 - 2012 Pueblo Reservoir 2-foot contours, 17 of 33 (NAVD88).

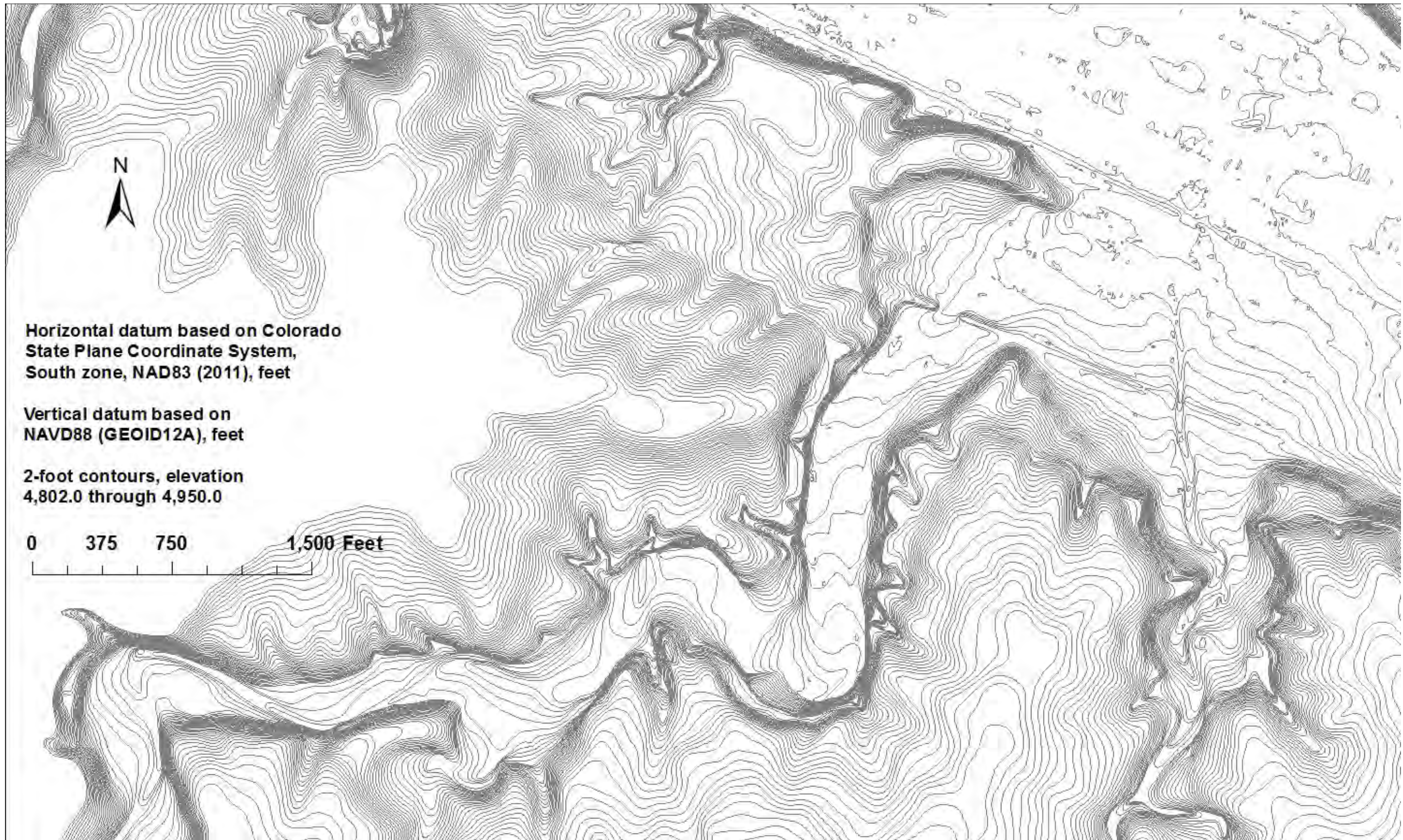


Figure 37 - 2012 Pueblo Reservoir 2-foot contours, 18 of 33 (NAVD88).

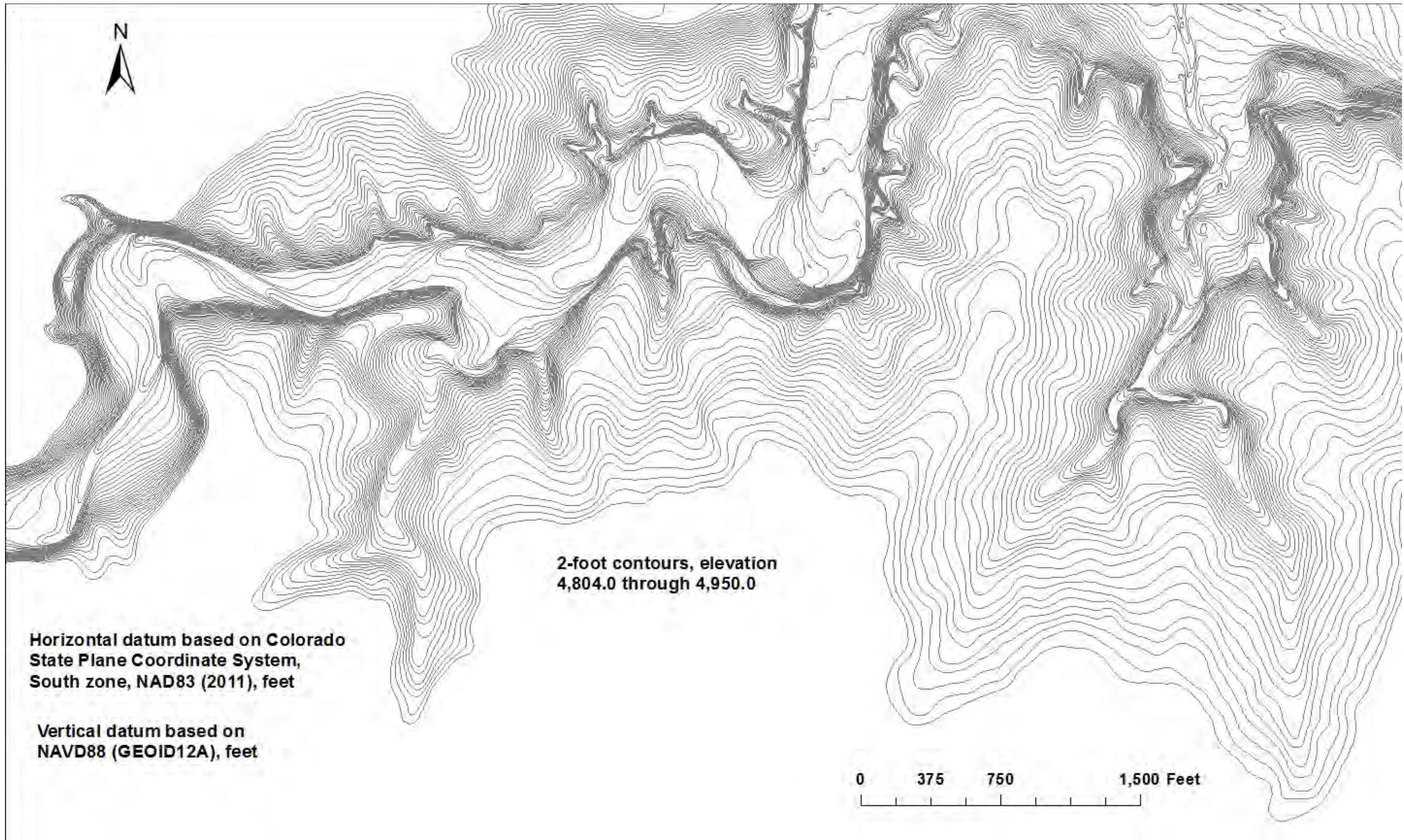


Figure 38 - 2012 Pueblo Reservoir 2-foot contours, 19 of 33 (NAVD88).

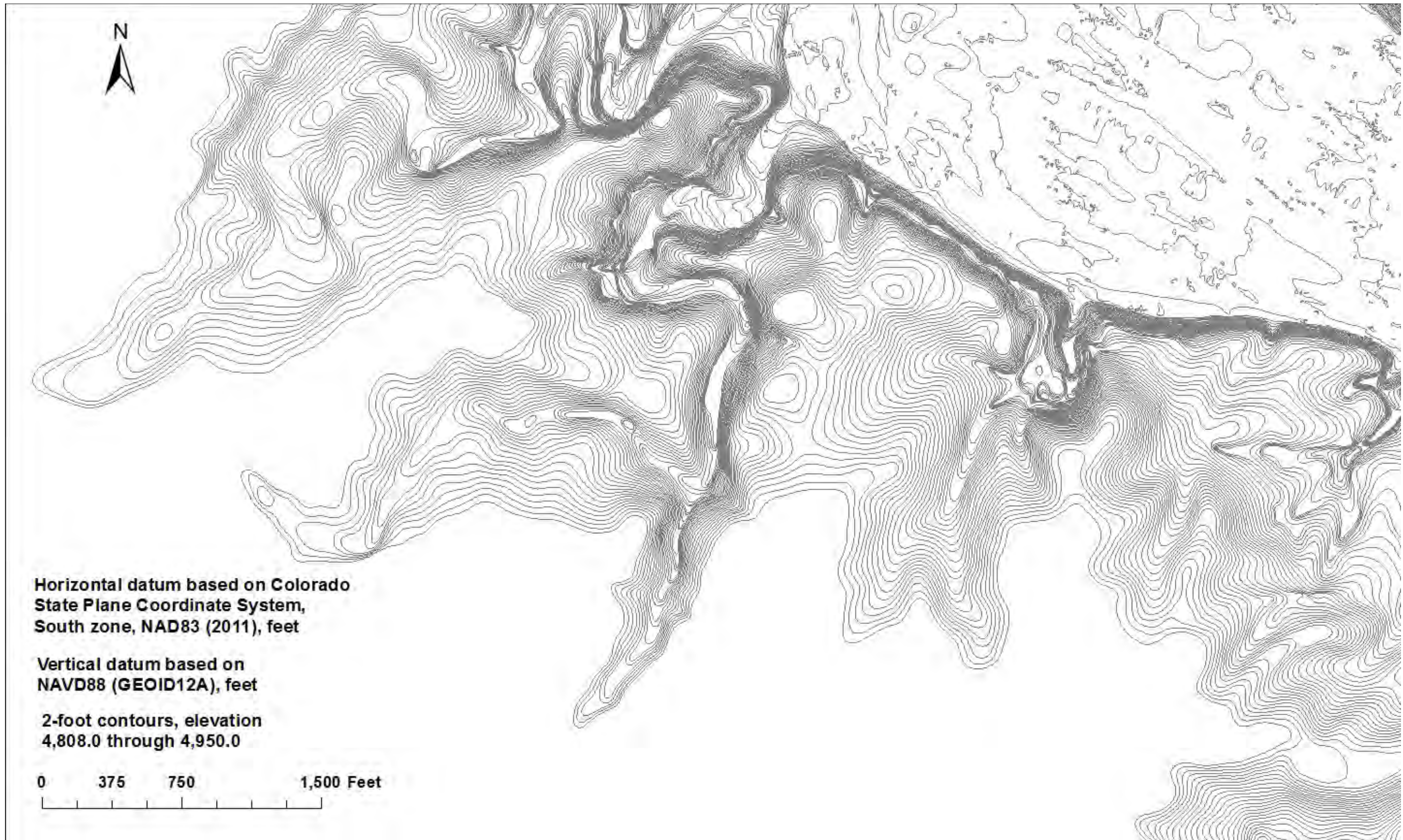


Figure 39 - 2012 Pueblo Reservoir 2-foot contours, 20 of 33 (NAVD88).

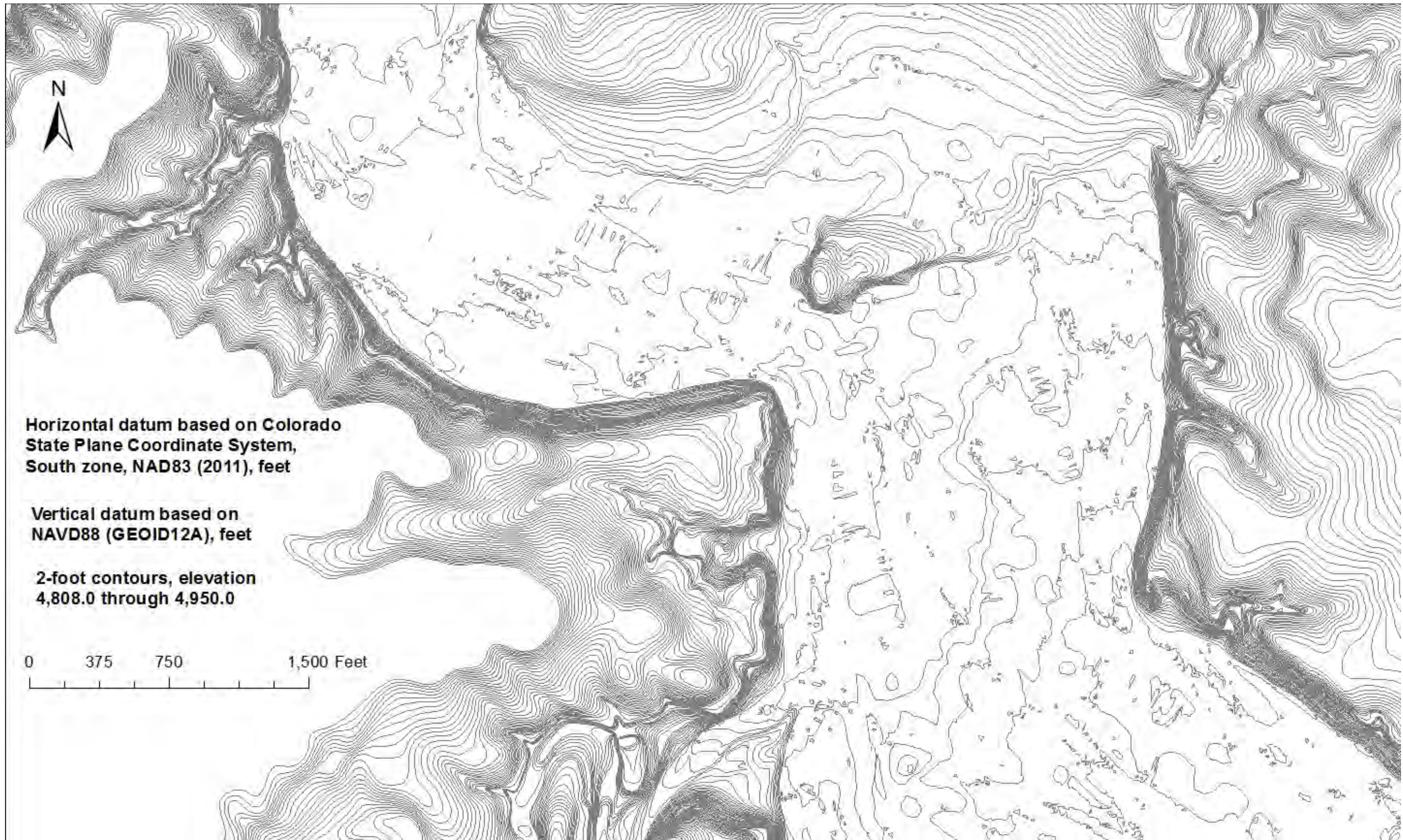


Figure 40 - 2012 Pueblo Reservoir 2-foot contours, 21 of 33 (NAVD88).

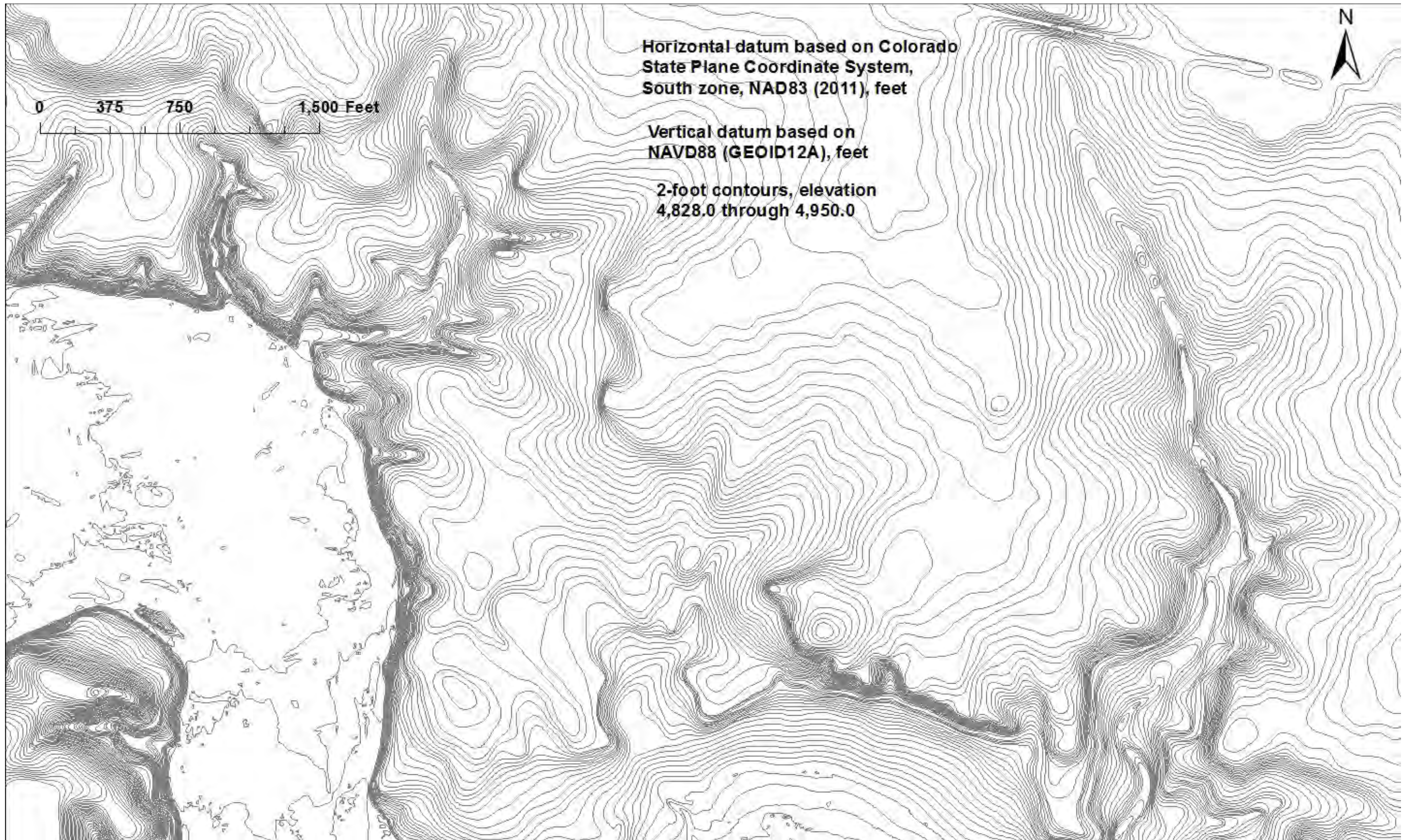


Figure 41 - 2012 Pueblo Reservoir 2-foot contours, 22 of 33 (NAVD88).

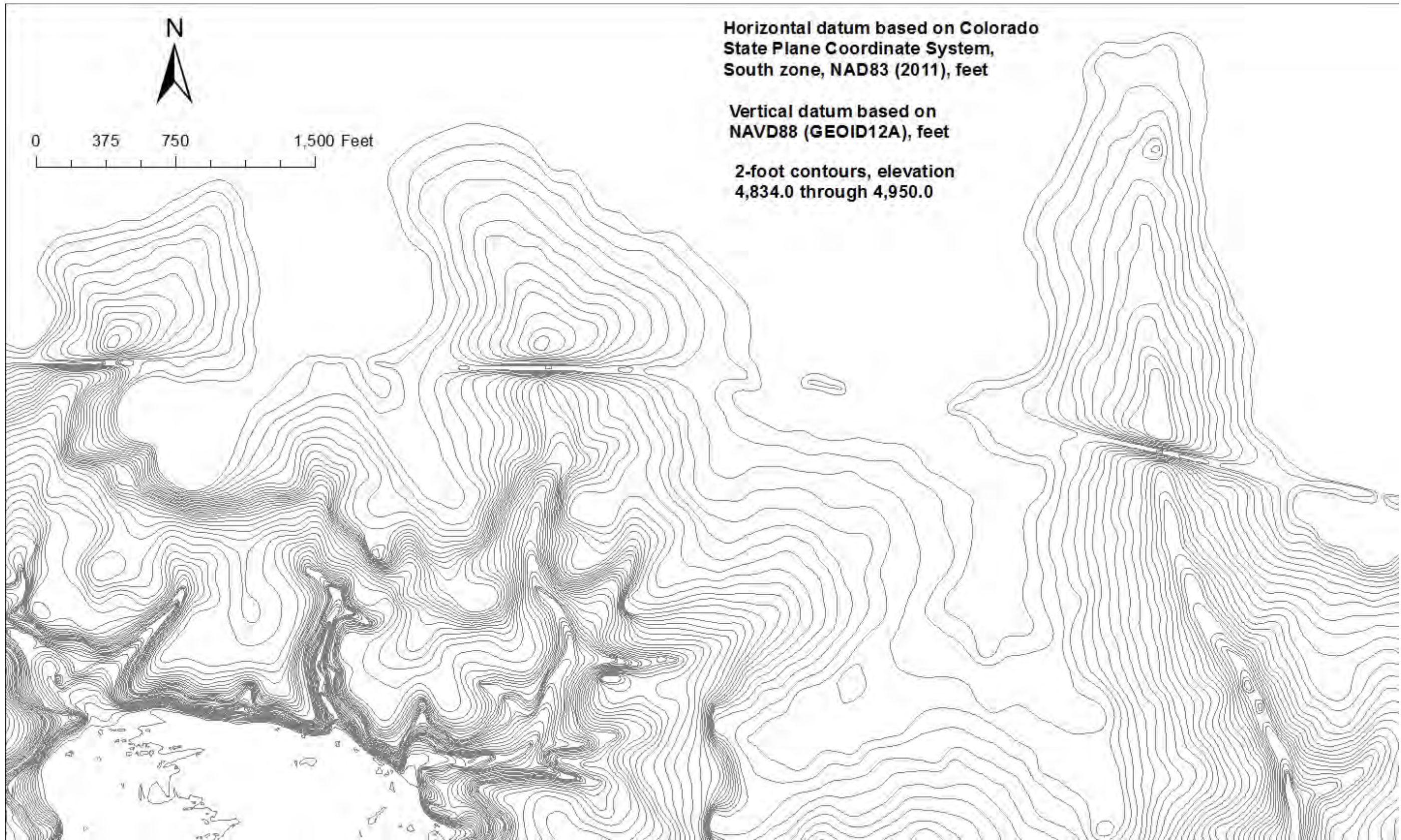


Figure 42 - 2012 Pueblo Reservoir 2-foot contours, 23 of 33 (NAVD88).

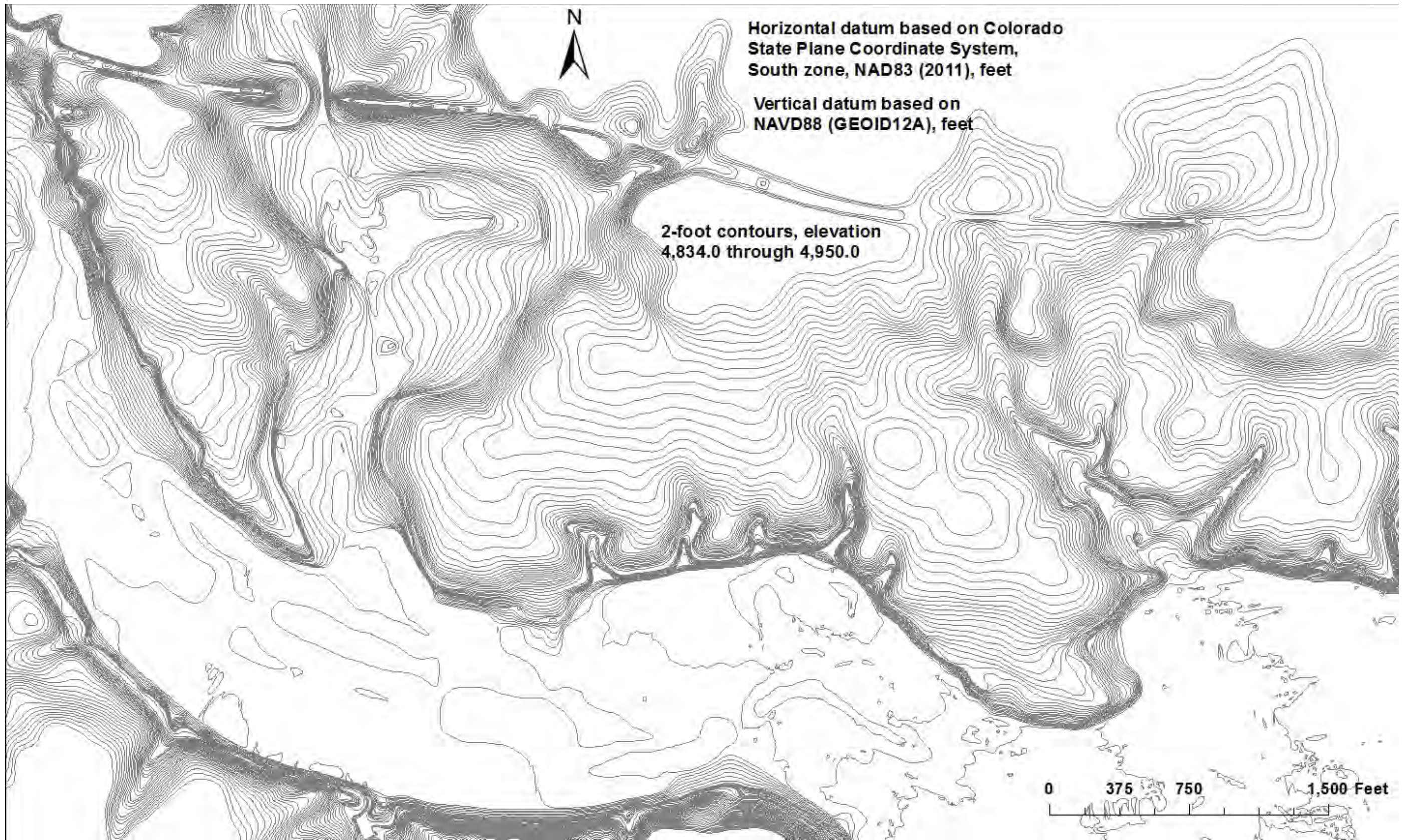


Figure 43 - 2012 Pueblo Reservoir 2-foot contours, 24 of 33 (NAVD88).

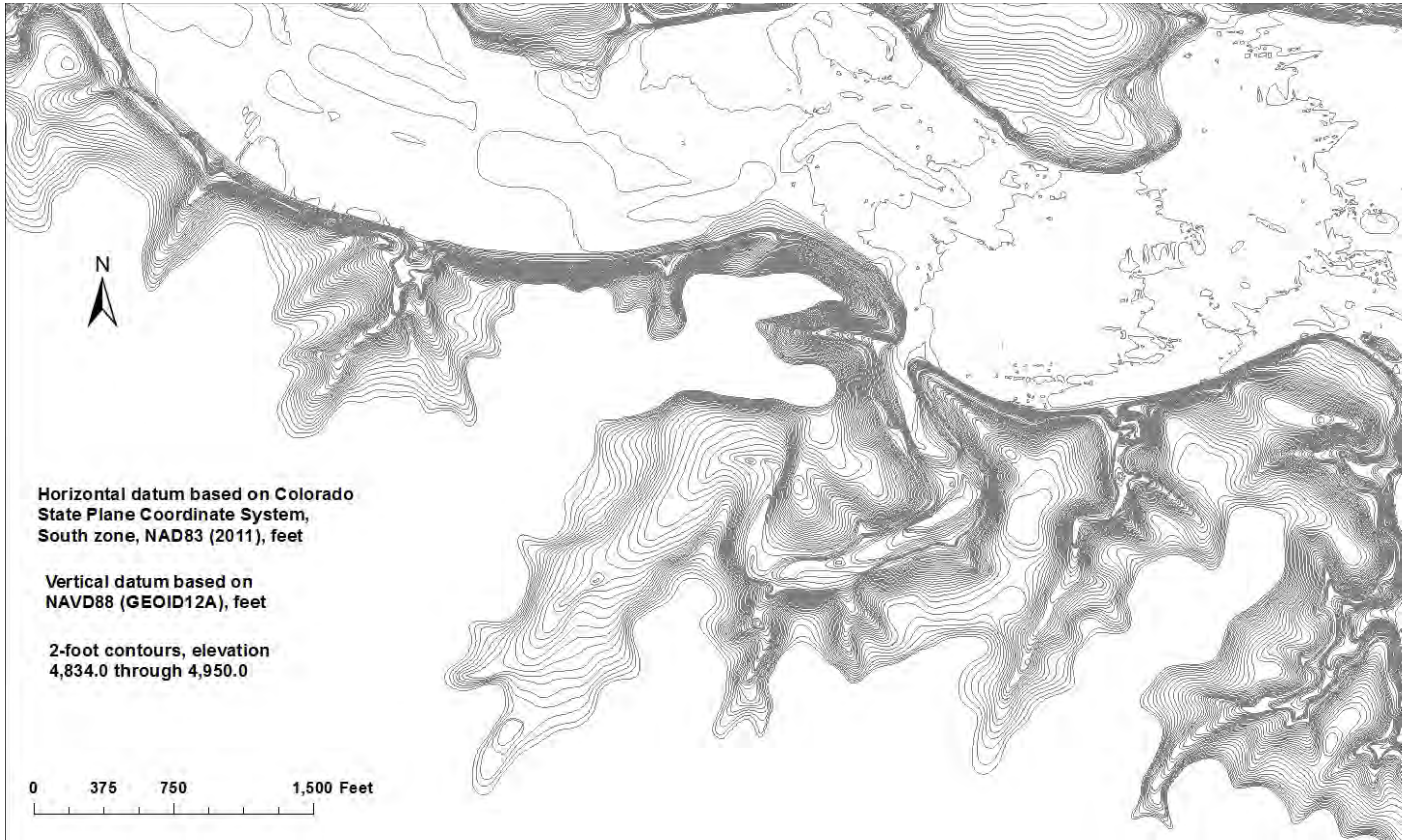


Figure 44 - 2012 Pueblo Reservoir 2-foot contours, 25 of 33 (NAVD88).

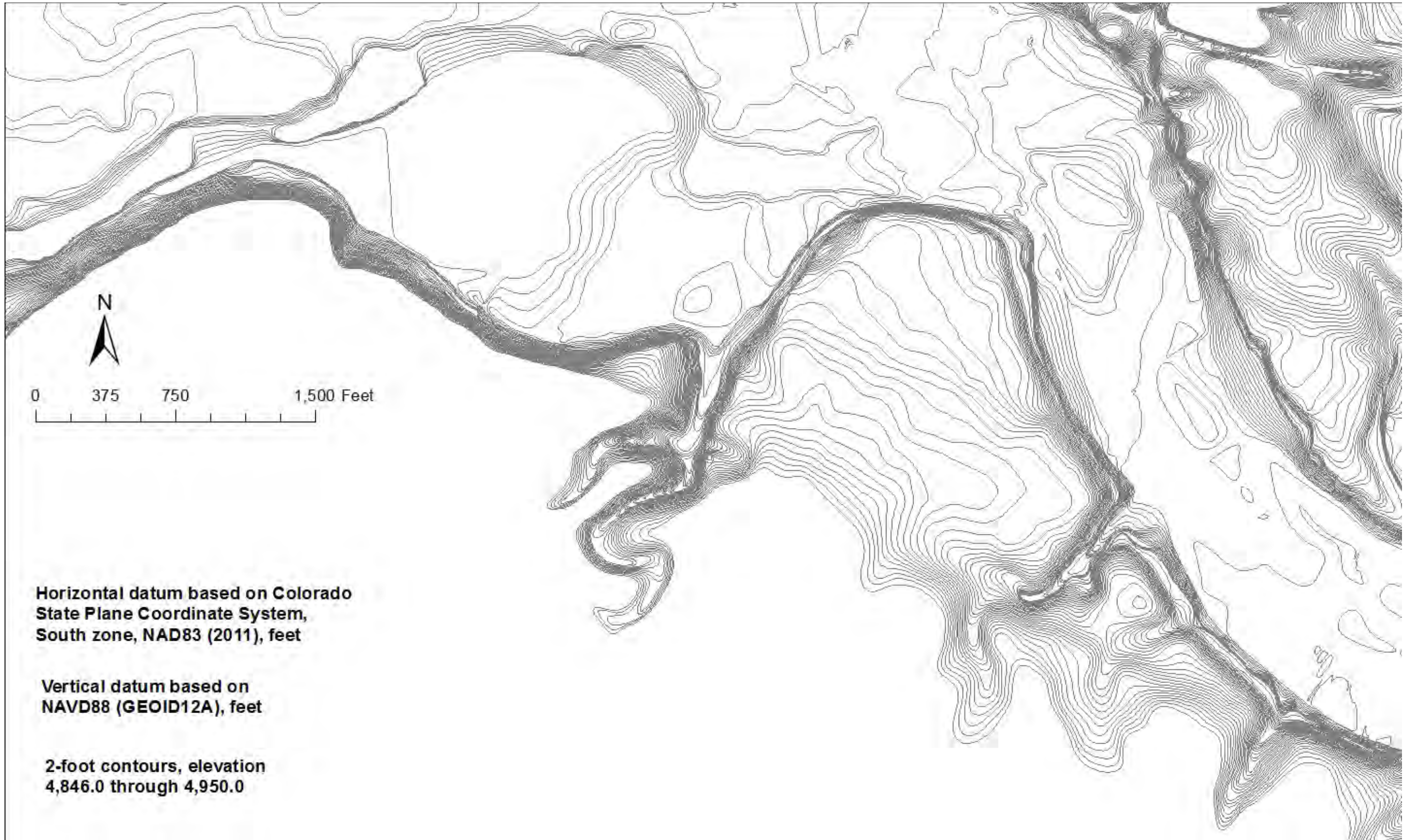


Figure 45 - 2012 Pueblo Reservoir 2-foot contours, 26 of 33 (NAVD88).

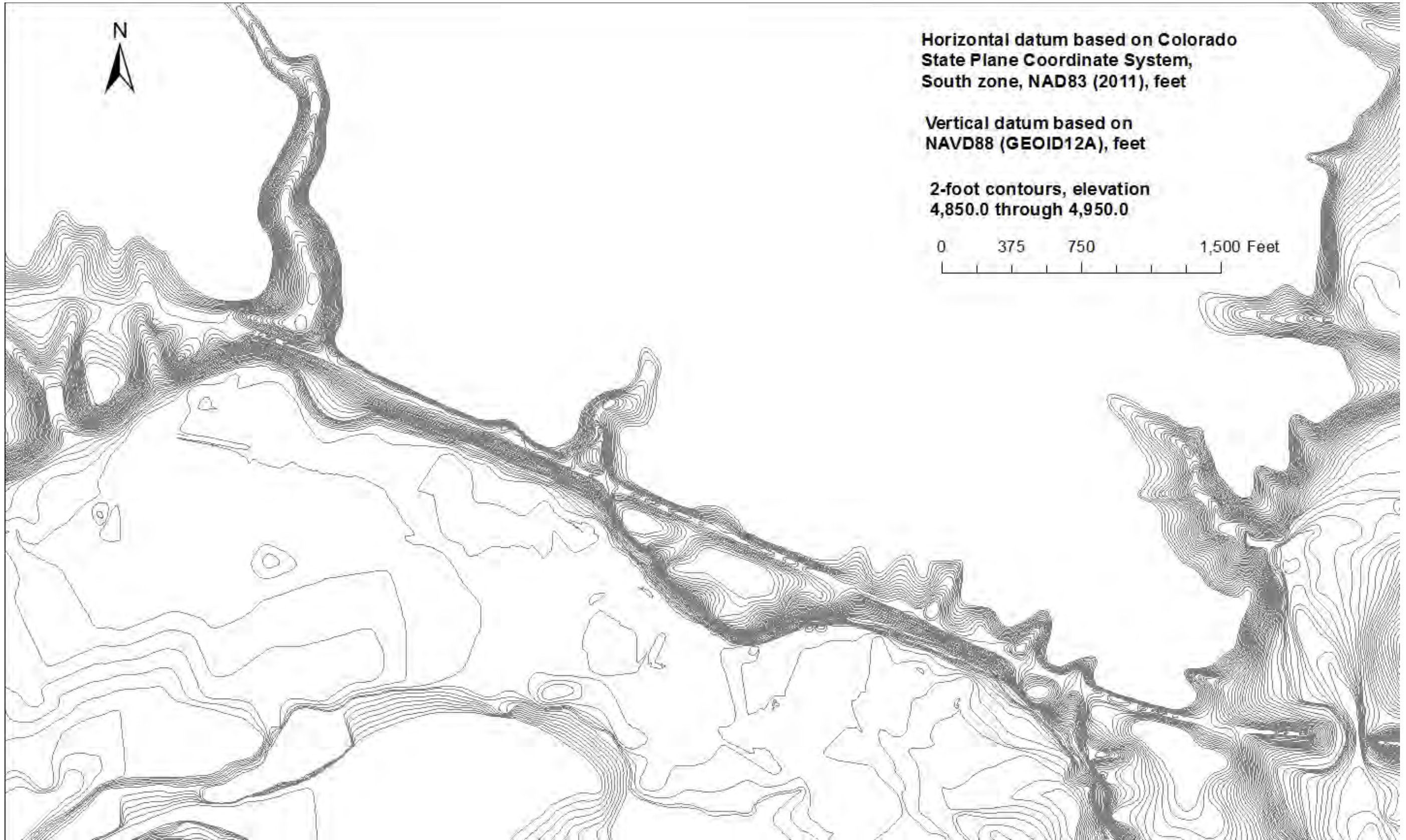


Figure 46 - 2012 Pueblo Reservoir 2-foot contours, 27 of 33(NAVD88).

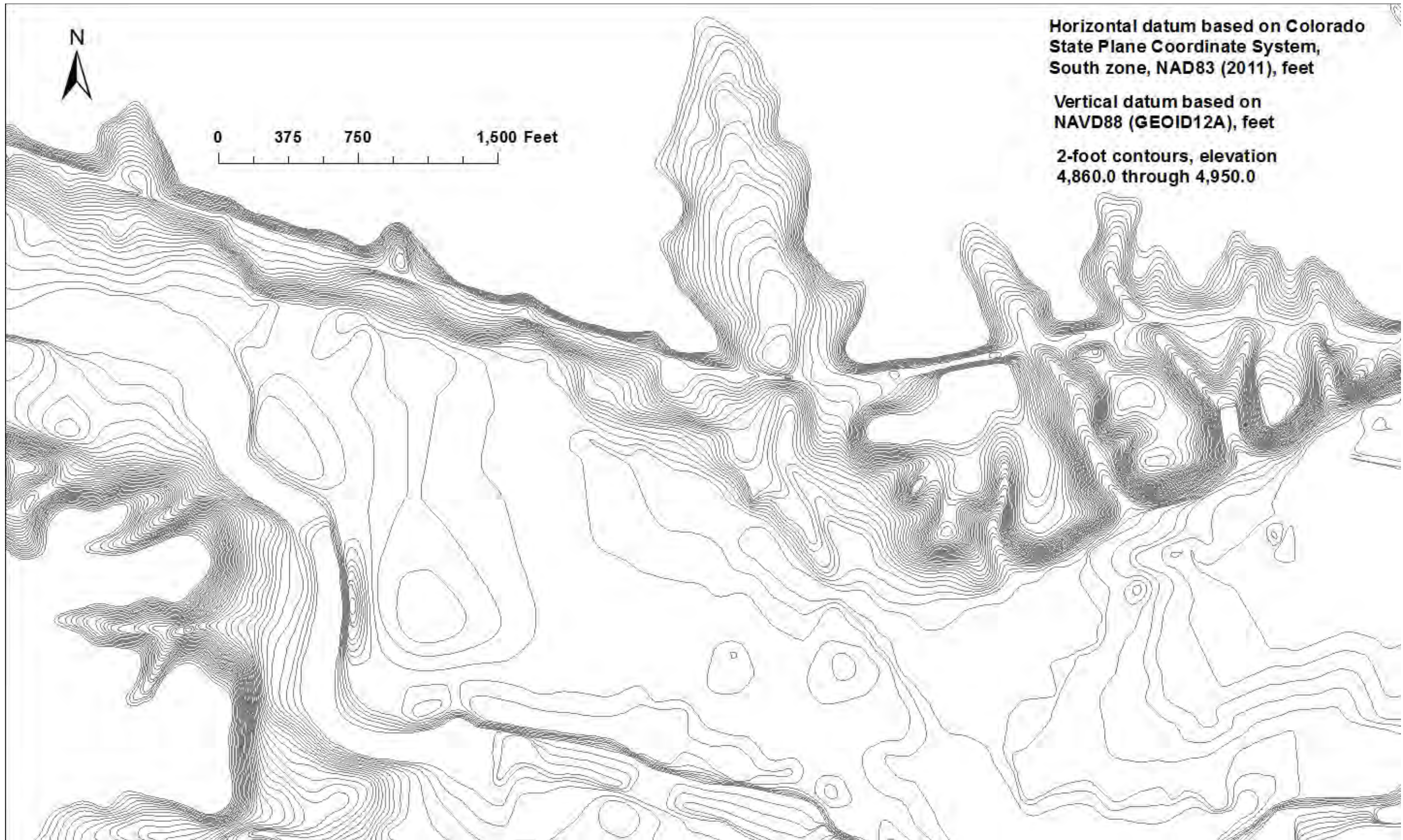


Figure 47 - 2012 Pueblo Reservoir 2-foot contours, 28 of 33(NAVD88).

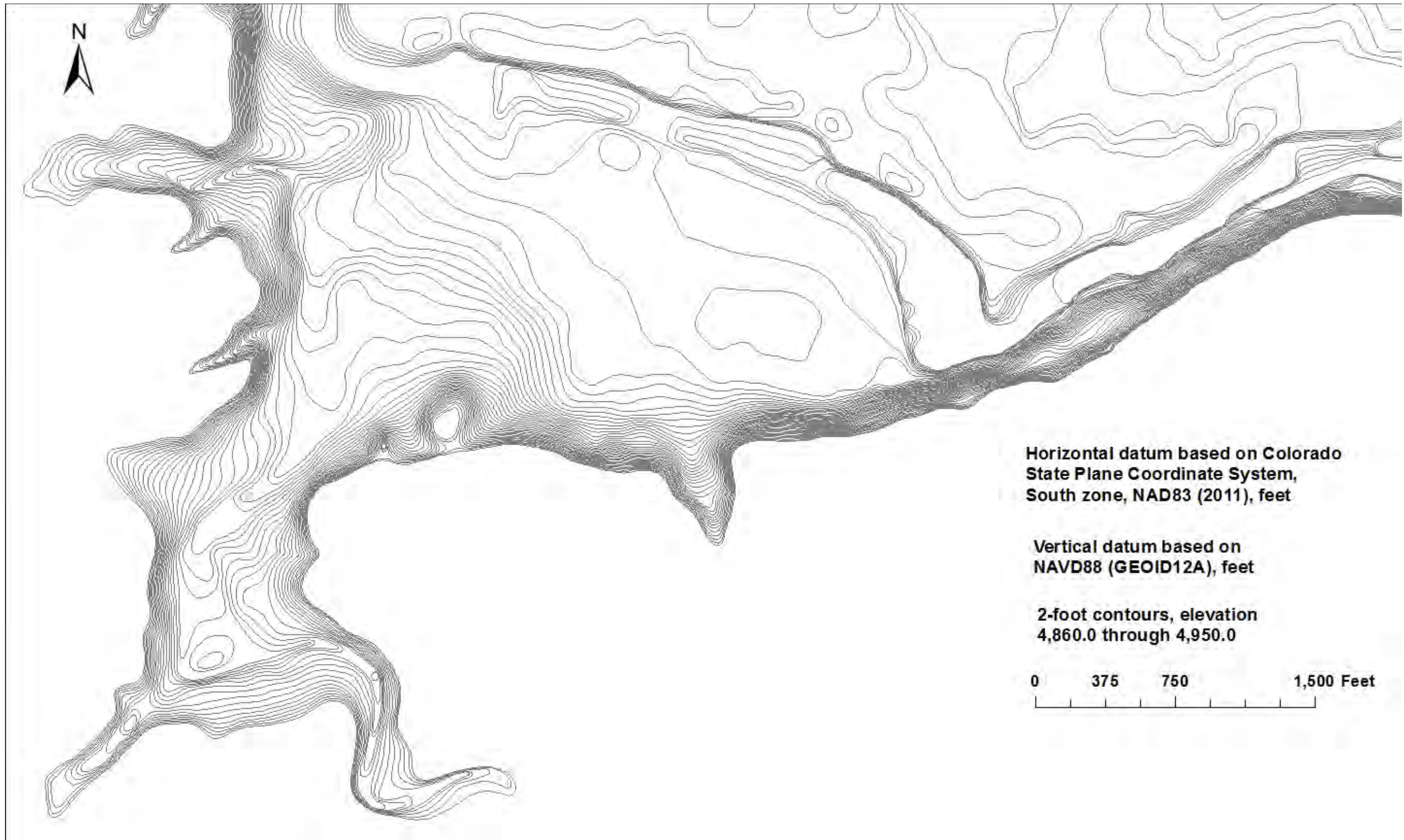


Figure 48 - 2012 Pueblo Reservoir 2-foot contours, 29 of 33(NAVD88).

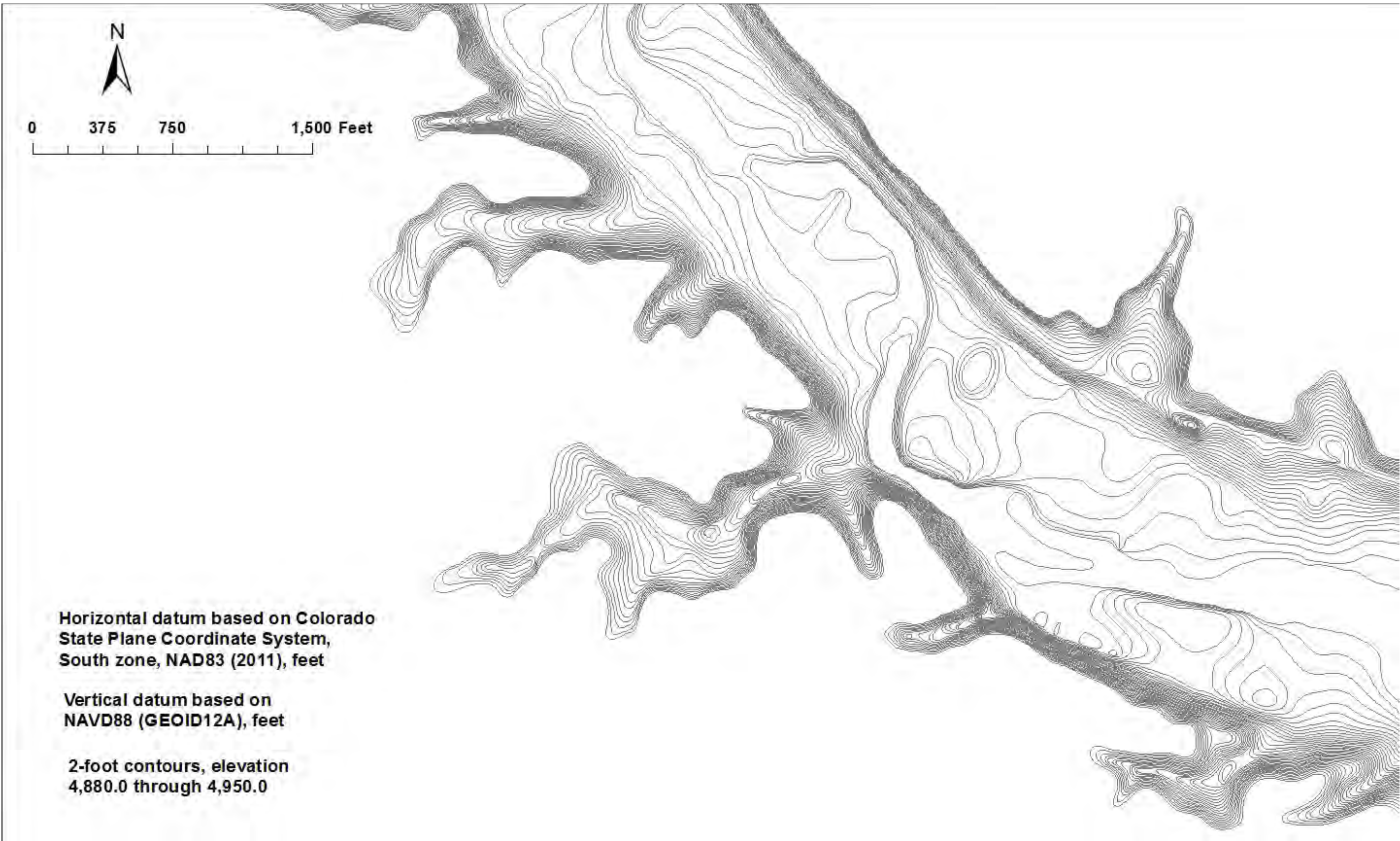


Figure 49 - 2012 Pueblo Reservoir 2-foot contours, 30 of 33 (NAVD88).

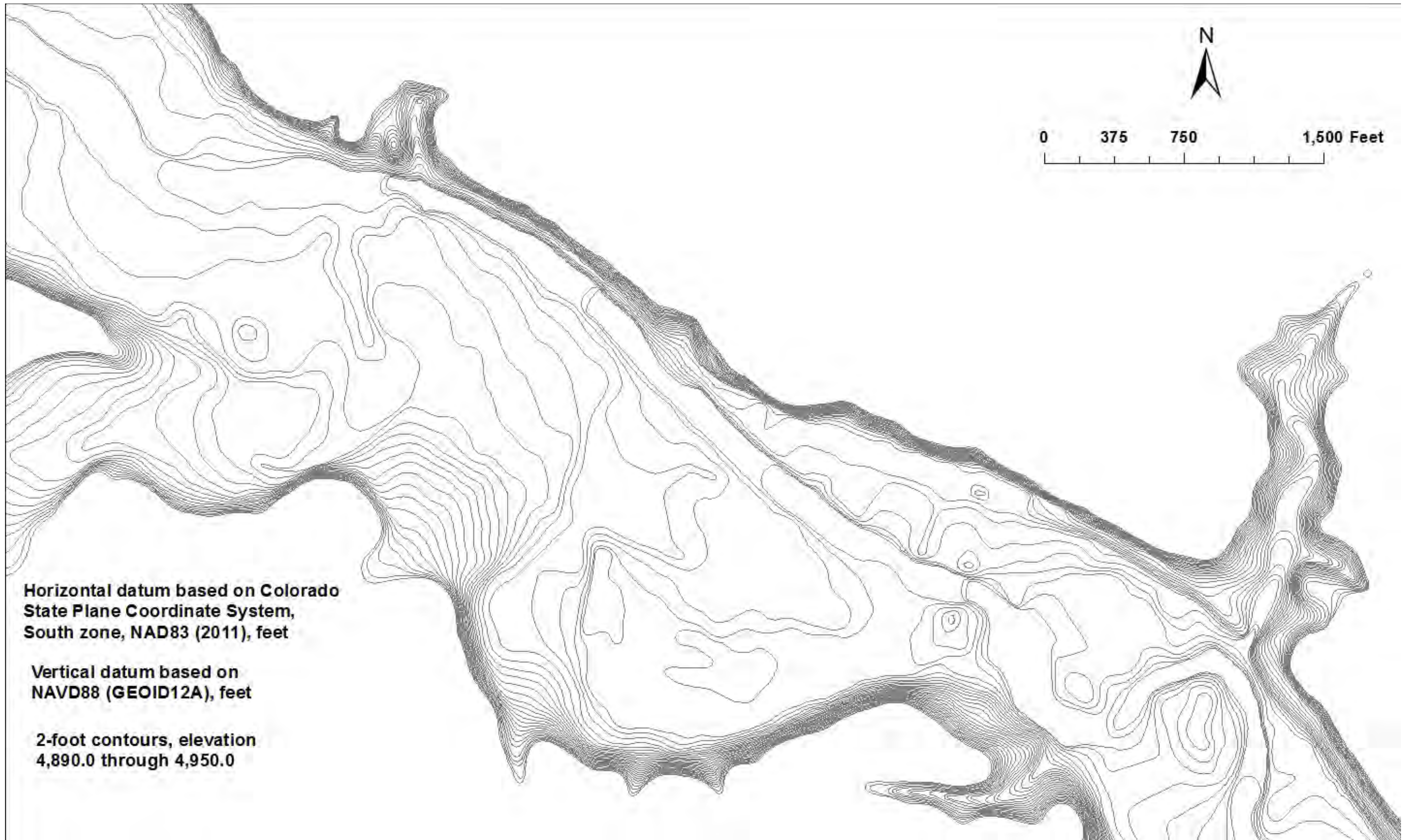


Figure 50 - 2012 Pueblo Reservoir 2-foot contours, 31 of 33 (NAVD88).

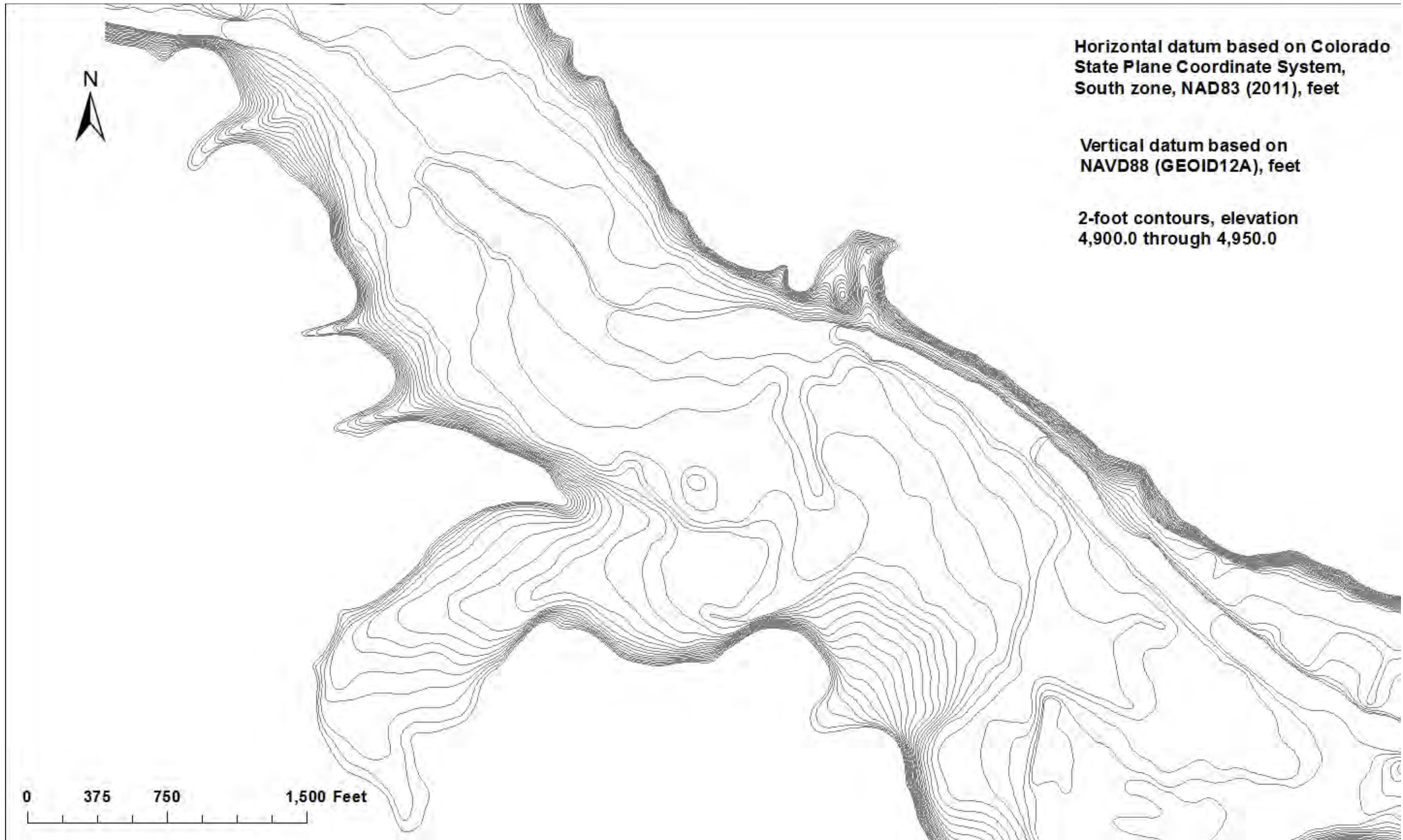
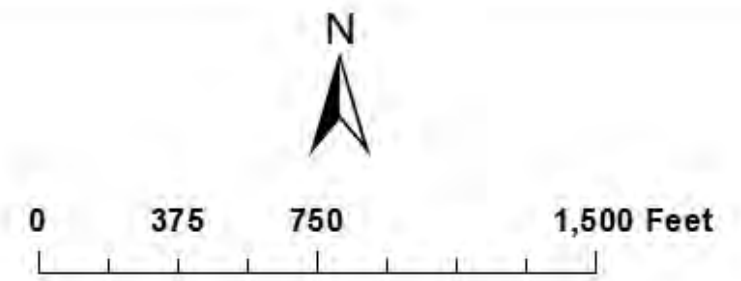


Figure 51 - 2012 Pueblo Reservoir 2-foot contours, 32 of 33 (NAVD88).



Horizontal datum based on Colorado State Plane Coordinate System, South zone, NAD83 (2011), feet

Vertical datum based on NAVD88 (GEOID12A), feet

2-foot contours, elevation 4,906.0 through 4,950.0

Figure 52 - 2012 Pueblo Reservoir 2-foot contours, 33 of 33 (NAVD88).

2012 Pueblo Reservoir Surface Area Methods

Using ArcGIS commands to compute areas at user-specified elevations, the 2012 surface areas for Pueblo Reservoir were computed at 2-foot increments directly from the reservoir TIN from minimum elevation 4,750 (NAVD88) to provide information for the area-capacity tables. The elevations of the computed surface areas were lowered 3.2 feet to match the water surface gage vertical datum and were used to develop the area and capacity tables for Pueblo Reservoir operations. As previously described, to complete the final 2012 area and capacity tables the upper surface areas from elevation 4,890.0 and above assumed no change in surface area since the 1993 survey.

2012 Pueblo Reservoir Storage Capacity Methods

The storage-elevation relationships based on the measured surface areas were developed using the area-capacity computer program ACAP (Bureau of Reclamation, 1985). The data input included the 2-foot computed surface areas from the 2012 topography from elevation 4,885 and below and the 5-foot surface areas from the 1993 survey from elevation 4,890.0 through 4,925.0. The ACAP program can compute the area and capacity at elevation increments from 0.01 to 1.0 foot by linear interpolation between the given contour surface areas. The program begins by testing the initial capacity equation over successive intervals to ensure that the equation fits within an allowable error limit. The error limit was set at 0.000001 for Pueblo Reservoir. The capacity equation is then used over the full range of intervals fitting within the allowable error limit. For the first interval at which the initial allowable error limit is exceeded, a new capacity equation (integrated from basic area curve over that interval) is used until it exceeds the error limit. Thus, the capacity curve is defined by a series of curves, each fitting a certain region of data. Through differentiation of the capacity equations, which are second order polynomials, final area equations are derived:

$$y = a_1 + a_2x + a_3x^2$$

where: y = capacity
 x = elevation above a reference base
 a₁ = intercept
 a₂ and a₃ = coefficients

Results of the Pueblo Reservoir area and capacity computations are listed in table 2 along in a separate set of 2012 area and capacity tables that have been published for 0.01, 0.1, and 1-foot elevation increments (Bureau of Reclamation, May 2012). A description of the computations and coefficients output from the ACAP program is included with those tables. As of May 2012, at conservation use elevation 4,880.49, the surface area was 4,453 acres with a total capacity of

245,862 acre-feet. At maximum and top of surcharge elevation 4,919.0, the surface area was 7,380 acres with a total capacity of 469,878 acre-feet.

Pueblo Reservoir Surface Area and Capacity Results

The area and capacity curves for the original, 1993 and 2012 surveys are plotted on Figure 53. Table 3 provides a comparison of the computed surface area and capacity values along with the estimated sediment accumulation. As stated previously, the area and capacity values are tied to the vertical datum currently used for measuring the reservoir water surface that is 3.2 feet lower than NAVD88 (GEOID12A). This study did not determine how this vertical datum related to the vertical datum of the project features such as the spillway crest elevation. The 2012 bathymetric survey and the other data sources summarized in the previous sections provided sufficient information for computing the surface areas from elevation 4,746.0 through 4,925.0. The ACAP program was used to compute the area and capacity values from the 2-foot elevation increment input surface areas for this study.

Longitudinal Distribution

To illustrate the bathymetry of the reservoir, the Arkansas River thalweg was plotted from the dam to the upper reach of the reservoir between elevation 4,740.0 and 4,900.0 as shown in Figure 54. The alignment started at the concrete section of the dam and followed the original river alignment as plotted on the USGS topography prior to reservoir development.

The longitudinal profiles were developed by sectioning the 2012 developed contours in ArcGIS and measuring the elevation at the sediment range line locations established prior to reservoir inundation. The original and 1993 topography was not available for use of the ArcGIS tools, but the measured bottom elevations at the sediment range lines were available and used to complete this plot. These profiles show the progressive sediment accumulation that has occurred over the years. The inlet sill to the lowest outlet works, elevation 4,764.0, remains above the current top of sediment deposition near the dam at elevation 4,752. The 1993 and 2012 plots show a steady buildup of sediment over time from the dam upstream, as opposed to the typical reservoir delta formation in the upper reaches of the reservoir.

RESERVOIR SEDIMENT
DATA SUMMARY

Pueblo Reservoir
NAME OF RESERVOIR

1
DATA SHEET NO.

D	1. OWNER: Bureau of Reclamation				2. STREAM: Arkansas River				3. STATE: Colorado					
A	4. SEC 36 TWP. 20 S RANGE 66 W				5. NEAREST P.O. Pueblo				6. COUNTY: Pueblo					
M	7. LAT 38 ° 16 ' 15 " LONG 104 ° 43 ' 30 "				8. TOP OF DAM ELEVATION: 4,925.0 ¹				9. SPILLWAY CREST EL. 4,898.7 ²					
R E S E R V O I R	10. STORAGE ALLOCATION		11. ELEVATION TOP OF POOL		12. Original SURFACE AREA, ACRES		13. Original CAPACITY, AC-FT		14. GROSS STORAGE ACRE-FEET		15. DATE STORAGE BEGAN			
	a. SURCHARGE		4,919.00 ³		7,380		131,504		489,625		1/9/74			
	b. FLOOD CONTROL		4,898.70		5,671		26,992		358,121					
	c. POWER													
	d. JOINT USE		4,893.80		5,353		66,266		331,129		16. DATE NORMAL OPERATIONS BEGAN			
	e. CONSERVATION		4,880.49		4,640		234,210		264,863		8/75			
	f. INACTIVE		4,796.70		1,322		26,895		30,653					
	g. DEAD		4,764.00		421		3,758		3,758					
17. LENGTH OF RESERVOIR 11.4 ⁴ MILES				AVG. WIDTH OF RESERVOIR 0.8 MILES										
B	18. TOTAL DRAINAGE AREA 4,669 ⁵ SQUARE MILES				22. MEAN ANNUAL PRECIPITATION 9-19 ⁶ INCHES									
A	19. NET SEDIMENT CONTRIBUTING AREA 4,170 ⁵ SQUARE MILES				23. MEAN ANNUAL RUNOFF 2.37 ⁷ INCHES									
S	20. LENGTH MILES		AVG. WIDTH MILES		24. MEAN ANNUAL RUNOFF 589,890 ⁸ ACRE-FEET									
I	21. MAX. ELEVATION		MIN. ELEVATION		25. ANNUAL TEMP, MEAN 17-54 °F RANGE -54 °F to 105 °F ⁶									
S U R V E Y	26. DATE OF SURVEY	27. PER. YRS	28. PER. YRS	29. TYPE OF SURVEY	30. NO. OF RANGES OR INTERVALS	31. SURFACE AREA, AC.	32. CAPACITY ACRE - FEET	33. C/I RATIO AF/AF						
	1/1974			Contour (D)	5-ft	4,640	264,863 ³	0.45						
	5/1993	19.3		Range (D)	31	4,611	256,949	0.44						
	5/2012	38.3		Contour (D)	2-ft	4,453 ⁹	245,862 ⁹	0.42						
D A T A	26. DATE OF SURVEY	34. PERIOD ANNUAL PRECIPITATION		35. PERIOD WATER INFLOW, ACRE-FEET			36. WATER INFLOW TO DATE, AF							
		a. MEAN ANN.	b. MAX. ANN.	c. TOTAL	a. MEAN ANN.	b. TOTAL								
	5/1993	595,355 ¹⁰	1,007,400	11,907,100	595,355	11,907,100								
	5/2012	562,405	1,258,000	10,685,700	589,890	22,592,800								
A	26. DATE OF SURVEY	37. PERIOD CAPACITY LOSS, ACRE-FEET			38. TOTAL SEDIMENT DEPOSITS TO DATE, AF									
		a. TOTAL	b. AVG. ANN.	c. /MI. ² -YR.	a. TOTAL	b. AVG. ANN.	c. /MI. ² -YR.							
	5/1993	7,914 ¹¹	410.0	0.098	7,914	410.0	0.098							
	5/2012	11,087	583.5	0.140	19,001	496.1	0.112							
26. DATE OF SURVEY	26. DATE OF SURVEY	39. AVG. DRY WT. (#/FT ³)		40. SED. DEP. TONS/MI. ² -YR		41. STORAGE LOSS, PCT.		42. SEDIMENT INFLOW, PPM						
		a. PERIOD	b. TOTAL TO DATE	a. AVG ANNUAL	b. TOTAL TO DATE	a. PER.	b. TOT.							
	5/1993	0.155 ¹¹	2.99	0.187	7.17									
	5/2012	0.187	7.17											
26. DATE OF SURVEY	43. DEPTH DESIGNATION RANGE IN FEET BELOW AND ABOVE CREST ELEVATION													
	4,770.0- 4,725.0	4,790.0- 4,770.0	4,800.0- 4,790.0	4,810.0- 4,800.0	4,820.0- 4,810.0	4,830.0- 4,820.0	4,840.0- 4,830.0	4,850.0- 4,840.0	4,860.0- 4,850.0	4,870.0- 4,860.0	4,800.49- 4,870.0			
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN DEPTH DESIGNATION													
5/2012	10.8	9.4	10.1	6.6	5.8	7.6	7.7	6.1	11.5	11.8	12.6			
26. DATE OF SURVEY	44. REACH DESIGNATION PERCENT OF TOTAL ORIGINAL LENGTH OF RESERVOIR													
	0-	10-	20-	30-	50-	60-	70-	80-	90-	100-	105-	110-	115-	120-
	10	20	30	40	60	70	80	90	100	105	111	115	120	125
PERCENT OF TOTAL SEDIMENT LOCATED WITHIN REACH DESIGNATION														

Table 2 - Reservoir sediment data summary (page 1 of 2).

45. RANGE IN RESERVOIR OPERATION ¹⁰							
YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AF	YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AF
1974	4,792.6	4,776.6	448,200	1975	4,800.4	4,790.5	567,900
1976	4,821.8	4,800.1	414,900	1977	4,830.2	4,799.6	234,000
1978	4,802.2	4,779.7	401,500	1979	4,822.1	4,797.0	581,400
1980	4,835.6	4,799.5	779,300	1981	4,879.6	4,820.0	327,400
1982	4,837.3	4,798.6	618,600	1983	4,879.6	4,820.0	944,100
1984	4,884.3	4,868.0	1,007,400	1985	4,886.9	4,875.0	978,000
1986	4,883.8	4,875.8	767,400	1987	4,881.9	4,872.6	792,400
1988	4,881.1	4,851.2	454,200	1989	4,873.7	4,838.6	467,600
1990	4,851.5	4,828.2	427,200	1991	4,854.5	4,824.5	506,400
1992	4,856.5	4,823.3	522,300	1993	4,864.0	4,834.3	666,900
1994	4,868.4	4,834.4	600,900	1995	4,881.5	4,834.2	1,258,000
1996	4,888.4	4,866.4	640,900	1997	4,885.6	4,865.5	781,600
1998	4,880.7	4,852.1	580,600	1999	4,881.6	4,851.4	759,900
2000	4,885.3	4,856.0	509,300	2001	4,873.4	4,834.1	461,200
2002	4,851.7	4,826.3	202,300	2003	4,840.7	4,820.6	334,500
2004	4,841.6	4,819.9	361,100	2005	4,851.2	4,831.7	411,100
2006	4,855.7	4,831.8	485,000	2007	4,866.6	4,840.7	635,100
2008	4,880.3	4,853.0	734,200	2009	4,879.7	4,860.2	605,100
2010	4,882.6	4,863.5	525,800	2011	4,882.6	4,857.8	622,400
2012	4,879.0	4,857.2	176,700				

46. ELEVATION - AREA - CAPACITY - DATA								
ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY
<u>2012</u>	<u>SURVEY</u> ¹²							
4,746.0	0	0	4,750.0	2	4	4,755.0	45	98
4,760.0	227	738	4,765.0	368	2,250	4,770.0	506	4,451
4,775.0	601	7,235	4,780.0	700	10,453	4,785.0	831	14,241
4,790.0	953	18,709	4,795.0	1,065	23,761	4,796.7	1,100	25,601
4,800.0	1,186	29,369	4,805.0	1,407	35,870	4,810.0	1,611	43,456
4,815.0	1,761	51,890	4,820.0	1,914	61,080	4,825.0	2,101	71,118
4,830.0	2,265	82,014	4,835.0	2,489	93,912	4,840.0	2,647	106,759
4,845.0	2,837	120,439	4,850.0	2,973	134,985	4,855.0	3,125	150,221
4,860.0	3,358	166,397	4,865.0	3,615	183,887	4,870.0	3,835	202,477
4,875.0	4,103	222,370	4,880.0	4,422	243,688	4,880.49	4,453	245,862
4,885.0	4,782	266,759	4,890.0	5,115	291,501	4,893.8	5,350	311,384
4,895.0	5,424	317,848	4,898.7	5,671	338,374	4,900.0	5,758	345,803
4,905.0	6,154	375,583	4,910.0	6,532	407,298	4,915.0	6,998	441,123
4,919.0	7,380	469,878	4,920.0	7,475	477,306	4,925.0	8,027	516,061

47. REMARKS AND REFERENCES

¹ All elevations are in feet tied to current water surface vertical datum that is 3.2 feet less than NAVD88. Question of design vertical datum. Design dam concrete crest el. 4,921.0, top parapet wall el. 4,925.25, and earthen crest elevation 4,925.0.

² Spillway crest elevation.

³ Original values recomputed using ACAP.

⁴ Length of reservoir computed in 1993 at elevation 4,900.

⁵ From USGS water records. Net area removes drainage area above Turquoise & Twin Lakes along with Clear Creek & Dewease Reservoirs.

⁶ Bureau of Reclamation Project Data Book, 1981.

⁷ From 1993 report and region water records.

⁸ 1974 through May 2012.

⁹ Surface area and capacity at conservation elevation 4,880.49.

¹⁰ Maximum & minimum elevations from available USBR regional records by water year. Elevations tied to operation gage vertical datum. Inflows from 1974 through 1993 from 1993 survey report. Inflows from 1994 through May 2012 from online regional computer records by water year.

¹¹ Total sediment inflow by comparing survey values with recomputed capacity from previous surveys.

¹² Capacity computed by Reclamation's ACAP computer program tied to the gage vertical datum that is 3.2 feet less than NAVD88 (GEOID12A). 2012 reservoir topography at 2-foot interval used to develop these 2012 tables.

48. AGENCY MAKING SURVEY Bureau of Reclamation

49. AGENCY SUPPLYING DATA Bureau of Reclamation | DATE March 2015

Table 2 - Reservoir sediment data summary (page 2 of 2).

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>
Elevation	Original	Original	1993	1993	1993	2012	2012	2012	Percent	Percent
Feet	Area	Capacity	Area	Capacity	Sediment	Area	Capacity	Sediment	Reservoir	Reservoir
	Acres	Ac-Ft	Acres	Ac-Ft	Volume	Acres	Ac-Ft	Volume	Sediment	Depth
					Ac-Ft			Ac-Ft		
4,925.0	8,027	535,807	8,027	527,626	8,181	8,027	516,061			100.0
4,920.0	7,475	497,052	7,475	488,871	8,181	7,475	477,306			97.5
4,919.0	7,380	489,625	7,380	481,444	8,181	7,380	469,878			97.0
4,915.0	6,998	460,870	6,998	452,689	8,181	6,998	441,123			95.0
4,910.0	6,532	427,045	6,532	418,864	8,181	6,532	407,298			92.5
4,905.0	6,154	395,330	6,154	387,149	8,181	6,154	375,583			90.0
4,900.0	5,758	365,550	5,758	357,369	8,181	5,758	345,803			87.5
4,898.7	5,671	358,121	5,671	349,940	8,181	5,671	338,374			86.8
4,895.0	5,424	337,595	5,424	329,414	8,181	5,424	317,848			85.0
4,893.8	5,353	331,129	5,350	322,949	8,180	5,350	311,384			84.4
4,890.0	5,127	311,217	5,115	303,066	8,151	5,115	291,501			82.5
4,885.0	4,853	286,267	4,823	278,221	8,046	4,782	266,759			80.0
4,880.49	4,640	264,863	4,611	256,949	7,914	4,453	245,862	19,001	100.0	77.7
4,880.0	4,616	262,595	4,587	254,696	7,899	4,422	243,688	18,907	99.5	77.5
4,875.0	4,358	240,160	4,238	232,634	7,526	4,103	222,370	17,790	93.6	75.0
4,870.0	4,070	219,090	3,992	212,059	7,031	3,835	202,477	16,613	87.4	72.5
4,865.0	3,836	199,325	3,763	192,671	6,654	3,615	183,887	15,438	81.2	70.0
4,860.0	3,588	180,765	3,530	174,439	6,326	3,358	166,397	14,368	75.6	67.5
4,855.0	3,361	163,392	3,298	157,369	6,023	3,125	150,221	13,171	69.3	65.0
4,850.0	3,131	147,162	3,089	141,401	5,761	2,973	134,985	12,177	64.1	62.5
4,845.0	2,925	132,022	2,910	126,404	5,618	2,837	120,439	11,583	61.0	60.0
4,840.0	2,772	117,780	2,737	112,286	5,494	2,647	106,759	11,021	58.0	57.5
4,835.0	2,636	104,260	2,579	98,996	5,264	2,489	93,912	10,348	54.5	55.0
4,830.0	2,442	91,565	2,368	86,629	4,936	2,265	82,014	9,551	50.3	52.5
4,825.0	2,239	79,862	2,167	75,291	4,571	2,101	71,118	8,744	46.0	50.0
4,820.0	2,032	69,185	2,005	64,861	4,324	1,914	61,081	8,105	42.7	47.5
4,815.0	1,882	59,400	1,813	55,316	4,084	1,761	51,890	7,510	39.5	45.0
4,810.0	1,689	50,472	1,643	46,676	3,796	1,611	43,456	7,016	36.9	42.5
4,805.0	1,532	42,420	1,431	38,991	3,429	1,407	35,870	6,550	34.5	40.0
4,800.0	1,387	35,122	1,280	32,214	2,908	1,186	29,369	5,753	30.3	37.5
4,796.7	1,322	30,653	1,200	28,121	2,532	1,100	25,601	5,052	26.6	35.8
4,795.0	1,288	28,435	1,159	26,116	2,319	1,065	23,761	4,674	24.6	35.0
4,790.0	1,065	22,552	1,007	20,701	1,851	953	18,709	3,843	20.2	32.5
4,785.0	934	17,555	904	15,923	1,632	831	14,241	3,314	17.4	30.0
4,780.0	813	13,187	794	11,677	1,510	700	10,453	2,734	14.4	27.5
4,775.0	695	9,417	691	7,964	1,453	601	7,235	2,182	11.5	25.0
4,770.0	474	6,495	472	5,056	1,439	506	4,451	2,044	10.8	22.5
4,765.0	447	4,192	446	2,762	1,430	368	2,250	1,942	10.2	20.0
4,764.0	421	3,758	420	2,329	1,429	342	1,895	1,863	9.8	19.5
4,760.0	318	2,280	318	853	1,427	227	738	1,542	8.1	17.5
4,755.0	199	987	16	18	969	45	98	889	4.7	15.0
4,752.8	146	608	0	0	608	21	28	580	3.1	13.9
4,750.0	78	295	0	0	295	2	4	291	1.5	12.5
4,745.0	15	62	0	0	62	0	0	62	0.3	10.0
4,740.0	2	20	0	0	20	0	0	20	0.1	7.5
4,735.0	2	10	0	0	10	0	0	10	0.1	5.0
4,730.0	1	2	0	0	2	0	0	2	0.0	2.5
4,725.0	0	0	0	0	0	0	0	0	0.0	0.0

- 1 Reservoir water surface elevation tied to water surface gage vertical datum, 3.2 feet less than NAVD88.
- 2 Original reservoir surface area.
- 3 Original reservoir capacity recomputed using ACAP from original measured surface areas.
- 4 1993 reservoir surface areas computed from a 1993 range line survey.
- 5 1993 reservoir capacity computed using ACAP.
- 6 1993 computed sediment volume, column (3) - column (5).
- 7 2012 reservoir surface area computed from a 2012 topographic mapping survey.
- 8 2012 reservoir capacity computed using ACAP.
- 9 2012 computed sediment volume, column (3) - column (9).
- 10 2012 percent of total sediment, 19,001 acre-feet, by indicated elevation zone.
- 11 Depth of reservoir expressed in percentage of total depth of 200.0 feet.

Table 3 - Pueblo Reservoir 2012 survey summary.

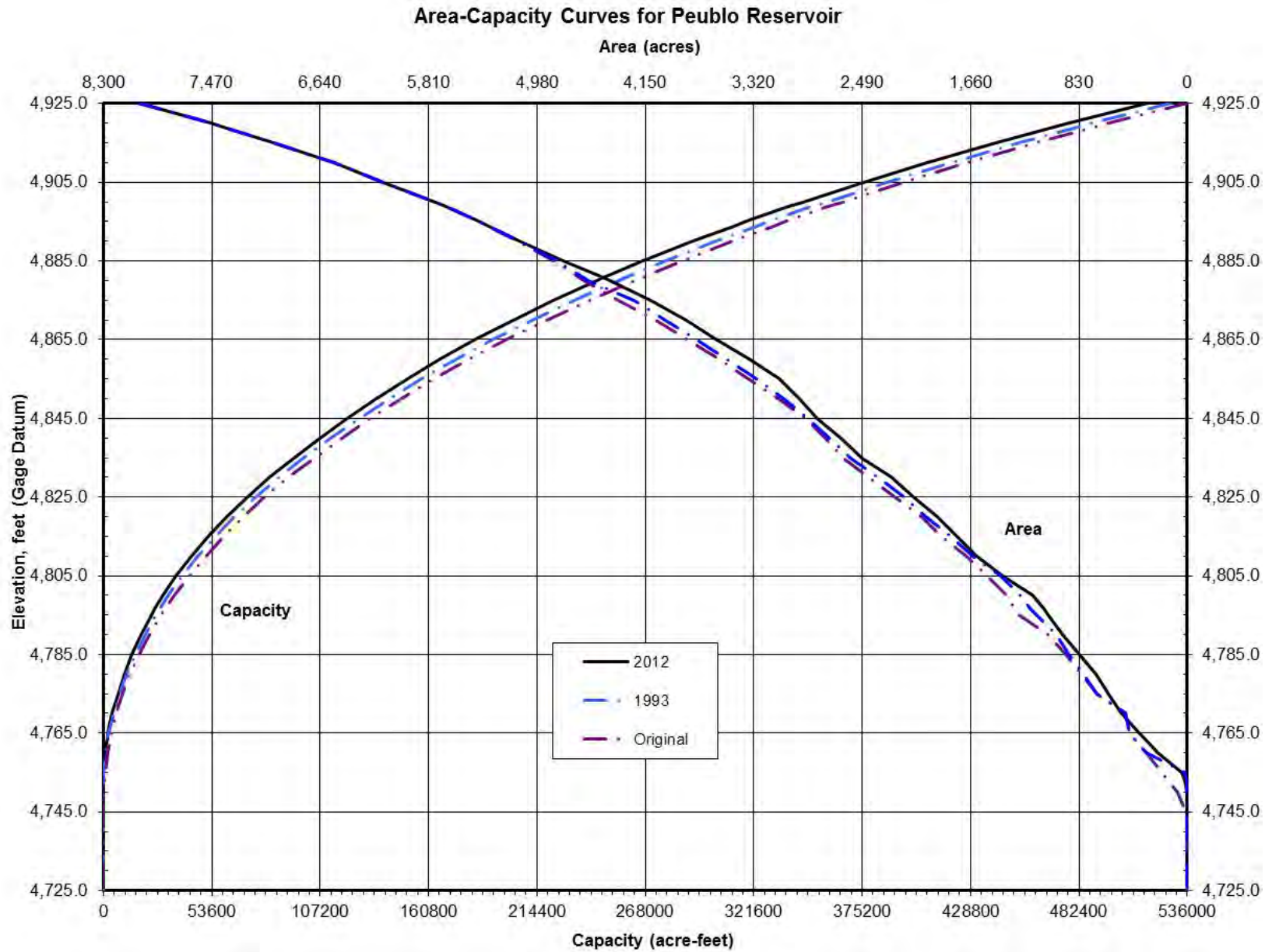


Figure 53 - Pueblo Reservoir area and capacity plots.

Pueblo Reservoir Longitudinal Profiles Original, 1993 and 2013 Comparison

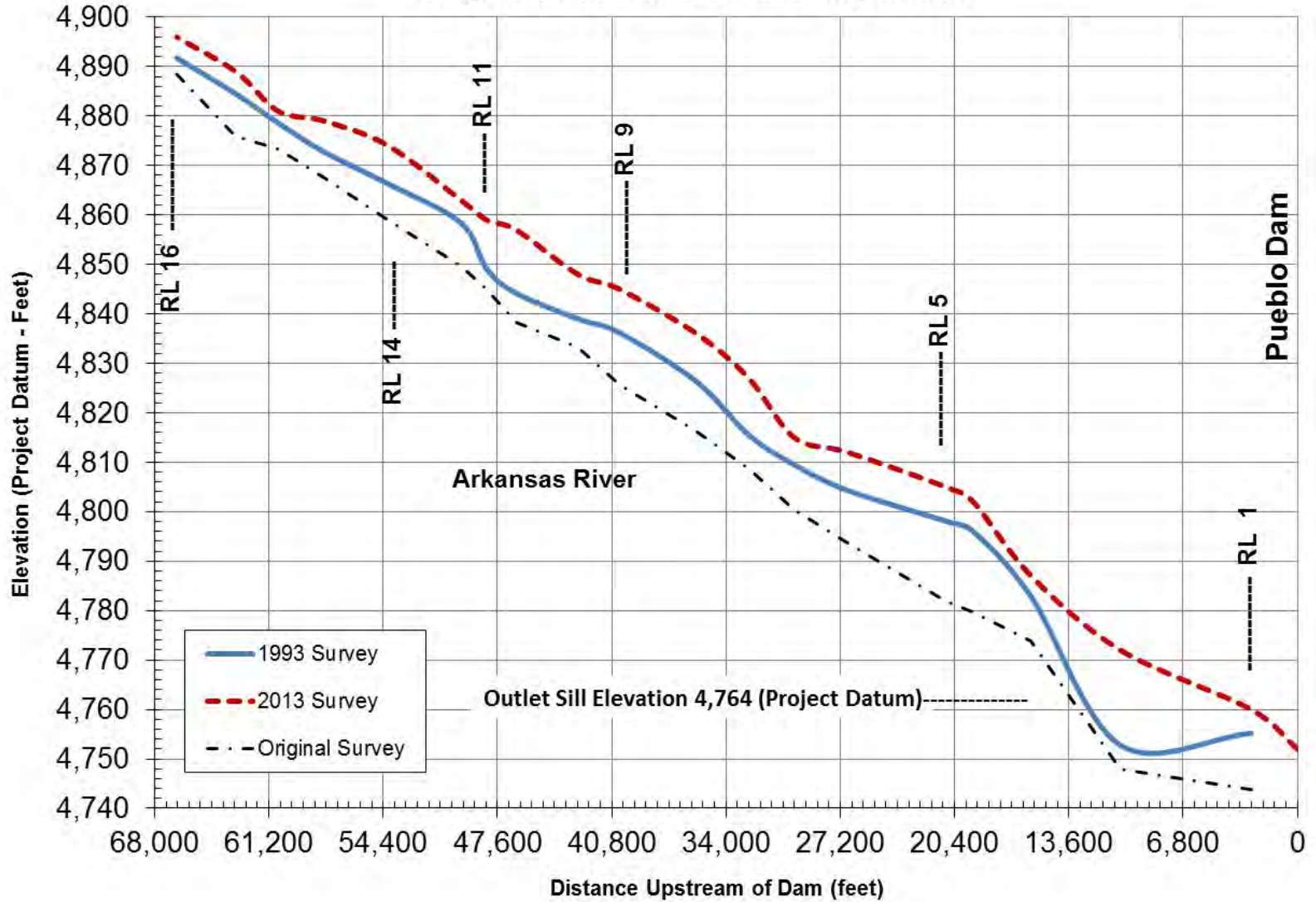


Figure 54 - Longitudinal profile of the Arkansas River from the dam upstream.

2012 Pueblo Reservoir Analyses

Results of the 2012 Pueblo Reservoir area and capacity computations are listed in Table 2 and Table 3. Table 3 lists the original and 1993 area and capacity values. The original surface areas were calculated from 5-foot contours of the reservoir area. The 1993 surface area and capacity values were computed from a survey of 31 sediment range lines established prior to closure of Pueblo Dam. The 1993 surface areas were computed by measuring elevation changes at these 31 range lines and applying a ratio of these measured changes to the original surface area values. The 2012 survey resulted in updated topography of Pueblo Reservoir from which surface areas and volumes were computed. The 2012 study was conducted near water surface elevation 4,873 or about fifty feet below top of dam elevation 4,925. Data obtained to allow completion of the reservoir topography above elevation 4,873 was not sufficiently accurate for this purpose. Therefore, the 2012 study assumed no change in reservoir surface areas since the last sediment survey in 1993 from elevation 4,890 and above. The only practical means to measure the reservoir topography above the collected bathymetric data would be employ an accurate aerial survey method using aerial methods such as LiDAR. If above water data is obtained in the future, it should be collected with the reservoir drawn down to provide overlap with the bathymetric survey.

The 2012 Pueblo Reservoir topography was developed with the elevations tied to NAVD88 (GEOID12A). The reservoir surface area, capacity, and sediment accumulation results were tied to the current vertical datum used to measure the reservoir water surface elevation that this study determined was approximately 3.2 feet lower than NAVD88 (GEOID12A). The tables within this report list the area and capacity results for the 2012 survey and compare the results to the original and 1993 surface area and capacity values. Figure 53 illustrates the differences in the Pueblo Reservoir surface area and capacity for the original, 1993, and 2012 surveys.

Table 2 shows elevation 4,880.49 as the current conservation level with elevation 4,893.8 as a joint use level. The flood control zone is between elevation 4,893.8 and the uncontrolled spillway crest at elevation 4,898.7. Until the reservoir level reaches the spillway crest, the outlet works are the only available means to release water from the reservoir. For this study, the 2012 area and capacity values were computed to top of dam crest elevation 4,925.0. The operation records show the reservoir's maximum water surface elevation of 4,888.4 was reached in 1996 that is below the flood control zone that begins at spillway crest elevation 4,898.7, meaning the reservoir has never operated in the flood zone and has never spilled.

Surface area and volume differences are referenced to current conservation elevation 4,880.49 or about eight feet below the maximum reservoir operation

level since dam closure. The 2012 survey measured a total decrease in capacity of 19,001 acre feet at elevation 4,880.49 since dam closure in January 1974. For the first 38.3 years of reservoir operation the average annual sediment accumulation is 496 acre-feet. A 1994 sediment distribution study included 94,939 acre-feet allowance for 81 years of sediment deposition between the reservoir streambed and elevation 4,898.7 or an average annual accumulation of 1,172 acre-feet. There were no details located on this study, but it is assumed the 1994 study used the original sediment projection for these results. The 2012 study only measured about 42 percent of the original annual projection of sediment accumulation. It's possible that future flood events could deposit more sediment within the reservoir boundary to bring the actual capacity loss closer to the original sediment projection. A resurvey, including improved above-water data collection, should be scheduled in the future if a significant change in the sediment basin runoff is noted.

Summary and Conclusions

This Reclamation report presents the results of the May 2012 survey of Pueblo Reservoir. The primary objectives of the survey were to gather data needed to:

- develop updated reservoir topography;
- compute current area-capacity relationships; and
- estimate sediment deposition since original and 1993 surveys.

A control survey was conducted using the Online Positioning User Service (OPUS) and RTK GPS to establish a horizontal and vertical control network near the reservoir for the hydrographic survey. OPUS is operated by the NGS and allows users to submit GPS data files that are processed with known point data to determine positions relative to the national control network. The GPS base was set over a temporary rebar and cap located where it provided continuous radio link throughout the bathymetric survey. From this location, measurements were obtained on the water surface and project features that were used to determine the vertical datum for developing the 2012 area and capacity values. Accurate measurements were also obtained on two brass monuments located below the dam that can be used by future surveys to better reference their vertical information to this study.

The study's horizontal control is in US Survey Feet, Colorado state plane south coordinates, in NAD83 (2011). The vertical control, in US Survey Feet, was tied to NAVD88 (Geoid12A) that is around 3.2 higher than the project's vertical datum used to measure the water surface elevation of Pueblo Reservoir. Information on how this vertical datum was established was not available. How this vertical datum relates to the top of the dam and spillway crest is also unknown. Unless noted, all elevations presented in this report are tied to the

reservoir water surface gage vertical datum. The developed reservoir topography presented in this report is referenced to NAVD88 (GEOID12A). The May 2012 underwater survey was conducted near reservoir elevation 4,873 as measured by the Reclamation gage at the dam and confirmed by RTK GPS measurements.

The bathymetric survey used sonic depth recording equipment interfaced with a RTK GPS for determining sounding locations within the reservoir. The system continuously recorded depth and horizontal coordinates as the survey boat navigated along the predetermined grid lines covering Pueblo Reservoir. The positioning system provided information to allow the boat operator to maintain a course along these grid lines. Bathymetric data was also collected as the vessel maneuvered along the shoreline between grid lines and as it moved to and from the boat ramp to the work areas.

The above-water topography for the 2012 study was developed from airborne collected digital data obtained as IFSAR bare-earth information for the reservoir area (Intermap, 2011). The IFSAR aerial was flown in 2007, but was the most recent and best available information for developing topography in the above water areas of the reservoir. IFSAR technology enables mapping of large areas quickly and efficiently, resulting in detailed information at a much reduced cost compared to other technologies such as aerial photogrammetry and LiDAR. The reported accuracies for the IFSAR data are 2 meters or better horizontally and 1 meter or better vertically in unobstructed flat-ground areas. Other technologies would produce more accurate data than IFSAR, but funding was not available to acquire those data for this study. The IFSAR data resulted in detailed topography of the upper reservoir area and elevations matched well with the 2012 bathymetric data in the open flat-bottom areas of the reservoir. During analysis, accuracy issues with the IFSAR data were noted along the very steep and at times vertical shoreline of the reservoir. In these areas, the IFSAR data was removed and an ArcGIS program interpolated contours from the surrounding data sets.

Additional data sources for the 2012 topography development included several years of USDA aerial images flown between 2005 and 2011 (USDA, 2010). The above-water topography near the shoreline for the 2012 field survey was determined by digitizing contour lines along the water's edge from these USDA images of the reservoir area. These contour outlines were used to assure coverage of the reservoir during the May 2012 survey. During analysis, portions of the digitized water surface edges from orthographic aerial images were used as break lines to assist in contour development.

The 2012 Pueblo Reservoir topographic map is a combination of the digitized water surface edge from the USDA photographs, IFSAR data, and 2012 underwater survey data, all tied to NAVD88 (GEOID12A). A computer program was used to generate the 2012 topography and resulting reservoir surface areas at predetermined contour intervals from the combined reservoir data at elevation 4,925.0 and below. Due to accuracy issues with the upper elevations of this

developed topography, the 2012 study assumed no change in reservoir surface area from elevation 4,890.0 and above since the 1993 reservoir survey. The 2012 area and capacity tables were produced using a computer program (ACAP) that calculated area and capacity values at prescribed elevation increments using a curve-fitting technique.

Tables 2 and 3 contain summaries of the Pueblo Reservoir and watershed characteristics for the 2012 survey. The 2012 survey determined the reservoir has a total storage capacity of 469,878 acre-feet with a surface area of 7,380 acres at maximum reservoir water surface elevation 4,919.0. At conservation water surface elevation 4,880.49 the total capacity was 245,862 acre-feet with a surface area of 4,453 acres. Since dam closure in January 1974 this study measured sediment accumulation of 19,001 acre-feet below reservoir elevation 4,880.49.

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