Analysis of Bottom Sediment to Estimate Nonpoint-Source Phosphorus Loads for 1981–96 in Hillsdale Lake, Northeast Kansas

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.40468	hectare
acre	43,560	square foot
acre	4,047	square meter
acre	0.001562	square mile
acre-foot (acre-ft)	43,560	cubic feet
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot (ft^3)	28.32	liter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic meter (m^3)	35.31	cubic foot
foot (ft)	0.3048	meter
gram (g)	0.03527	ounce
inch (in.)	2.54	centimeter
kilogram (kg)	2.205	pound
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot
meter (m)	3.281	foot
mile (mi)	1.609	kilometer
milligram per liter (mg/L)	1.0	part per million
milligram per kilogram (mg/kg)	1.0	part per million
pound (lb)	0.45351	kilogram
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$^{o}C = 5/9\ (^{o}F - 32)$$
$$^{o}F = 9/5\ (^{o}C) + 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Bottom sediment in Hillsdale Lake, northeast Kansas, was analyzed as a means of estimating the annual load of total phosphorus deposited in the lake from nonpoint sources. Topographic, bathymetric, and sediment-core data were used to estimate the total mass of phosphorus in the lake-bottom sediment. Available streamflow and water-quality data were used to compute the mean annual mass of phosphorus (dissolved plus suspended) exiting the lake as well as the mean annual load of phosphorus added to the lake from point sources. A simple mass balance then was used to compute the mean annual load of phosphorus from nonpoint sources.

Mean annual sediment deposition from 1981 through 1996 was estimated to be 265 million pounds (120 million kilograms). The total mass of phosphorus in the lake-bottom sediment was estimated to be 924,000 kilograms, with a mean annual load of 62,000 kilograms. The mean annual mass of phosphorus exiting in the lake outflow was estimated to be about 8,000 kilograms. The mean annual loads of phosphorus added to the lake from point and nonpoint sources were estimated to be 5,000 and 65,000 kilograms, respectively. Thus, the contribution to the total mean annual phosphorus load in Hillsdale Lake from point sources is about 7 percent and from nonpoint sources, about 93 percent.

INTRODUCTION

Hillsdale Lake is a Federal impoundment on Big Bull Creek in northwest Miami County, northeast Kansas (fig. 1). Completed in 1981, the lake is used for flood control, water supply, fish and wildlife habitat, and recreation. With the rapid expansion of urbanization in southern Johnson County, the use of the lake as a water-supply source is expected to increase substantially. As early as 1985, concerns existed that water quality in Hillsdale Lake may be affected by urbanization and increased point- and nonpoint-source discharges of phosphorus within the basin. Hillsdale Lake is reportedly the third-most, point-source-affected Federal lake in Kansas (Carney, 1994).

Phosphorus is an important nutrient because it is the principal limiting factor for primary production in most freshwater environments (Hakanson and Jansson, 1983). If phosphorus concentrations are too large, algal growth may become excessive and cause taste and odor problems for water suppliers. Additionally, excessive algal growth may be detrimental to aquatic life in, as well as discourage recreational use of, the lake. On the basis of widely accepted chlorophyll-a criteria, Hillsdale Lake has been classified as eutrophic by the Kansas Department of Health and Environment (KDHE) (Carney, 1994). A eutrophic lake contains nutrient-rich water and supports high biotic productivity (Cole, 1983).

Sediment deposition in a lake is important because about 95 percent of the phosphorus in streams tends to adhere to sediment particles (Hem, 1985). The sediment transported by streams and deposited in a lake acts as a sink where phosphorus may be stored and as a source of phosphorus to the overlying water and biota (Baudo and others, 1990). Although the release of

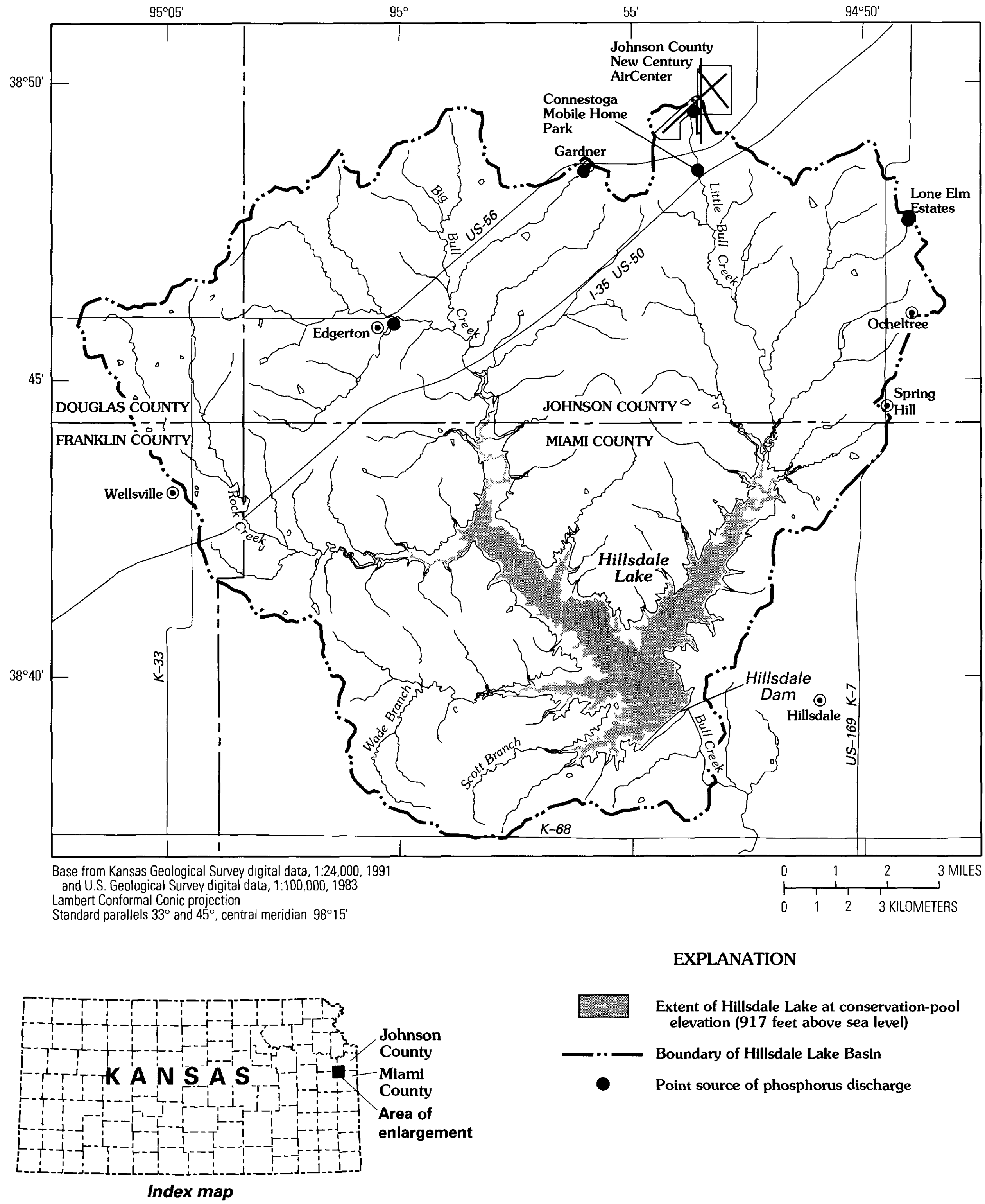


Figure 1. Location of Hillsdale Lake Basin in northeast Kansas and point sources of phosphorus discharge within the basin.

phosphorus from lake-bottom sediment may occur under aerobic or anoxic conditions, the release rate is typically much greater during anoxic conditions (Bostrom and others, 1982; Wetzel, 1983). However, Welch and Cooke (1995) state that several mechanisms can combine to produce relatively high phosphorus release rates in shallow, aerobic lakes. Hillsdale Lake is typified by aerobic conditions with water depths ranging from shallow to relatively deep (50 ft or more).

Aside from resuspension, the release of phosphorus from lake-bottom sediment involves a mobilization from particulate to dissolved form followed by transport into the water column. Important environmental factors in the mobilization of phosphorus include redox potential, pH, and temperature. Transport processes include diffusion, turbulence, and bioturbation (Hakanson and Jansson, 1983).

In 1991, the Hillsdale Water-Quality Protection Project was initiated by the Hillsdale Lake Region Resource Conservation and Development Council (RC&D) to establish long-term protection of the lake and drainage area. The goal of the project is to implement a nonpoint-source pollution-control program to manage further nutrient enrichment of Hillsdale Lake. Specifically, the objectives are to maintain a mean annual total phosphorus concentration of 0.06 mg/L or less in Hillsdale Lake water and a mean annual total phosphorus concentration of 0.10 mg/L, a low-flow mean concentration of 0.05 mg/L, and a runoff mean concentration of 0.40 mg/L in lake tributary water. RC&D began water-quality sampling of the streams flowing into Hillsdale Lake in 1993. The sampling was performed during storm-runoff and base-flow conditions.

In a recent study, the U.S. Geological Survey (USGS) focused on determining both point and nonpoint sources of phosphorus during low-flow conditions (Putnam, 1997). Results of the study indicate that the point sources in the Hillsdale Lake Basin (fig. 1) are significant contributors to the phosphorus loads in Big Bull Creek and Little Bull Creek during low-flow conditions. The mean concentrations of total phosphorus ranged from 0.05 to 4.9 mg/L in water from 44 sites sampled in the Hillsdale Basin during low-flow conditions from May 1994 through May 1995. Because concentrations in water from these sites equaled or exceeded the RC&D proposed low-flow total phosphorus concentration of 0.05 mg/L, it was concluded that nonpoint-source contamination is significant during low-flow conditions in the areas of the basin with no point-source discharges (Putnam, 1997).

Several studies have provided estimates of annual point- and nonpoint-source loads of phosphorus to Hillsdale Lake. Montgomery (1991) used a modeling approach and the limited water-quality data available to estimate a mean annual phosphorus load of about 24,000 kg, with respective contributions from point and nonpoint sources of 20 and 80 percent. Carney (1994) also used a modeling approach and the limited water-quality data available to estimate a mean annual phosphorus load of about 19,000 kg, with respective contributions from point and nonpoint sources of 26 and 74 percent. Carney's study also indicated the need for a reduction of annual phosphorus loads from both point and nonpoint sources by 28 to 45 percent (Carney, 1994). Using water-quality data collected in 1994, a study by the Johnson County Environmental Department (JCED) and the RC&D estimated the annual total phosphorus load contributed to Hillsdale Lake to be about 65,000 kg, of which 92 percent was from nonpoint sources (Holt, 1996). Because of the limited historical water-quality data available and the large hydrologic variability over time, an alternative approach was needed to determine the annual phosphorus loads to Hillsdale Lake from point and nonpoint sources.

A 2-year study by USGS, in cooperation with JCED and the Johnson County Unified Wastewater Districts, was begun in 1996 to estimate the historical phosphorus loads to the lake as well as the historical contributions of point and nonpoint sources. The historical perspective is important because regulatory and remediation strategies may be different depending on the total and relative contributions of phosphorus from the various point and nonpoint sources within the Hillsdale Lake Basin. The specific study objectives were to:

1. estimate the volume and mass of bottom sediment in the lake as well as the mean annual deposition since closure of Hillsdale Dam in 1981;
2. estimate the total mass of phosphorus in the lake-bottom sediment as well as the mean annual load; and
3. estimate the historical mean annual phosphorus loads to the lake from nonpoint sources.

The purpose of this report is to present the results of the USGS study to estimate the historical loads of phosphorus from nonpoint sources to Hillsdale Lake. From a national perspective, the methods and results presented in this report provide guidance and perspective for future lake studies concerned with the issues of sedimentation and water quality.

Description of Hillsdale Lake Basin

The Hillsdale Lake Basin is a 144-mi^2 area in Douglas, Franklin, Johnson, and Miami Counties, northeast Kansas. The lake has a surface area of 4,580 acres and a water-storage capacity of 68,000 acre-ft at the conservation-pool elevation of 917 ft above sea level. Water storage in Hillsdale Lake began on September 19, 1981, and the lake reached conservation-pool elevation on February 23, 1985. Principal tributaries that contribute flow directly to Hillsdale Lake include Big Bull Creek, Little Bull Creek, Rock Creek, Wade Branch, and Scott Branch (fig. 1). Bedrock in the basin is mostly Pennsylvanian-age limestone and shale. The predominate land use in the basin is agriculture, with about 40 percent of the land used for cultivated crops (Putnam, 1997). About 20 percent of the basin is wooded (Carney, 1994). Land use in the remainder of the basin is dominated by additional agricultural uses (for example, feedlots and pasture) as well as urban and residential uses.

Several point sources of phosphorus discharge are located within the Hillsdale Lake Basin and include wastewater-treatment facilities at Gardner, Edgerton, and the Johnson County New Century AirCenter and wastewater lagoons at Connestoga Mobile Home Park and Lone Elm Estates (Carney, 1994) (fig. 1). Nonpoint sources of phosphorus in the Hillsdale Lake Basin include soils, bedrock, septic systems, feedlots, and cropland.

Long-term (1961–90) mean annual precipitation, as computed for Paola, Kansas, located 5 mi south of Hillsdale Lake, is 40.8 in. About 76 percent of the annual precipitation is received during the growing season (April through October) (National Oceanic and Atmospheric Administration, 1993).

Acknowledgments

The author gratefully acknowledges the water-quality information provided by JCED and KDHE and the water-quality, sediment, topographic, and bathymetric information provided by the U.S. Army Corps of Engineers (COE).

METHODOLOGY

The objectives of this study were accomplished using available as well as newly collected information. Available information included COE data on total phosphorus concentrations in the lake outflow, JCED and KDHE data on annual phosphorus loads from the five largest point sources in the basin, COE 1978 topographic survey information for the lake (pre-impoundment), COE 1993 and 1996 bathymetric information for the lake, USGS discharge data for the lake outflow, and USGS 1:24,000-scale topographic quadrangles that were used as base maps for the study. New information was obtained through lake-bottom sediment coring and additional bathymetric surveying.

Sediment-Core Collection and Analysis

Bottom-sediment cores were collected during the summer and fall of 1996 at 53 sites (fig. 2) within the lake using a gravity corer. The liner used in the corer was cellulose acetate butyrate transparent tubing with a 2.875-in. outside diameter and a 2.625-in. inside diameter. The coring sites were located to provide a spatially representative sample of lake-bottom sediment both in and outside of submerged stream channels. A total of 22 in-channel and 31 out-of-channel sites were cored. Several of the cores were collected on or near the range lines used in the bathymetric surveys (fig. 2). The latitude and longitude for each coring site was obtained using global-positioning-system (GPS) technology with a horizontal accuracy ranging from 15.1 to 32.8 ft and a mean horizontal accuracy of 22.3 ft.

The sediment cores were refrigerated and typically processed within 48 hours of collection at the USGS laboratory in Lawrence, Kansas. Initially, each core was extracted from the liner and placed in a tray. Maintained at a slight incline to preserve the vertical integrity of the sediment, the core was split longitudinally (that is, lengthwise) to expose the relatively undisturbed inner part of the core for examination and sampling. On the basis of differences in moisture content, texture, and organic matter content (for example, root hairs, sticks, seed pods, leaves), the boundary between the lake-bottom sediment and the underlying pre-impoundment land-surface (or channel-bed) material was determined. The lake-bottom sediment was characterized by higher moisture content, finer texture,

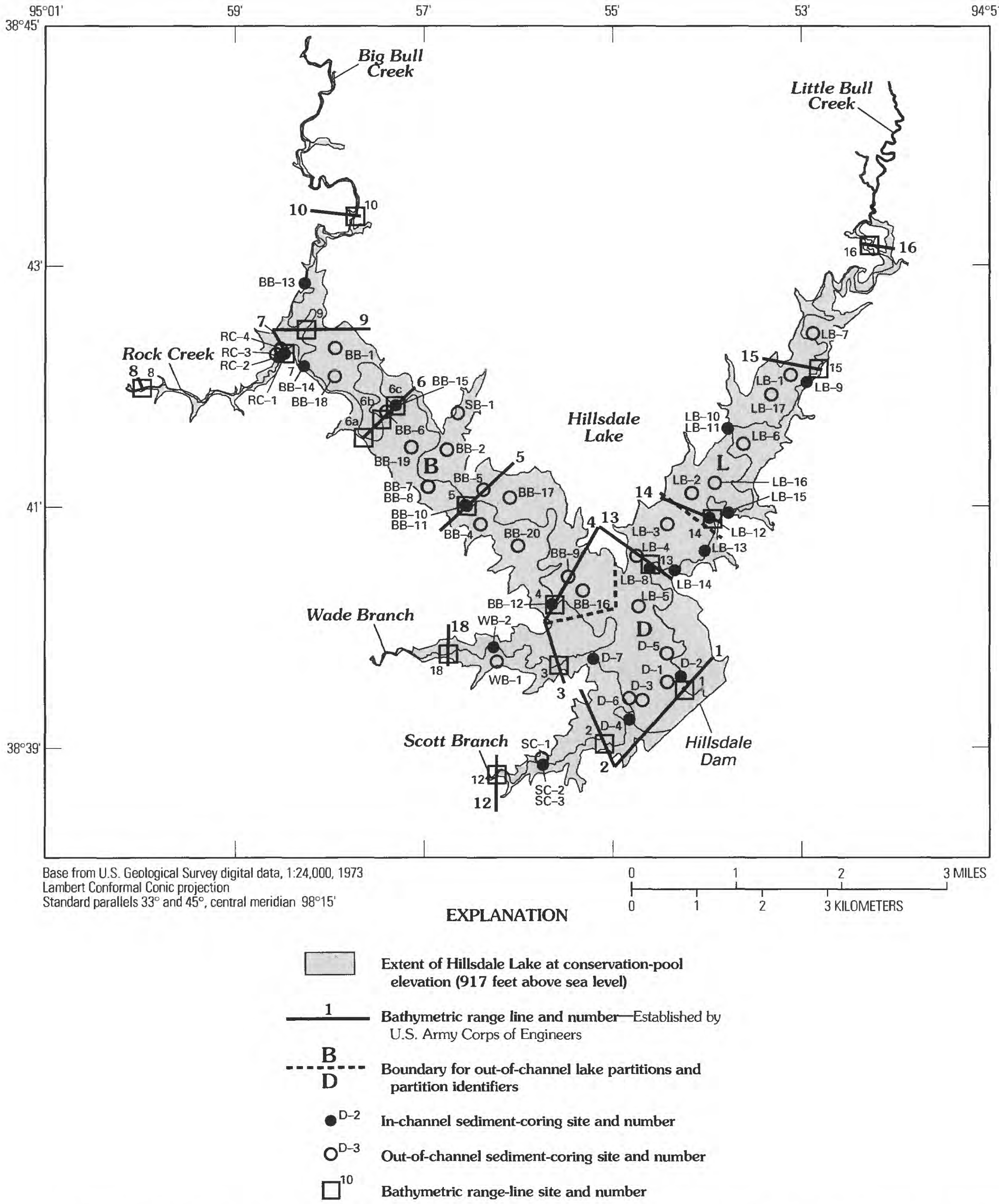


Figure 2. Location of sediment-coring sites, bathymetric range lines, and boundaries of out-of-channel lake partitions at Hillsdale Lake.

and little if any visible organic matter as compared to the underlying material. The thickness of the lake-bottom sediment in each core was measured to the nearest 0.01 ft.

The number of samples extracted from each core was dependent on the thickness of the lake-bottom sediment. Typically, a minimum of 0.2 ft of sediment was required for sample processing. Cores collected at the submerged in-channel coring sites typically had sediment thicknesses of several feet. For these in-channel cores, there was sufficient sediment for the extraction of five samples to assess the distribution of phosphorus concentrations with depth. Cores collected at the out-of-channel sites typically had sediment thicknesses of less than 0.5 ft. For these out-of-channel cores, either one or two samples were extracted depending on the sediment thickness. Each core was divided into segments of equal length. Then, an equal volume of sediment (defined as the space occupied by the sediment particles, water, and gases as measured in cubic units) was extracted longitudinally from both halves of each segment and combined.

The combined sediment volume was homogenized and quartered into subsamples of at least 10 g each. Two of the subsamples were placed in separate sample bottles, labeled, and refrigerated for subsequent phosphorus analysis. One subsample was analyzed for percent moisture content. This subsample was weighed to the nearest 0.10 g, oven dried at about 45 °C for 48 hours, and reweighed. Oven drying of the subsample continued as it was reweighed on a daily basis until no additional moisture loss was observed. The percent moisture content then was computed as follows:

$$M = [(w-m)/w](100), \tag{1}$$

where M is the percent moisture content,
w is the wet weight of the sample (in grams), and
m is the mass (dry weight) of the sample (in grams).

Analyses of sediment samples for percent moisture content were performed at the USGS laboratory in Lawrence, Kansas.

Sediment density as bulk density also was estimated for most of the in-channel cores as well as a few out-of-channel cores for which sufficient sediment volume was available. Bulk density was computed as follows:

$$BD = m/v, \tag{2}$$

where BD is the bulk density (in kilograms per cubic meter),
m is the mass (dry weight) of the sample (in kilograms), and
v is the volume of the sample (in cubic meters).

The volume for a cylindrical core sample was computed as:

$$v = h(\pi d^2/4), \tag{3}$$

where v is the volume of the sample (in cubic meters),
h is the height of the cylinder (in meters), and
d is the diameter of the cylinder (in meters) (Gordon and others, 1992).

The bulk densities then were converted to pounds per cubic foot for use in subsequent computations. Analyses of sediment samples for bulk density were performed at the USGS laboratory in Lawrence, Kansas.

For the in-channel cores that were divided into five segments of equal length, the second and fourth segments were sampled for bulk-density analysis. The two results then were averaged to estimate a representative bulk density for the site. For the out-of-channel cores, the limited amount of bottom sediment dictated that a single segment, either the middle half or the entire thickness of the core, be sampled. For each segment, one-half of the sediment volume, split longitudinally, was extracted for bulk-density analysis. The other half of the segment was required for phosphorus analysis. The bulk-density samples then were weighed, oven dried, and reweighed as previously described to estimate the mass of the samples.

Analyses of bottom-sediment samples for total phosphorus concentration were performed at the USGS National Water-Quality Laboratory in Arvada, Colorado, using the method described by Fishman and Friedman (1989). In this report, results are reported as mass (dry weight) of total phosphorus. As part of the study, 27 quality-assurance samples in the form of duplicate samples were analyzed. A total of 140 analyses were performed. Data for all bottom-sediment samples analyzed for total phosphorus are stored in the USGS WATSTORE data storage and retrieval system and the U.S. Environmental Protection Agency's STORET system.

Bathymetric Surveys

Bathymetric surveys were performed independently by USGS and COE during the summer of 1996 using GPS technology to record the geographic location of the boat on the lake and a fathometer system to determine the depth to the sediment/water interface. The GPS and fathometer data were recorded digitally using a data-logging unit. The bathymetric surveys were conducted along 16 range lines that were established by the COE in 1978 (fig. 2; see also figs. 8–23 in the "Supplemental Information" section at the end of this report). USGS collected additional bathymetric data along lines running between and across the 16 COE range lines (see figs. 24–34 in the "Supplemental Information" section). The additional bathymetric data were not used for the estimates provided in this report as there were no preceding data to provide a basis for comparison. However, the additional bathymetric data may provide supplemental baseline data for future studies of Hillsdale Lake. The latitude and longitude coordinates for the end points of COE range lines used in this study are provided in table 13 in the "Supplemental Information" section. The reliability of the fathometer was verified twice each day by suspending a metal pipe at known depths directly below the transducer. The accuracy of both USGS and COE bathymetric data is ± 0.25 ft (Steve Sando, U.S. Geological Survey, oral commun., 1996; Harry Hartwell, U.S. Army Corps of Engineers, oral commun., 1997). A graphic comparison of the 1996 USGS bathymetric data, the 1978 COE topographic survey data, and the 1993 and 1996 COE bathymetric data for several range lines indicated consistency among the data sets (see figs. 8–13 in the "Supplemental Information" section). Therefore, it is believed that both the USGS and COE 1996 bathymetric data sets provide representative lake-bottom elevation information.

Estimation of Bottom-Sediment Thickness, Volume, and Mass

Total bottom-sediment volume (sediment plus water and gases) in Hillsdale Lake was estimated using a partitioning approach in which the conservation-pool surface area of the lake was divided into in-channel and out-of-channel components. The channels were divided further into segments as determined by the locations where the bathymetric range lines intersect the channels. The range-line intersections served as the end points for the channel segments (fig. 2). Likewise, the out-of-channel component was divided further into three lake partitions as guided by bottom-sediment thickness information. The out-of-channel lake partitions consist of the Big Bull Creek arm (including Rock Creek), the Little Bull Creek arm, and the main body of the lake near the dam (including Wade Branch and Scott Branch). Respectively, the out-of-channel lake partitions were identified as B, L, and D (fig. 2). Bottom-sediment volume was computed for all components as the total surface area multiplied by the mean thickness of the lake-bottom sediment. The in- and out-of-channel results then were combined to provide an estimate of the total volume of bottom sediment in the lake.

The mean thickness of the lake-bottom sediment was estimated using the coring data for the out-of-channel sites and the bathymetric data for the in-channel sites. Because the bathymetric data have an accuracy of about ± 0.25 ft, the bathymetric methodology was not considered sensitive enough to reliably measure out-of-channel sediment deposits that may only be a few hundredths of a foot thick. Conversely, the bathymetric data were considered to be the best source of information available for the in-channel thickness estimates given the limitation (described in the following paragraph) associated with the use of a gravity corer to sample soft lake-bottom sediment.

With a gravity corer, a phenomenon referred to as "core shortening" results in a recovered sediment-core sample that may be only about one-half of the actual thickness of sediment penetrated (Emery and Hulsemann, 1964). Core shortening is caused by the friction of the sediment against the inner wall of the sample tube as the corer penetrates the sediment (Emery and Hulsemann, 1964; Hongve and Erlandsen, 1979; Blomqvist, 1985; Blomqvist and Bostrom, 1987). In "normal" lake-bottom sediment at Hillsdale Lake, which is characterized by uniform texture with decreasing water content at depth, core shortening results in a core sample that provides a thinned but complete representation of all of the sediment layers that were penetrated (Emery and Hulsemann, 1964; Hongve and Erlandsen, 1979). Because, as the corer enters the sediment, there is a lag phase before initiation of core shortening (Blomqvist, 1985), the phenomenon is not considered to be a significant factor for the typically thin sediment layer encountered at the out-of-channel coring sites. However, at the in-channel sites where the sediment layer is thicker, substantial core shortening was observed. Therefore, the bathymetric data provided the best estimate of actual bottom-sediment thickness in the submerged channels.

Bottom-sediment thickness in the submerged channels was estimated at the sites where COE bathymetric range lines intersect the channels (fig. 2). At each range-line site (that is, a channel-segment end point), bottom-sediment thickness was computed as the difference between the mean 1996 and the mean 1978 (pre-impoundment) channel-bed elevation. The mean 1996 channel-bed elevation was determined using either USGS or COE bathymetric data depending on which data set provided the most complete information for the channel. Each channel segment was assigned a bottom-sediment thickness computed as the mean of the bathymetry-derived sediment thicknesses for the two range-line sites that defined the segment. Channel segments with the edge of the conservation pool as their upstream limit were assumed to have no sediment accumulation at these locations. This assumption is based on bathymetric evidence that indicates little or no sediment deposition in the upstream-most reaches of the tributaries. For example, the Big Bull Creek, Little Bull Creek, and Rock Creek channels had little if any sediment deposition at their upstream-most range-line sites (fig. 2). The most probable explanation for this condition is that the stream velocity at these sites is sufficiently high to transport incoming sediment farther downstream where eventually it is deposited.

Channel widths were estimated using the 1978 topographic survey data and the 1996 bathymetric data. The channel width at each range-line site was estimated only for the sediment-filled part of the channel as opposed to the entire bankfull channel. The channel length for each channel segment was estimated by digitizing the channels from USGS 1:24,000-scale topographic quadrangles and intersecting the bathymetric range lines using geographic-information-system software.

The sediment-thickness, channel-width, and channel-length data were used to estimate the bottom-sediment volume for each channel segment. Then, the segment volumes were summed to estimate the volume of bottom sediment in each channel as well as the total in-channel bottom-sediment volume for the lake.

The total mass (dry weight) of bottom sediment in the lake was estimated using the same lake components as described previously. Using the representative bulk density for bottom sediment at each of the in-channel coring sites, a mean bulk density was computed for each channel segment and used to convert bottom-sediment volume to bottom-sediment mass. Total in-channel bottom-sediment mass then was estimated as the sum of the sediment mass estimated for the individual channel segments. Because few bulk-density values were estimated for the out-of-channel coring sites, additional bulk-density estimates were computed using a regression-derived relation between bulk density and percent moisture content. A mean bulk density was computed for bottom sediment in out-of-channel lake partitions B and L and used to convert bottom-sediment volume to bottom-sediment mass. Because no bulk-density information was available for out-of-channel sites in partition D, an estimated mean bulk density was derived using the relation of mean in-channel to out-of-channel bulk densities in partitions B and L. A comparison showed that out-of-channel bulk densities were an average of 7.5 percent greater than in-channel bulk densities in lake partitions B and L. Therefore, the mean bulk density for out-of-channel sites in partition D was computed as the mean of the in-channel sites plus 7.5 percent.

Because it was not feasible to accurately distinguish annual layers of sediment deposition in the core samples, mean annual sediment deposition was estimated by dividing the total mass of bottom sediment by the number of years of deposition. Because the reservoir began filling in September 1981, about 15 years of sediment deposition had occurred in the lake at the time the core and bathymetric data were collected during the summer and fall of 1996. Therefore, mean annual sediment deposition was estimated as the total mass of bottom sediment divided by 15.

Estimation of Phosphorus Loads

The total mass of phosphorus (dry weight of total phosphorus) in the lake-bottom sediment was estimated as bottom-sediment mass multiplied by the mean total phosphorus concentration. The in- and out-of-channel components of the lake-bottom sediment were estimated separately and then summed to provide an estimate of the total mass of phosphorus in the sediment. Mean annual phosphorus loading to the bottom sediment was estimated as the total mass of phosphorus divided by 15.

The mean annual load (mass) of phosphorus added to the lake from point-source discharges was estimated on the basis of water-quality and flow data obtained from JCED and KDHE for the five largest point sources within the Hillsdale Basin. Included were the wastewater-treatment facilities at Edgerton, Gardner, and the Johnson County New Century AirCenter as well as the wastewater lagoons at Connestoga Mobile Home Park and Lone Elm Estates (fig. 1).

The annual amount of total phosphorus exiting the lake was estimated using available COE water-quality data on total phosphorus concentrations in the lake outflow and available USGS data on the quantity of flow. The flow-weighted, mean total phosphorus concentration and the mean annual discharge were determined and then multiplied to provide an estimate of the total phosphorus leaving the lake each year.

The mean annual load of total phosphorus contributed from nonpoint sources was estimated using the following mass balance:

$$NPSL + PSL = OFL + SL, \qquad (4)$$

where *NPSL* is the mean annual nonpoint-source load (in kilograms),

PSL is the mean annual point-source load (in kilograms),

OFL is the mean annual outflow load (in kilograms), and

SL is the mean annual lake-bottom sediment load (in kilograms).

Lacking the data to reliably quantify the residence or storage time of phosphorus in the streams downstream from the point sources, all phosphorus from the point sources was assumed to be transported to Hillsdale Lake each year. The temporal variability of phosphorus concentrations and storage in the lake-water column was assumed to be neglible. Therefore, the water-column component in the mass balance was considered insignificant relative to the other components and was not included.

SEDIMENT DEPOSITION IN HILLSDALE LAKE

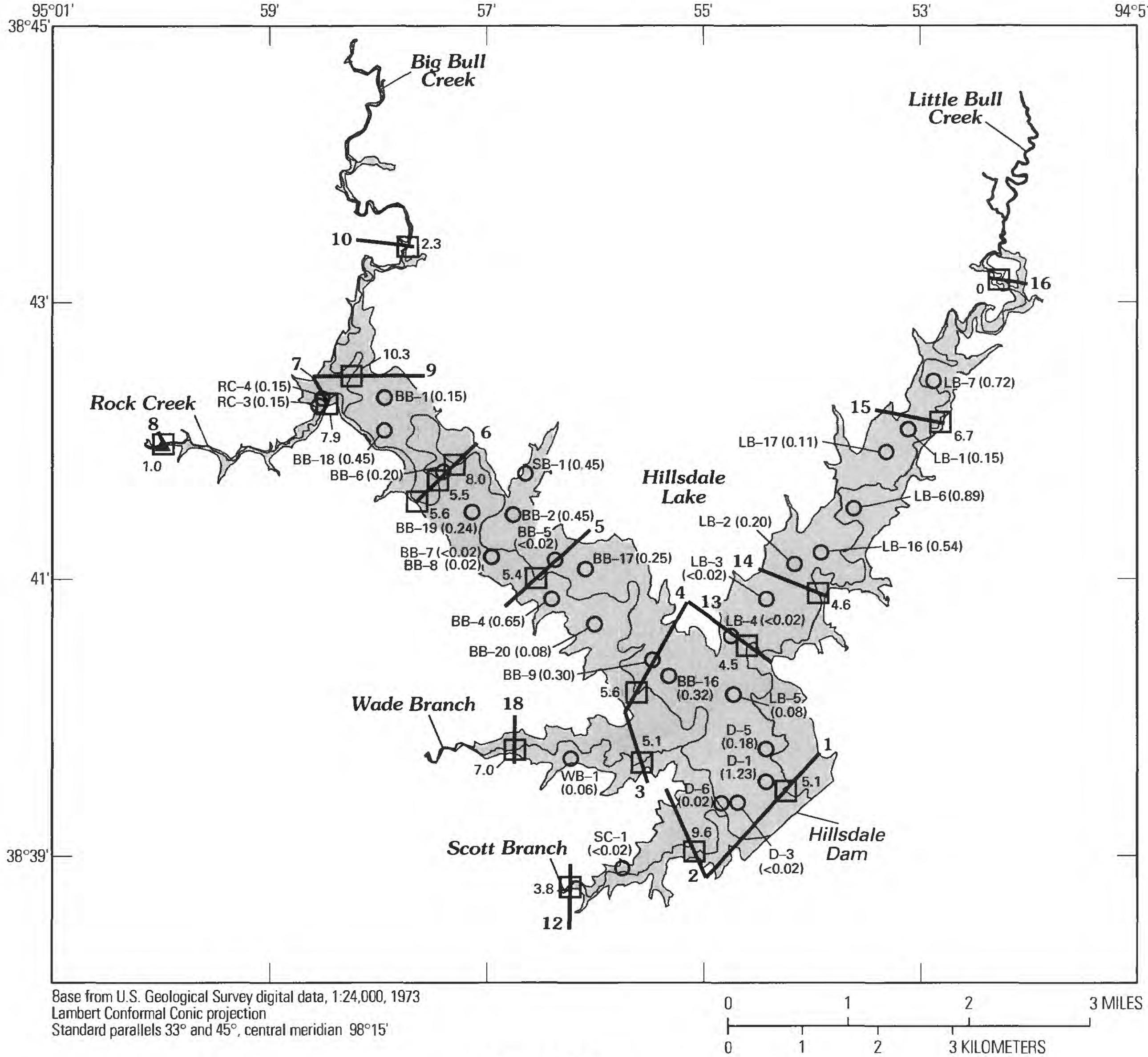
Estimation of the total and mean annual sediment deposition in Hillsdale Lake was a multistep process. Initially, sediment-core and bathymetric data were collected to quantify bottom-sediment thickness in the lake. Sediment cores were collected both in and outside of the submerged stream channels (fig. 2).

Bathymetry-derived, in-channel bottom-sediment thicknesses (table 1 and fig. 3) were used to estimate the mean bottom-sediment thickness for each channel segment. At each bathymetric range-line site, bottom-sediment thickness was computed as the difference between the 1996 and the 1978 (pre-impoundment) mean channel-bed elevations. A comparison of sediment thickness using the 1993 and 1996 bathymetry at 10 range-line sites indicated that about 13 percent of that thickness was deposited in the channels after 1993. This converts to a mean annual depositional rate of about 4.3 percent of the total thickness for 1994–96 as compared to 7.3 percent for 1981–93. However, the difference could be due simply to 1 or 2 years of exceptionally large or small deposition. A longitudinal view of sediment deposition in the Big Bull Creek and Little Bull Creek channels is pro-

Table 1. In-channel bottom-sediment thickness estimated from 1996 bathymetry and 1978 topographic information at bathymetric range-line sites in Hillsdale Lake

Bathymetric range-line site, in upstream-to-downstream order (fig. 3)	Submerged channel	Bottom-sediment thickness, in feet
10	Big Bull Creek	2.3
9	do.	10.3
6a[1]	do.	5.6
6b[1]	do.	5.5
6c[1]	do.	8.0
5	do.	5.4
4	do.	5.6
16	Little Bull Creek	0
15	do.	6.7
14	do.	4.6
13	do.	4.5
1	do.	5.1
18	Wade Branch	7.0
3	do.	5.1
12	Scott Branch	3.8
2	do.	9.6
8	Rock Creek	1.0
7	do.	7.9

[1]Range line 6 crosses the Big Bull Creek channel three times. Sites 6a, 6b, and 6c are the upstream, intermediate, and downstream crossings, respectively.



EXPLANATION

Extent of Hillsdale Lake at conservation-pool elevation (917 feet above sea level)

1 — **Bathymetric range line and number**—Established by U.S. Army Corps of Engineers

BB-17 (0.25) ○ **Out-of-channel sediment-coring site and number**—Number in parentheses ( ) is bottom-sediment thickness, in feet

7.9 □ **Bathymetric range-line site**—Number is bottom-sediment thickness, in feet, as estimated from 1996 bathymetric survey and 1978 topographic information

Figure 3. Estimated bottom-sediment thickness in Hillsdale Lake, 1996.

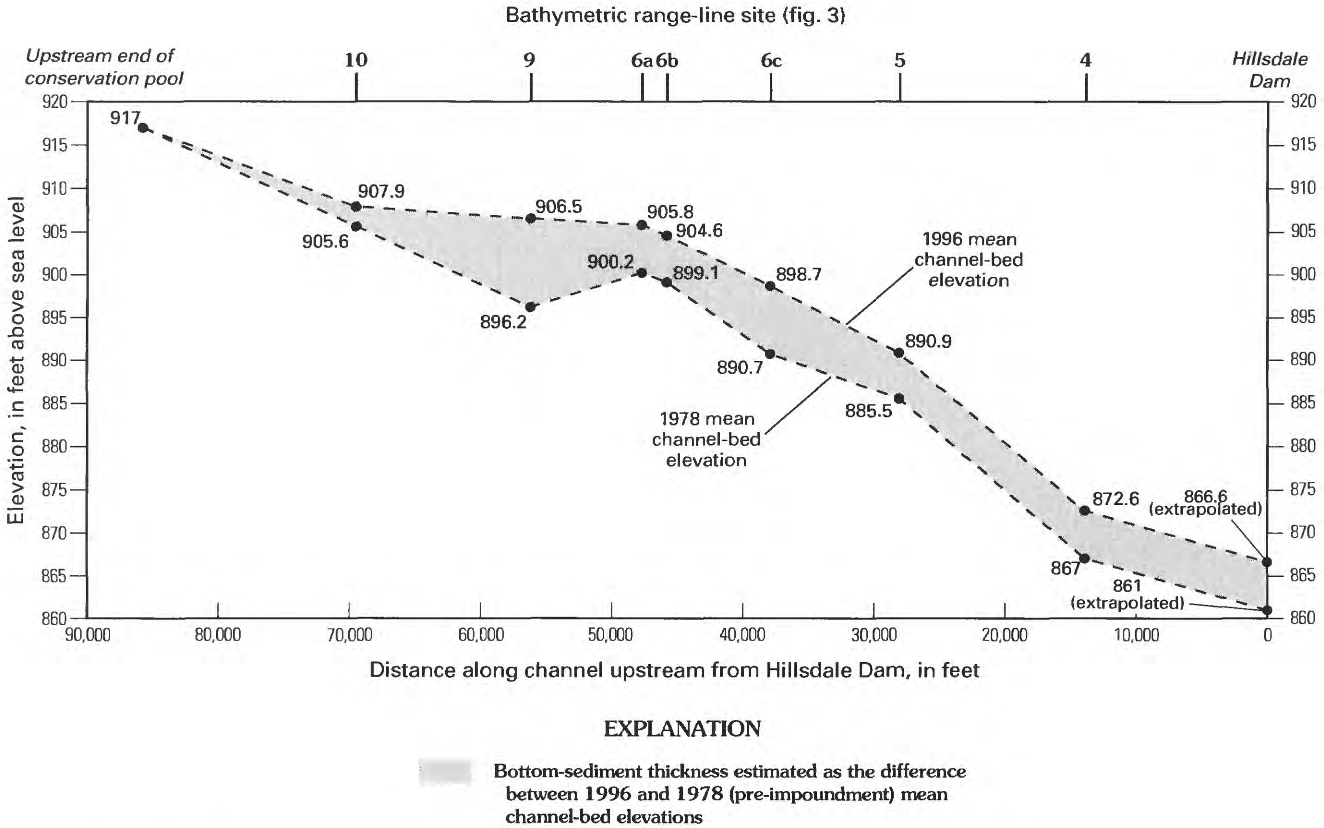


Figure 4. Estimated bottom-sediment thickness in the Big Bull Creek channel of Hillsdale Lake, 1996.

vided in figures 4 and 5, respectively. Table 2 provides the estimated channel length, mean channel width, mean bottom-sediment thickness, and bottom-sediment volume for each channel segment.

Bottom-sediment thicknesses measured in sediment-core samples collected at 31 out-of-channel sites are provided in table 3 and figure 3. Because of the atypically thick sediment encountered (1.23 ft) at site D–1 and the proximity to a small tributary of the main Little Bull Creek channel, there is uncertainty as to whether site D–1 is more representative of in- or out-of-channel conditions. Therefore, site D–1 was excluded from the calculation of mean sediment thickness for the out-of-channel sites.

To calculate mean values for the out-of-channel bottom-sediment thicknesses, the six cores with a thickness listed as less than 0.02 ft were assigned a value of 0.01 ft. The out-of-channel lake-bottom sediment ranged in thickness from less than 0.02 to 0.89 ft, with a mean sediment thickness of 0.24 ft. In general, the out-of-channel sediment appeared to be thickest in the Big Bull Creek and Little Bull Creek arms of the lake and thinnest in the main body near the dam (fig. 3).

Table 4 provides the estimated area, mean bottom-sediment thickness, and bottom-sediment volume for each out-of-channel lake partition.

The total volume of bottom sediment in the lake was estimated as the sum of the bottom-sediment volumes determined for the in-channel and out-of-channel components of the lake (table 5). The total in- and out-of-channel bottom-sediment volumes were 51,300,000 and 40,100,000 ft^3, respectively. Therefore, the total estimated volume of bottom sediment in the lake was 91,400,000 ft^3 or about 2,100 acre-ft. In comparison, the COE, using bathymetry only, estimated the total bottom-sediment volume in 1993 to be 1,928 acre-ft (Phil Snell, U.S. Army Corps of Engineers, oral commun., 1997). The 2,100 acre-ft of sediment occupies about 3 percent of the lake's original water-storage capacity of 68,000 acre-ft at conservation pool.

Respectively, the in- and out-of-channel components represent about 6 and 94 percent of the total conservation-pool surface area of the lake. However, the in-channel component represents about 56 percent of the total volume of bottom sediment. Thus, as noted by

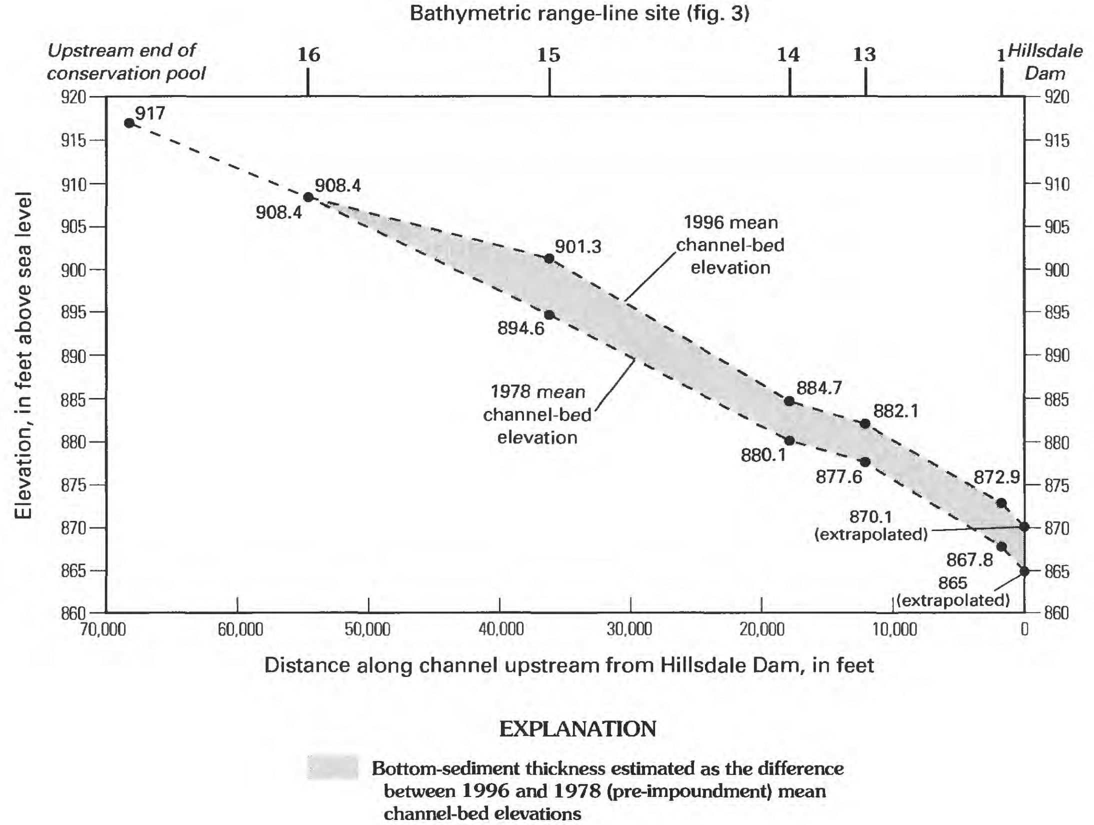


Figure 5. Estimated bottom-sediment thickness in the Little Bull Creek channel of Hillsdale Lake, 1996.

Thornton and others (1990), initial sediment deposition is greatest in the submerged channels.

Bottom-sediment mass was estimated as the bottom-sediment volume multiplied by the mean bulk density of the sediment. Bulk densities were estimated at 18 in-channel (table 6) and 12 out-of-channel (table 7) sites in the lake (fig. 6). Of the 12 out-of-channel sites, bulk-density values for 8 sites were estimated using a relation between bulk density and percent moisture content. A statistical analysis was performed using 19 sites for which bulk-density and percent-moisture-content information was available. For sites having data for multiple depth intervals, the uppermost depth interval was used on the assumption that it would most closely approximate conditions at the out-of-channel sites for which bulk density was being estimated. A Pearson's correlation coefficient of -0.94 ($R^2 = 0.89$) was calculated, thus indicating a strong inverse relation between bulk density and percent moisture content (see fig. 35 in the "Supplemental Information" section). A regression analysis was used to determine the following relation:

$$BD = -1.07M + 96.68, \qquad (5)$$

where BD is the bulk density, and

M is the percent moisture content. This relation was used to estimate the bulk density at the eight out-of-channel sites.

Estimated bulk densities ranged from a mean of 28.0 lb/ft^3 at site D–2 (in-channel site) to 59.9 lb/ft^3 at site BB–4 (out-of-channel site), with an overall mean of 42.8 lb/ft^3. The range of estimated bulk densities is consistent with bulk densities estimated at nine sites within the lake by COE in 1993 (Al Coop, U.S. Army Corps of Engineers, written commun., 1996). COE bulk densities ranged from 30.0 to 50.1 lb/ft^3. In

Table 2. Estimated length, mean width, mean bottom-sediment thickness, and bottom-sediment volume in submerged stream-channel segments in Hillsdale Lake, 1996

[length and volume values have been rounded to three significant figures]

Channel segment (fig. 3)	Channel length, in feet	x	Mean channel width, in feet	x	Mean bottom-sediment thickness, in feet	=	Bottom-sediment volume[1], in cubic feet
Big Bull Creek							
Upstream end of conservation pool to range line 10	16,300		30		1.2		587,000
Range lines 10 to 9	13,300		45		6.3		3,770,000
Range lines 9 to 6a	8,440		50		8.0		3,380,000
Range lines 6a to 6c	9,880		55		6.4		3,480,000
Range lines 6c to 5	9,750		65		6.7		4,250,000
Range lines 5 to 4	14,200		55		5.5		4,300,000
Range line 4 to dam	13,900		60		5.6		4,670,000
Little Bull Creek							
Upstream end of conservation pool to range line 16	13,600		20		0		0
Range lines 16 to 15	18,300		35		3.4		2,180,000
Range lines 15 to 14	18,300		55		5.7		5,740,000
Range lines 14 to 13	5,680		60		4.6		1,570,000
Range line 13 to dam	12,100		60		4.8		3,480,000
Wade Branch							
Upstream end of conservation pool to range line 18	5,010		40		3.5		701,000
Range line 18 to confluence with Big Bull Creek	11,600		50		6.1		3,540,000
Scott Branch							
Upstream end of conservation pool to range line 12	569		95		1.9		103,000
Range line 12 to confluence with Big Bull Creek	12,000		100		6.7		8,040,000
Rock Creek							
Upstream end of conservation pool to range line 8	893		15		.5		6,700
Range line 8 to confluence with Big Bull Creek	11,100		30		4.5		1,500,000

[1]Bottom-sediment volume is calculated as channel length multiplied by mean channel width multiplied by mean bottom-sediment thickness.

Table 3. Bottom-sediment thickness measured in core samples collected at out-of-channel sites in Hillsdale Lake, 1996

[<, less than]

Out-of-channel site (fig. 3)	Date sampled (month/day/year)	Latitude (decimal degrees)	Longitude (decimal degrees)	Bottom-sediment thickness, in feet
BB–1	07/17/96	38.70555	94.96526	0.15
BB–2	07/17/96	38.69129	94.94543	.45
BB–4	09/05/96	38.68106	94.93949	.65
BB–5	09/05/96	38.68581	94.93903	<.02
BB–6	09/05/96	38.69659	94.95620	.20
BB–7	09/05/96	38.68620	94.94874	<.02
BB–8	09/05/96	38.68619	94.94878	.02
BB–9	09/16/96	38.67375	94.92407	.30
BB–16	10/28/96	38.67183	94.92141	.32
BB–17	10/28/96	38.68470	94.93427	.25
BB–18	11/01/96	38.70161	94.96529	.45
BB–19	11/01/96	38.69171	94.95172	.24
BB–20	11/01/96	38.67809	94.93286	.08
D–1	07/16/96	38.65906	94.90649	1.23
D–3	08/28/96	38.65651	94.91091	<.02
D–5	10/28/96	38.66299	94.90653	.18
D–6	10/28/96	38.65647	94.91346	.02
LB–1	07/16/96	38.70164	94.88448	.15
LB–2	06/25/96	38.68532	94.90209	.20
LB–3	08/29/96	38.68102	94.90643	<.02
LB–4	08/29/96	38.67660	94.91189	<.02
LB–5	08/29/96	38.66960	94.91153	.08
LB–6	09/04/96	38.69201	94.89300	.89
LB–7	09/04/96	38.70742	94.88062	.72
LB–16	10/28/96	38.68670	94.89798	.54
LB–17	10/28/96	38.69888	94.88793	.11
RC–3	10/08/96	38.70462	94.97537	.15
RC–4	10/08/96	38.70547	94.97489	.15
SB–1	09/05/96	38.69638	94.94357	.45
SC–1	09/16/96	38.64858	94.92868	<.02
WB–1	09/16/96	38.66194	94.93664	.06

Table 4. Estimated area, mean bottom-sediment thickness, and bottom-sediment volume in out-of-channel lake partitions of Hillsdale Lake, 1996

[area and volume values have been rounded to three significant figures]

Out-of-channel lake partition (fig. 2)	Area, in square feet	x	Mean bottom-sediment thickness, in feet	=	Bottom-sediment volume[1], in cubic feet
B	77,300,000		0.26		20,100,000
D	72,300,000		.05		3,620,000
L	37,200,000		.44		16,400,000

[1]Bottom-sediment volume calculated as out-of-channel area multiplied by mean bottom-sediment thickness.

Table 5. Estimated bottom-sediment volume for Hillsdale Lake, 1996

[all values have been rounded to three significant figures]

Lake component (fig. 2)	Bottom-sediment volume, in cubic feet	Percentage of total bottom-sediment volume
Out-of-channel	40,100,000	43.9
In-channel		
Big Bull Creek	24,400,000	26.7
Little Bull Creek	13,000,000	14.2
Wade Branch	4,240,000	4.6
Scott Branch	8,140,000	8.9
Rock Creek	1,510,000	1.7
Total for in-channel component	51,300,000	56.1
Total for lake	**91,400,000**	**100**

general, the bulk density of channel sediment was highest in the upstream parts of the lake and lowest downstream near the dam. For example, the bulk density of bottom sediment in the Big Bull Creek channel ranged from a mean of 49.4 lb/ft^3 at upstream site BB–13 to a mean of 28.8 lb/ft^3 at site D–4 near the dam (fig. 6). The out-of-channel sites did not exhibit the same upstream-to-downstream trend of decreasing bulk densities.

Table 6. Estimated bulk density of bottom sediment at in-channel sites in Hillsdale Lake, 1996

[bulk-density values have been rounded to three significant figures]

In-channel site (fig. 6)	Sample depth, in feet	Bulk density, in pounds per cubic foot
BB–10	0.58–1.16	35.8
BB–10	1.74–2.32	41.9
BB–11	0.68–1.36	33.7
BB–11	2.04–2.72	39.6
BB–12	0.72–1.44	29.0
BB–12	2.16–2.88	30.3
BB–13	1.01–2.02	47.1
BB–13	3.03–4.04	51.7
BB–14	0.83–1.66	44.9
BB–14	2.49–3.32	52.3
BB–15	0.86–1.72	38.2
BB–15	2.58–3.44	49.0
D–2	0–0.68	21.5
D–2	0.68–1.36	24.7
D–2	1.36–2.04	26.4
D–2	2.04–2.72	31.2
D–2	2.72–3.40	36.5
D–4	0.22–0.44	27.7
D–4	0.66–0.88	29.9
LB–8	0.22–0.44	29.6
LB–8	0.66–0.88	42.2
LB–9	0.69–1.38	40.0
LB–9	2.07–2.76	49.9
LB–10	0.78–1.56	29.5
LB–10	2.34–3.12	40.0
LB–11	0.79–1.58	32.7
LB–11	2.37–3.16	36.2
LB–13	0.48–0.96	31.1
LB–13	1.44–1.92	38.0
LB–14	0.45–0.90	35.7
LB–14	1.35–1.80	37.2
LB–15	0.49–0.98	49.1
LB–15	1.47–1.96	49.2
RC–2	0.98–1.96	44.4
RC–2	2.94–3.92	54.7
SC–3	0.20–0.60	48.0
WB–2	0.52–1.04	34.9
WB–2	1.56–2.08	46.6

Table 7. Estimated bulk density of bottom sediment at out-of-channel sites in Hillsdale Lake, 1996

[bulk-density values have been rounded to three significant figures]

Out-of-channel site (fig. 6)	Sample depth, in feet	Bulk density, in pounds per cubic foot
BB–1[1]	0–0.15	57.1
BB–2[1]	0–0.45	42.6
BB–4	0.16–0.48	59.9
BB–6[1]	0–0.20	53.9
BB–9[1]	0–0.30	35.7
BB–18	0–0.38	44.8
LB–1[1]	0–0.15	58.2
LB–2[1]	0–0.20	53.3
LB–6[1]	0–0.89	30.9
LB–7	0.18–0.54	48.1
LB–16	0–0.52	28.6
SB–1[1]	0–0.45	46.9

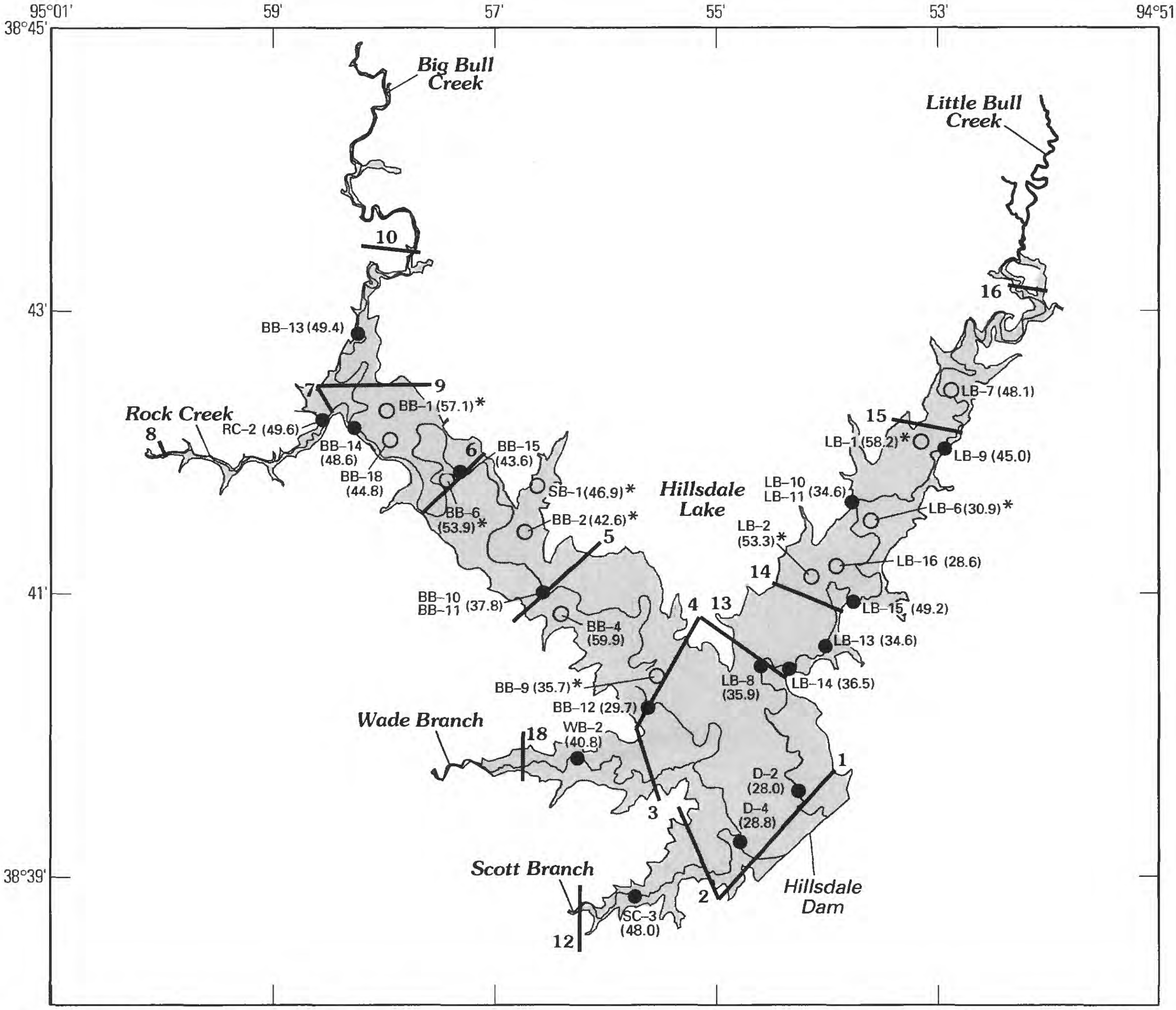
[1]Bulk density estimated using a regression equation that expresses the relation to moisture content.

The total in-channel mass of bottom sediment in the lake, estimated as the sum of the sediment mass computed for the individual channel segments (fig. 2), was 2,136 million lb. Total out-of-channel bottom-sediment mass, estimated as the sum of the sediment mass computed for the three lake partitions (fig. 2), was 1,837 million lb. Therefore, the total estimated mass of bottom sediment in the lake is 3,973 million lb of which about 54 percent is in the submerged channels. Tables 8 and 9 detail the bottom-sediment mass estimated for the in- and out-of-channel lake components, respectively. Table 10 provides an overall summary of bottom-sediment mass estimated for the lake.

Annual sediment deposition was estimated by dividing the total mass of bottom sediment in the lake by the number of years of deposition (that is, 15). The mean annual sediment deposition was estimated to be 265 million lb or 120 million kg.

PHOSPHORUS IN HILLSDALE LAKE

Concentrations of total phosphorus in the lake-bottom sediment were determined for both in- and out-of-channel sites. To facilitate comparisons, a depth-integrated mean was calculated (excluding the



Base from U.S. Geological Survey digital data, 1:24,000, 1973
Lambert Conformal Conic projection
Standard parallels 33° and 45°, central meridian 98°15'

EXPLANATION

Extent of Hillsdale Lake at conservation-pool elevation (917 feet above sea level)

1 — **Bathymetric range line and number**—Established by U.S. Army Corps of Engineers

BB-13 (37.8) ● **In-channel sediment-coring site and number**—Number in parentheses ( ) is mean bulk density, in pounds per cubic foot

BB-4 (59.9) ○ **Out-of-channel sediment-coring site and number**—Number in parentheses ( ) is mean bulk density, in pounds per cubic foot

* **Asterisk indicates that sediment bulk density, in pounds per cubic foot, was estimated using a regression equation**

Figure 6. Estimated bulk density of bottom sediment in Hillsdale Lake, 1996.

Table 8. Estimated bottom-sediment volume, mean bulk density, and mass in submerged channels of Hillsdale Lake, 1996

[all values have been rounded to three significant figures]

Channel segment (fig. 2)	Bottom-sediment volume, in cubic feet	x	Mean bulk density, in pounds per cubic foot	=	Bottom-sediment mass[1], in pounds
Big Bull Creek					
Upstream end of conservation pool to range line 10	587,000		49.4		29,000,000
Range lines 10 to 9	3,770,000		49.4		186,000,000
Range lines 9 to 6a	3,380,000		47.4		160,000,000
Range lines 6a to 6c	3,480,000		44.9		156,000,000
Range lines 6c to 5	4,250,000		40.7		173,000,000
Range lines 5 to 4	4,300,000		33.8		145,000,000
Range line 4 to dam	4,670,000		29.3		137,000,000
Little Bull Creek					
Upstream end of conservation pool to range line 16	0		45.0		0
Range lines 16 to 15	2,180,000		45.0		98,100,000
Range lines 15 to 14	5,740,000		42.9		246,000,000
Range lines 14 to 13	1,570,000		35.6		55,900,000
Range line 13 to dam	3,480,000		32.0		111,000,000
Wade Branch					
Upstream end of conservation pool to range line 18	701,000		40.8		28,600,000
Range line 18 to confluence with Big Bull Creek	3,540,000		40.8		144,000,000
Scott Branch					
Upstream end of conservation pool to range line 12	103,000		48.0		4,940,000
Range line 12 to confluence with Big Bull Creek	8,040,000		48.0		386,000,000
Rock Creek					
Upstream end of conservation pool to range line 8	6,700		49.6		332,000
Range line 8 to confluence with Big Bull Creek	1,500,000		49.6		74,400,000

[1]Bottom-sediment mass is calculated as bottom-sediment volume multiplied by mean bulk density.

Table 9. Estimated bottom-sediment volume, mean bulk density, and mass in out-of-channel lake partitions of Hillsdale Lake, 1996

[all values have been rounded to three significant figures]

Out-of-channel lake partition (fig. 2)	Bottom-sediment volume, in cubic feet	x	Mean bulk density, in pounds per cubic foot	=	Bottom-sediment mass[1], in pounds
B	20,100,000		48.7		979,000,000
D	3,620,000		38.8		140,000,000
L	16,400,000		43.8		718,000,000

[1]Bottom-sediment mass is calculated as bottom-sediment volume multiplied by mean bulk density.

Table 10. Estimated bottom-sediment mass in Hillsdale Lake, 1996

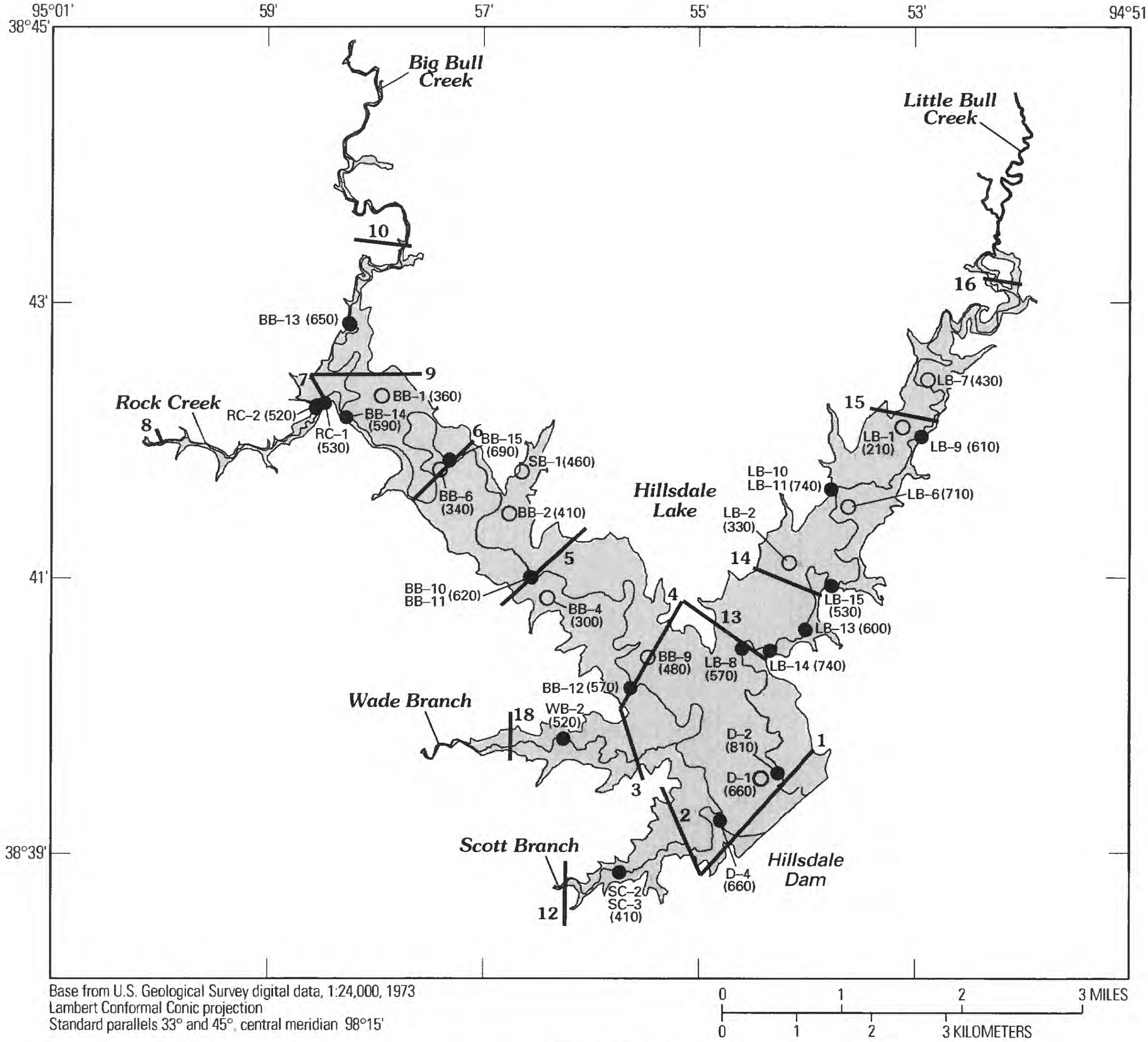
[all values have been rounded to three or four significant figures]

Lake component (fig. 2)	Bottom-sediment mass, in pounds	Percentage of total bottom-sediment mass
Out-of-channel	1,837,000,000	46.2
In-channel		
Big Bull Creek	986,000,000	24.8
Little Bull Creek	511,000,000	12.9
Wade Branch	173,000,000	4.4
Scott Branch	391,000,000	9.8
Rock Creek	74,700,000	1.9
Total for in-channel component	2,136,000,000	53.8
Total for lake	**3,973,000,000**	**100**

duplicate samples) to provide a representative phosphorus concentration for each site sampled (fig. 7). The in-channel phosphorus concentrations (table 11) showed no apparent trend with depth. Likewise, there was no apparent upstream-to-downstream trend observed for either the in- or out-of-channel (table 12) phosphorus concentrations. Overall, the depth-integrated, mean phosphorus concentrations for the in-channel bottom sediment ranged from 410 to 810 mg/kg, with a mean of 610 mg/kg. The depth-integrated, mean phosphorus concentrations for the out-of-channel bottom sediment ranged from 210 to 710 mg/kg, with a mean of 400 mg/kg (excluding site D–1 due to uncertainty as to whether site D–1 is more representative of in- or out-of-channel conditions). These results are in general agreement with COE phosphorus concentration data determined for seven sites within the lake in 1993 and(or) 1995 (Al Coop, U.S. Army Corps of Engineers, written commun., 1996). For COE sites having multiple-date phosphorus concentration data, the mean phosphorus concentration was calculated as a basis for comparison with the single-date USGS phosphorus concentration data. The adjusted COE phosphorus concentration data ranged from 470 to 900 mg/kg, with a mean of 680 mg/kg. Sedimentary rocks may contain phosphorus concentrations in the range of about 280 to 730 mg/kg (Hem, 1985). Thus, a substantial part of the observed phosphorus concentrations in the Hillsdale Lake bottom sediment may originate from soils and limestone and shale bedrock within the basin.

For quality-assurance purposes, 27 duplicate bottom-sediment samples were analyzed for total phosphorus concentration. In comparison, the duplicates differed from the original samples by an average of ±9 percent. This is considered to be within the range of acceptable variability for the analysis of total phosphorus concentrations in bottom sediment.

The total mass of phosphorus in the lake-bottom sediment was estimated by calculating the mass of phosphorus separately for the in- and out-of-channel components of the lake and then summing. The in-channel mass of phosphorus was estimated as the total in-channel mass of bottom sediment multiplied by the mean phosphorus concentration for all the in-channel sites (that is, 610 mg/kg). Likewise, the out-of-channel mass of phosphorus was estimated as the total out-of-channel mass of bottom sediment multiplied by the mean phosphorus concentration for all the out-of-channel sites (that is, 400 mg/kg). The mean phosphorus concentrations were used given that no upstream-to-downstream trend in phosphorus concentrations was observed in the lake-bottom sediment. The total in- and out-of-channel mass of phosphorus was estimated to be 591,000 and 333,000 kg, respectively. Therefore, the total mass of phosphorus in the bottom sediment was estimated to be 924,000 kg, of which 64 percent is in the submerged channels. The mean annual load of phosphorus in the bottom sediment was estimated to be 62,000 kg for 1981–96.



EXPLANATION

Extent of Hillsdale Lake at conservation-pool elevation (917 feet above sea level)

1 — **Bathymetric range line and number**—Established by U.S. Army Corps of Engineers

BB-10 (620) ● **In-channel sediment-coring site and number**—Number in parentheses ( ) is depth-integrated mean total phosphorus concentration in lake-bottom sediment, in milligrams per kilogram

BB-4 (300) ○ **Out-of-channel sediment-coring site and number**—Number in parentheses ( ) is total phosphorus concentration or depth-integrated mean total phosphorus concentration in lake-bottom sediment, in milligrams per kilogram

Figure 7. Total phosphorus concentrations in bottom sediment of Hillsdale Lake, 1996.

Table 11. Total phosphorus concentrations and percent moisture content of bottom sediment at in-channel sites in Hillsdale Lake, 1996

[all values have been rounded to two significant figures; mg/kg, milligrams per kilogram; dup, duplicate sample]

In-channel site (fig. 7)	Sample depth, in feet	Total phosphorus concentration (mg/kg)	Percent moisture content
BB–10	0–0.58	660	64
	0–0.58dup	460	64
	0.58–1.16	630	58
	0.58–1.16dup	660	58
	1.16–1.74	580	54
	1.16–1.74dup	550	54
	1.74–2.32	700	54
	1.74–2.32dup	610	54
	2.32–2.90	600	44
	2.32–2.90dup	510	44
BB–11	0–0.68	540	63
	0.68–1.36	490	59
	1.36–2.04	660	55
	2.04–2.72	730	53
	2.72–3.40	580	45
[1]Depth-integrated mean for sites BB–10 and BB–11		620	
BB–12	0–0.72	650	67
	0.72–1.44	480	61
	1.44–2.16	600	58
	2.16–2.88	600	58
	2.88–3.33	500	52
Depth-integrated mean		570	
BB–13	0–1.01	610	54
	1.01–2.02	610	46
	2.02–3.03	660	43
	3.03–4.04	670	43
	4.04–5.05	680	40
Depth-integrated mean		650	
BB–14	0–0.83	520	52
	0.83–1.66	530	48
	1.66–2.49	580	46
	2.49–3.32	580	43
	3.32–3.87	730	47
Depth-integrated mean		590	

In-channel site (fig. 7)	Sample depth, in feet	Total phosphorus concentration (mg/kg)	Percent moisture content
BB–15	0–0.86	640	61
	0.86–1.72	790	57
	0.86–1.72dup	720	57
	1.72–2.58	710	50
	2.58–3.44	650	46
	2.58–3.44dup	690	46
	3.44–4.30	670	45
[1]Depth-integrated mean		690	
D–2	0–0.68	840	72
	0.68–1.36	840	68
	0.68–1.36dup	850	68
	1.36–2.04	800	64
	1.36–2.04dup	880	64
	2.04–2.72	840	62
	2.04–2.72dup	710	62
	2.72–3.40	750	55
	2.72–3.40dup	690	55
[1]Depth-integrated mean		810	
D–4	0–0.22	630	70
	0.22–0.44	680	65
	0.22–0.44dup	650	65
	0.44–0.66	730	63
	0.44–0.66dup	760	63
	0.66–0.88	710	61
	0.66–0.88dup	720	61
	0.88–1.10	570	51
	0.88–1.10dup	530	51
[1]Depth-integrated mean		660	
LB–8	0–0.22	620	68
	0.22–0.44	670	64
	0.44–0.66	480	56
	0.66–0.88	590	54
	0.88–1.10	480	42
Depth-integrated mean		570	

Table 11. Total phosphorus concentrations and percent moisture content of bottom sediment at in-channel sites in Hillsdale Lake, 1996—Continued

In-channel site (fig. 7)	Sample depth, in feet	Total phosphorus concentration (mg/kg)	Percent moisture content
LB–9	0–0.69	630	57
	0.69–1.38	600	52
	1.38–2.07	620	47
	2.07–2.76	560	41
	2.76–3.47	640	45
Depth-integrated mean		610	
LB–10	0–0.78	760	65
	0.78–1.56	770	60
	1.56–2.34	880	55
	2.34–3.12	690	53
	3.12–3.62	690	49
LB–11	0–0.79	750	63
	0–0.79dup	750	63
	0.79–1.58	850	57
	1.58–2.37	690	52
	2.37–3.16	730	54
	3.16–3.94	590	44
[1]Depth-integrated mean for sites LB-10 and LB-11		740	
LB–13	0–0.48	610	67
	0.48–0.96	580	59
	0.48–0.96dup	600	59
	0.96–1.44	580	54
	0.96–1.44dup	570	54
	1.44–1.92	690	56
	1.92–2.42	550	48
[1]Depth-integrated mean		600	
LB–14	0–0.45	720	58
	0.45–0.90	700	52
	0.90–1.35	740	53
	1.35–1.80	830	53
	1.80–2.24	700	49
Depth-integrated mean		740	

In-channel site (fig. 7)	Sample depth, in feet	Total phosphorus concentration (mg/kg)	Percent moisture content
LB–15	0–0.49	470	50
	0.49–0.98	470	45
	0.98–1.47	510	44
	1.47–1.96	560	44
	1.96–2.21	630	45
Depth-integrated mean		530	
RC–1	0–0.50	460	48
	0.50–1.0	480	47
	1.0–1.5	570	50
	1.5–2.0	560	47
	2.0–2.5	580	45
Depth-integrated mean		530	
RC–2	0–0.98	480	52
	0.98–1.96	520	48
	1.96–2.94	580	45
	2.94–3.92	550	41
	3.92–4.90	450	34
Depth-integrated mean		520	
SC–2	0–0.44	460	56
	0.44–0.87	340	37
SC–3	0–0.40	480	54
	0.40–0.80	330	37
Depth-integrated mean for sites SC–2 and SC–3		410	
WB–2	0–0.52	540	57
	0.52–1.04	600	55
	1.04–1.56	540	49
	1.56–2.08	550	46
	2.08–2.60	390	35
Depth-integrated mean		520	

[1]Computed without the duplicate samples.

Table 12. Total phosphorus concentrations and percent moisture content of bottom sediment at out-of-channel sites in Hillsdale Lake, 1996

Out-of-channel site (fig. 7)	Sample depth, in feet	Total phosphorus concentration (mg/kg)	Percent moisture content
BB–1	0–0.15	360	37
	0–0.15dup	360	37
BB–2	0–0.22	450	55
	0–0.22dup	410	55
	0.22–0.45	370	46
	0.22–0.45dup	360	46
[1]Depth-integrated mean		410	
BB–4	0–0.33	290	44
	0.33–0.65	300	36
Depth-integrated mean		300	
BB–6	0–0.2	340	40
BB–9	0–0.3	480	57
[2]D–1	0–0.13	680	83
	0–0.13dup	700	83
	0.13–0.68	680	70
	0.13–0.68dup	770	70
	0.68–1.23	620	62
	0.68–1.23dup	600	62
[1]Depth-integrated mean		660	
LB–1	0–0.15	210	36
	0–0.15dup	220	36
LB–2	0–0.1	340	41
	0.1–0.2	310	40
Depth-integrated mean		330	
LB–6	0–0.44	750	65
	0.44–0.89	670	58
Depth-integrated mean		710	
LB–7	0–0.36	450	51
	0–0.36dup	400	51
	0.36–0.72	410	42
	0.36–0.72dup	490	42
[1]Depth-integrated mean		430	
SB–1	0–0.22	470	50
	0.22–0.45	440	43
Depth-integrated mean		460	

[1]Computed without duplicate samples.

[2]Site D–1 was excluded from the computation of mean total phosphorus concentration for the out-of-channel sites due to uncertainty as to whether the site is more representative of in- or out-of-channel conditions.

ESTIMATED ANNUAL PHOSPHORUS LOADS FROM NONPOINT SOURCES

Estimation of annual loads of phosphorus from nonpoint sources to Hillsdale Lake was accomplished using the following mass balance:

$$NPSL + PSL = OFL + SL, \quad (4)$$

where *NPSL* is the mean annual nonpoint-source load (in kilograms),

PSL is the mean annual point-source load (in kilograms),

OFL is the mean annual outflow load (in kilograms), and

SL is the mean annual lake-bottom sediment load (in kilograms).

Available and(or) newly collected data were used to quantify the *PSL*, *OFL*, and *SL* variables in the relation, thereby allowing *NPSL* to be determined. The annual load of phosphorus to Hillsdale Lake from point sources, computed as the mean of the estimates provided by three previous studies (Montgomery, 1991; Carney, 1994; Holt, 1996), was about 5,000 kg. The mean annual load of phosphorus deposited in the lake-bottom sediment was estimated to be about 62,000 kg.

The mean annual mass of phosphorus exiting Hillsdale Lake was estimated using available data on total phosphorus concentrations in the lake outflow and mean annual discharge. COE data on total phosphorus concentrations consisted of 43 samples collected during 1984–95 (Al Coop, U.S. Army Corps of Engineers, written commun., 1996). Phosphorus concentrations ranged from 0.01 to 1.8 mg/L, with a flow-weighted mean of 0.07 mg/L. USGS streamflow data for the same time period indicated a range in mean annual discharge of 12 to 263 ft^3/s, with a mean of 120 ft^3/s. The mean annual mass of phosphorus (dissolved plus suspended) leaving the lake, calculated as the mean phosphorus concentration (0.07 mg/L) multiplied by the mean annual discharge (120 ft^3/s), was estimated to be about 8,000 kg.

By solving equation 4, the mean annual load of total phosphorus contributions to the lake from nonpoint sources was estimated to be about 65,000 kg. Therefore, of the mean annual total phosphorus load of 70,000 kg, the contributions from point sources represent about 7 percent and from nonpoint sources, about 93 percent. Additional study may be helpful in determining the availability of phosphorus as it relates to eutrophication processes within the lake.

SUMMARY

Bottom sediment in Hillsdale Lake, northeast Kansas, was analyzed as a means of estimating the annual loads of total phosphorus deposited in the lake from nonpoint sources. A combination of topographic, bathymetric, and sediment-coring data was used to estimate the total volume of bottom sediment in the lake. Laboratory analyses of the core samples provided information on the percent moisture content, bulk density, and phosphorus concentrations of the bottom sediment and were used to estimate the total mass of bottom sediment and phosphorus in the lake. Available streamflow and water-quality data were used to compute the mean annual mass of phosphorus (dissolved plus suspended) exiting the lake as well as the mean annual load of phosphorus deposited in the lake from point sources. The mean annual load of phosphorus from nonpoint sources then was calculated using a simple mass balance.

The total volume of bottom sediment in the lake was estimated to be 91,400,000 ft^3. The total mass of sediment was estimated to be 3,973 million lb, with a mean annual (1981–96) sediment deposition of 265 million lb (120 million kg). Of the total sediment mass, about 54 percent is in the submerged channels. The total mass of phosphorus in the lake-bottom sediment was estimated to be 924,000 kg, with a mean annual load of 62,000 kg. The mean annual mass of phosphorus (dissolved plus suspended) exiting in lake outflow was estimated to be about 8,000 kg. The mean annual loads of phosphorus to the lake from point and nonpoint sources were estimated to be 5,000 and 65,000 kg, respectively. Thus, the contribution to the total mean annual phosphorus load in Hillsdale Lake from point sources is about 7 percent and from nonpoint sources, about 93 percent. Point sources of phosphorus in the Hillsdale Lake Basin include wastewater-treatment facilities and wastewater lagoons. Nonpoint sources of phosphorus in the basin include soils, bedrock, septic systems, feedlots, and cropland.

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SUPPLEMENTAL INFORMATION

Table 13. Latitude and longitude coordinates for the end points of the U.S. Army Corps of Engineers range lines used in bathymetric surveys of Hillsdale Lake[1]

Range line (fig. 2)	End point A latitude (decimal degrees)	End point A longitude (decimal degrees)	End point B latitude (decimal degrees)	End point B longitude (decimal degrees)
1	38.6473	94.9158	38.6625	94.8982
2	38.6473	94.9158	38.6582	94.9219
3	38.6589	94.9248	38.6675	94.9283
4	38.6675	94.9283	38.6806	94.9187
5	38.6801	94.9467	38.6895	94.9336
6	38.6930	94.9606	38.7001	94.9511
7	38.7049	94.9740	38.7081	94.9764
8	38.6996	94.9992	38.7015	95.0002
9	38.7081	94.9764	38.7082	94.9591
10	38.7246	94.9696	38.7238	94.9607
12	38.6412	94.9368	38.6491	94.9367
13	38.6807	94.9185	38.6734	94.9056
14	38.6847	94.9076	38.6813	94.8971
15	38.7040	94.8896	38.7024	94.8789
16	38.7198	94.8720	38.7191	94.8661
18	38.6613	94.9454	38.6671	94.9453

[1]Range lines 11 and 17 were not used in the study. Respectively, the range lines are located upstream from Hillsdale Lake on the Big Bull Creek and Little Bull Creek channels. Because neither range line was considered necessary for estimating total sediment deposition in the lake, they were not surveyed by the U.S. Army Corps of Engineers or the U.S. Geological Survey in 1996.

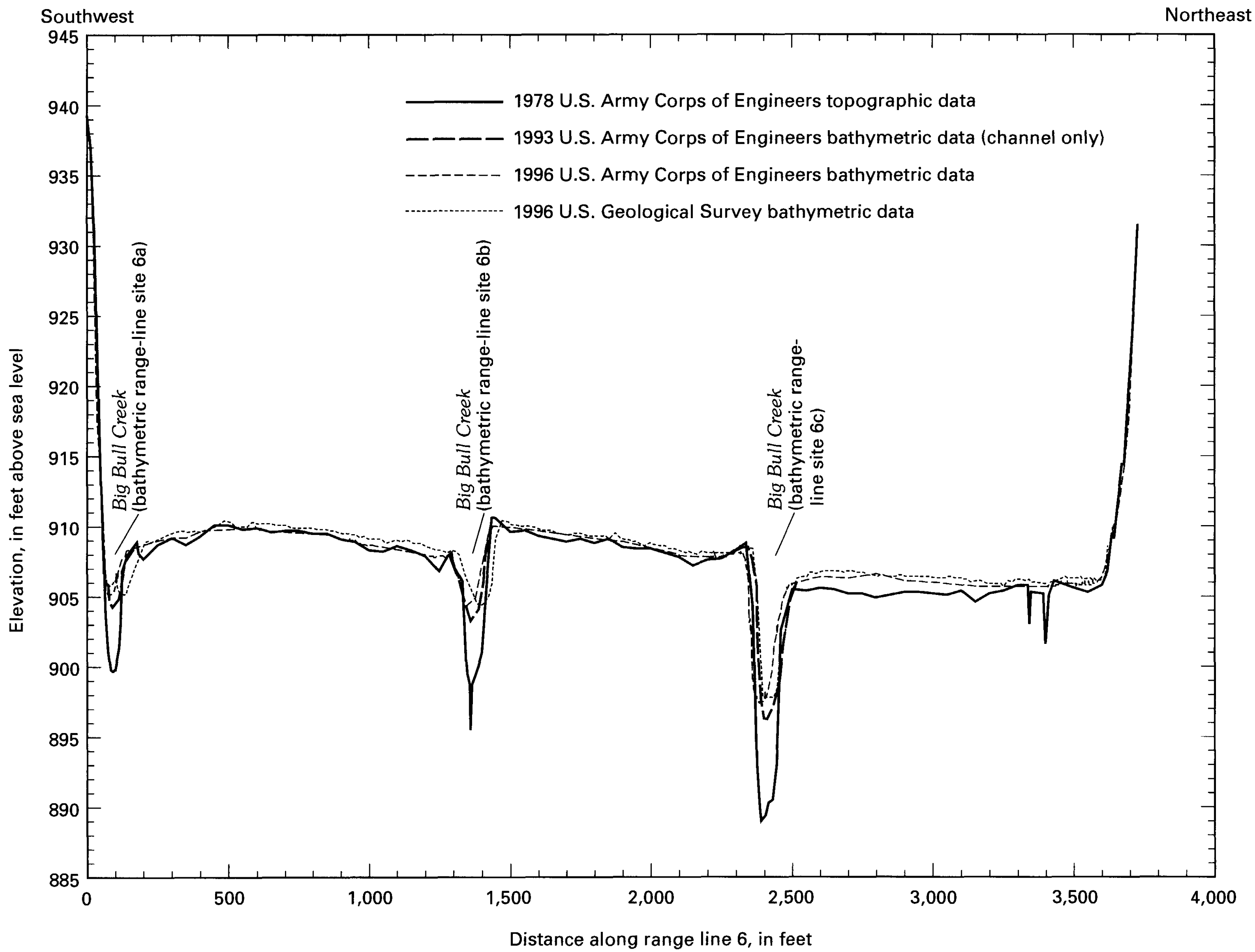

Figure 8. Comparison of 1996 U.S. Geological Survey bathymetric data, 1978 U.S. Army Corps of Engineers topographic data, and 1993 and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 6. Location of range line shown in figure 2.

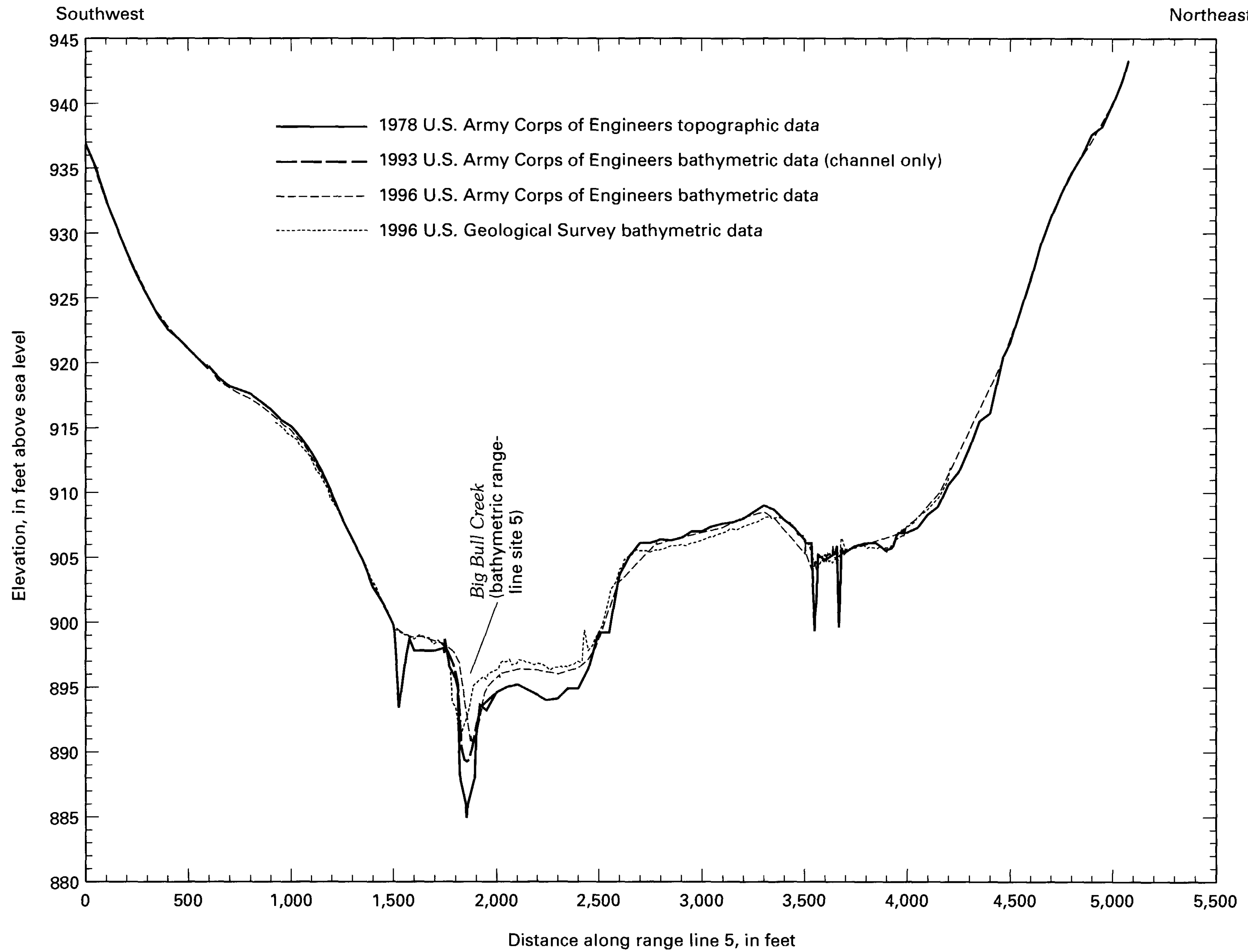

Figure 9. Comparison of 1996 U.S. Geological Survey bathymetric data, 1978 U.S. Army Corps of Engineers topographic data, and 1993 and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 5. Location of range line shown in figure 2.

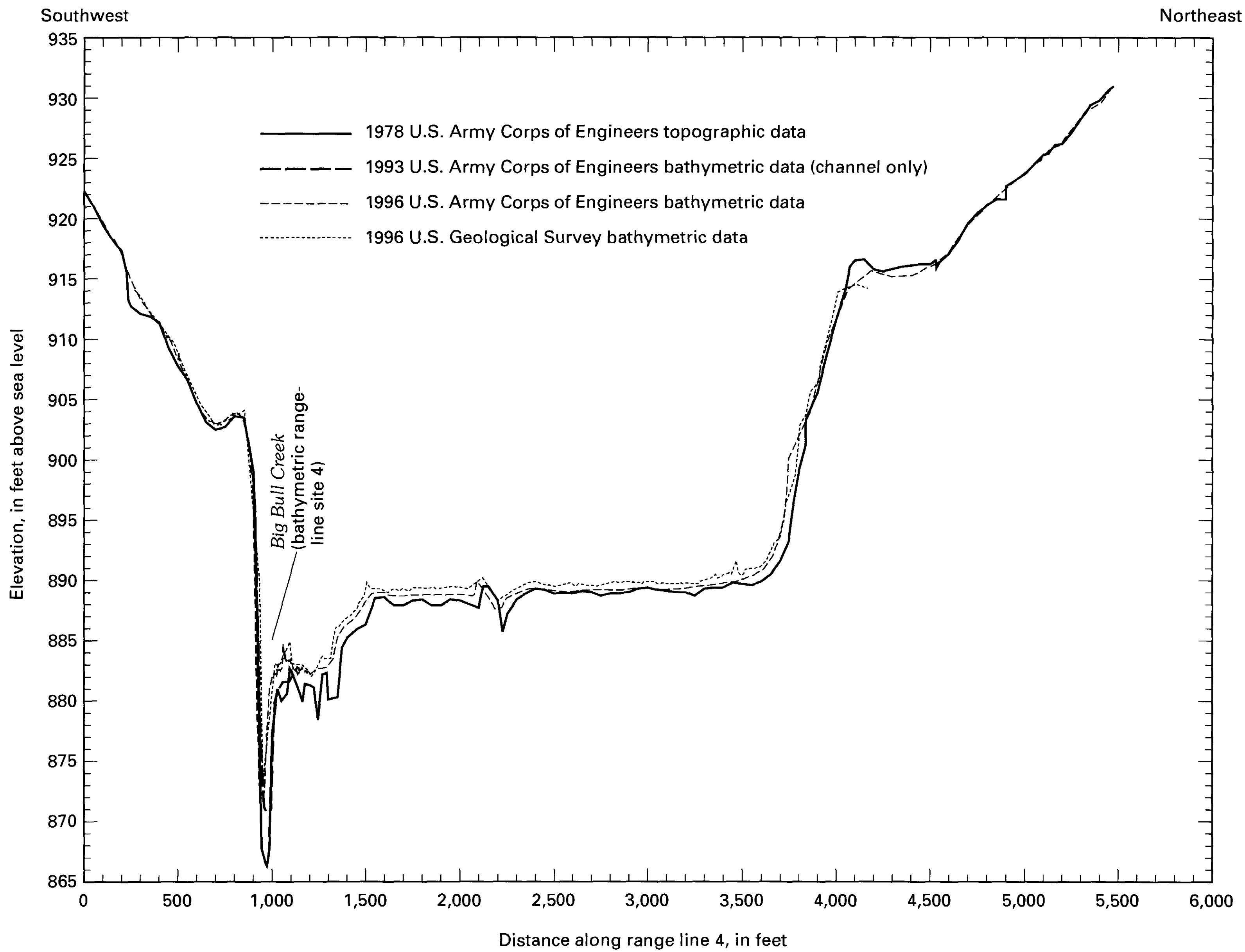

Figure 10. Comparison of 1996 U.S. Geological Survey bathymetric data, 1978 U.S. Army Corps of Engineers topographic data, and 1993 and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 4. Location of range line shown in figure 2.

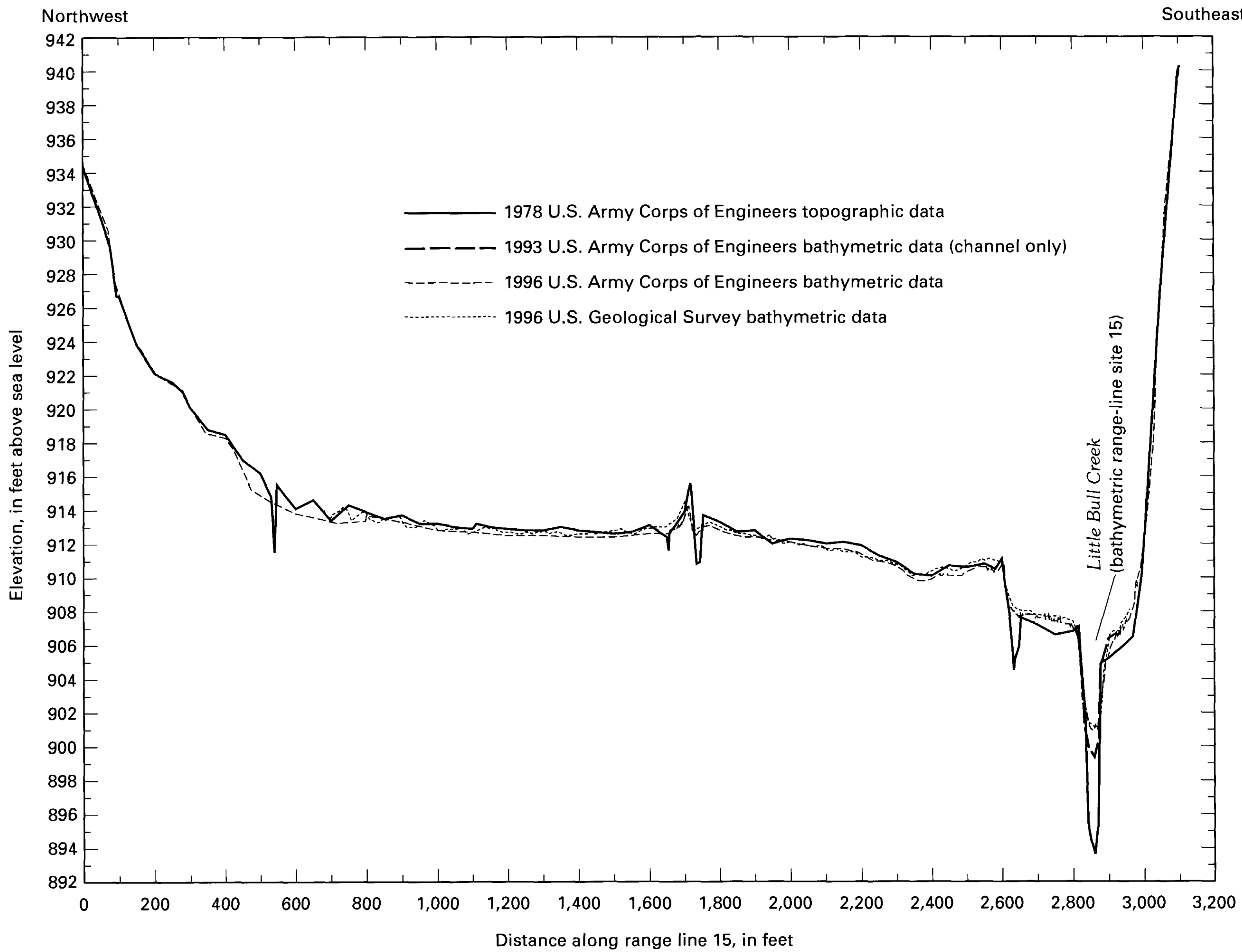

Figure 11. Comparison of 1996 U.S. Geological Survey bathymetric data, 1978 U.S. Army Corps of Engineers topographic data, and 1993 and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 15. Location of range line shown in figure 2.

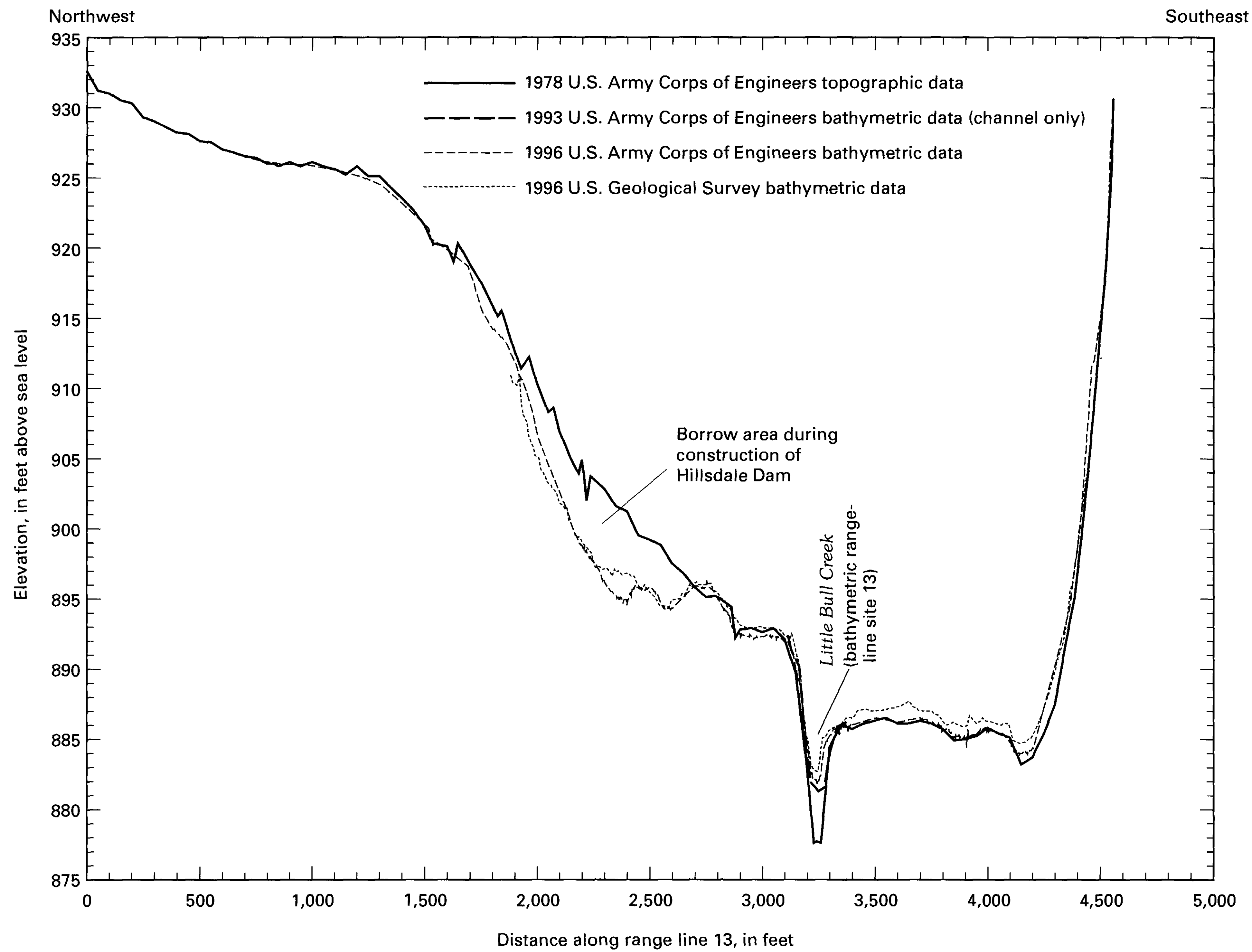

Figure 12. Comparison of 1996 U.S. Geological Survey bathymetric data, 1978 U.S. Army Corps of Engineers topographic data, and 1993 and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 13. Location of range line shown in figure 2.

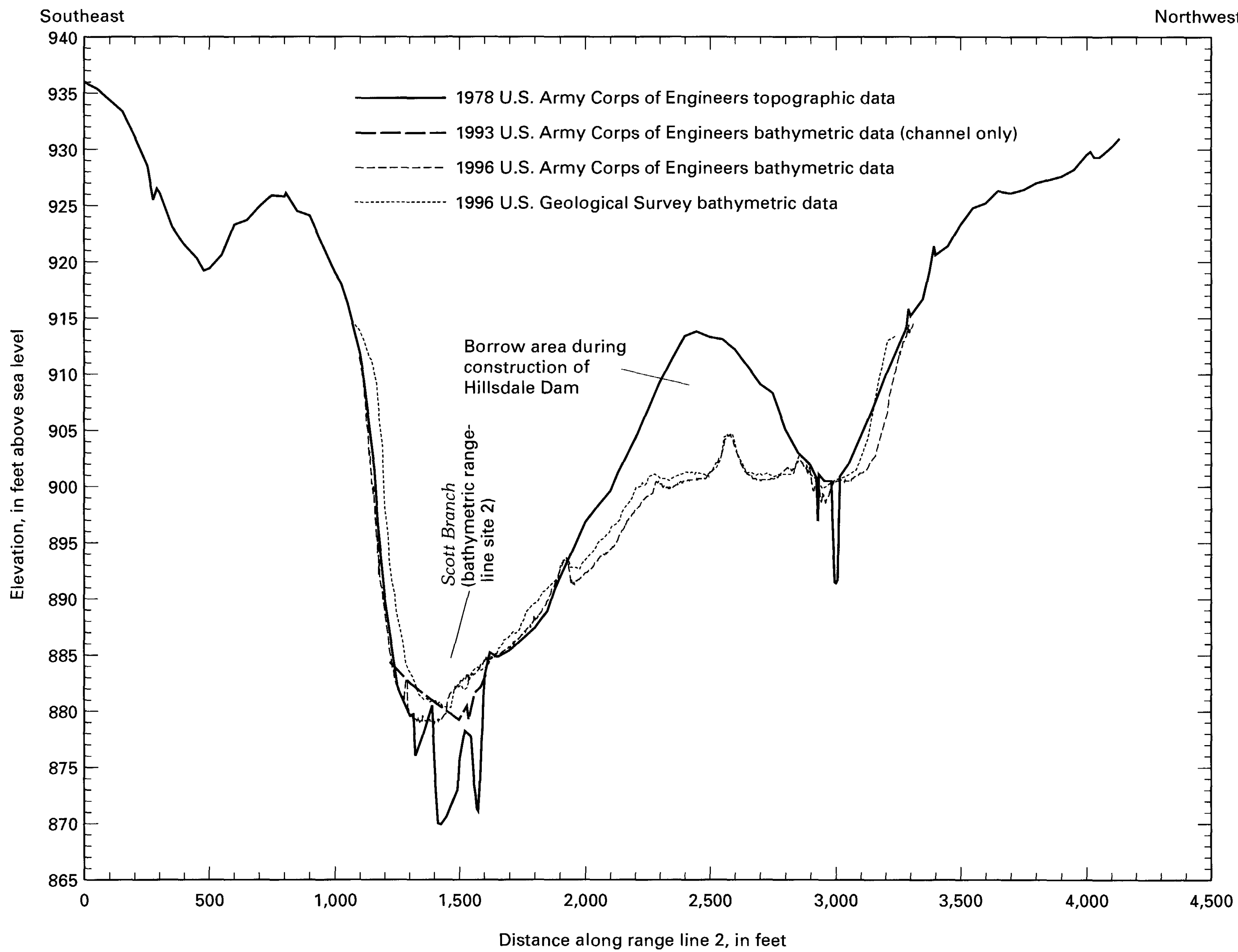

Figure 13. Comparison of 1996 U.S. Geological Survey bathymetric data, 1978 U.S. Army Corps of Engineers topographic data, and 1993 and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 2. Location of range line shown in figure 2.

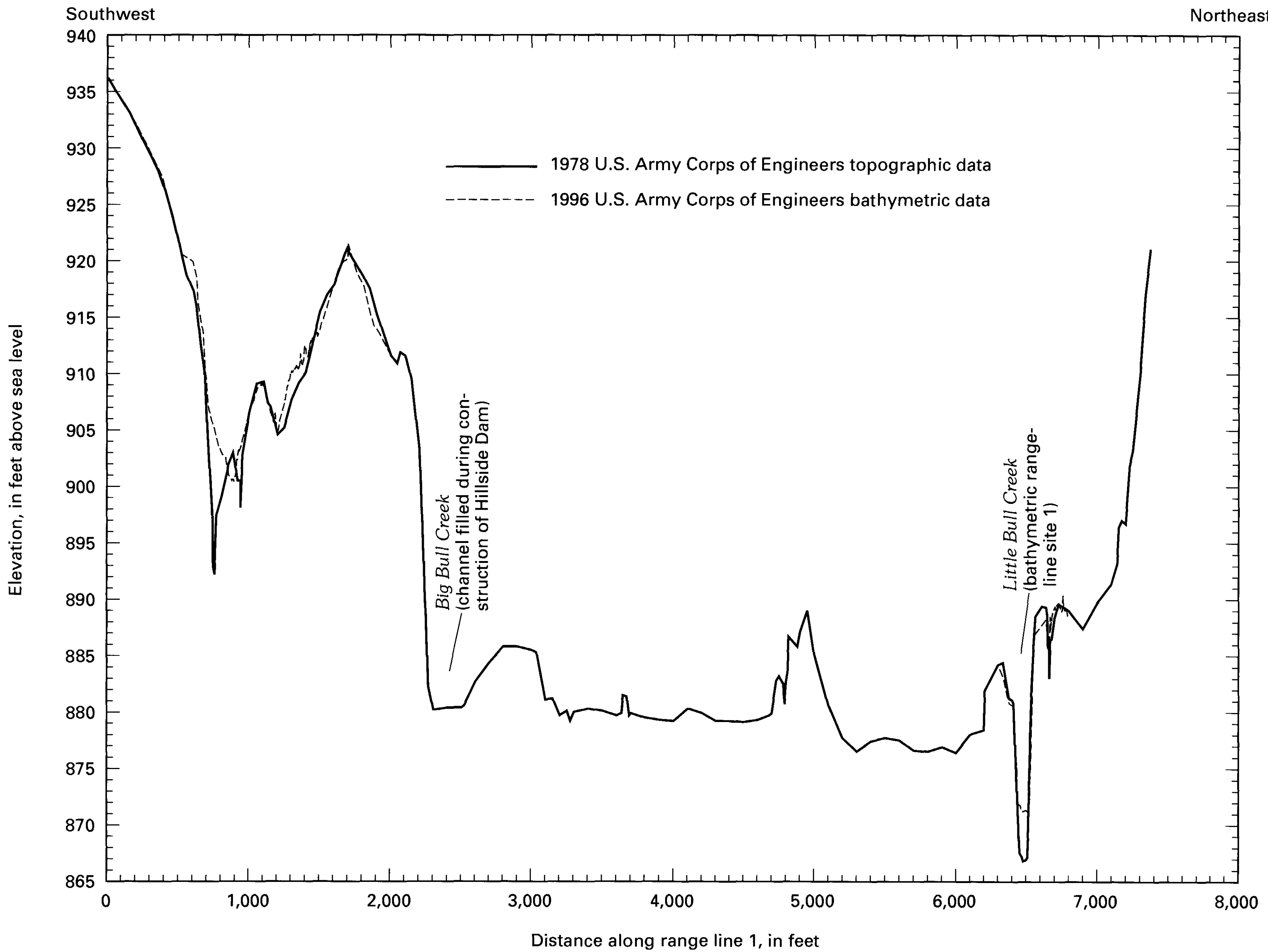

Figure 14. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 1. Location of range line shown in figure 2.

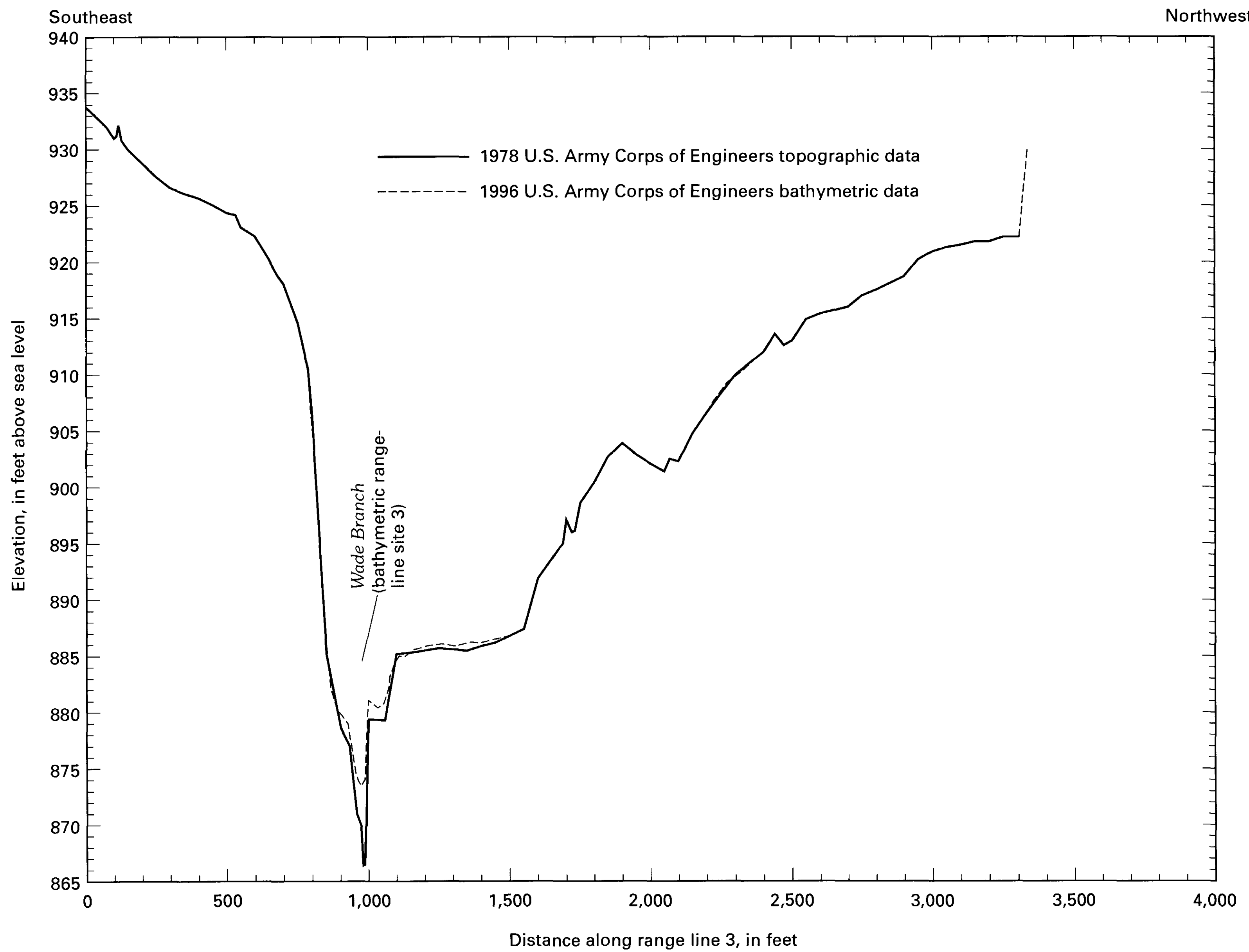

Figure 15. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 3. Location of range line shown in figure 2.

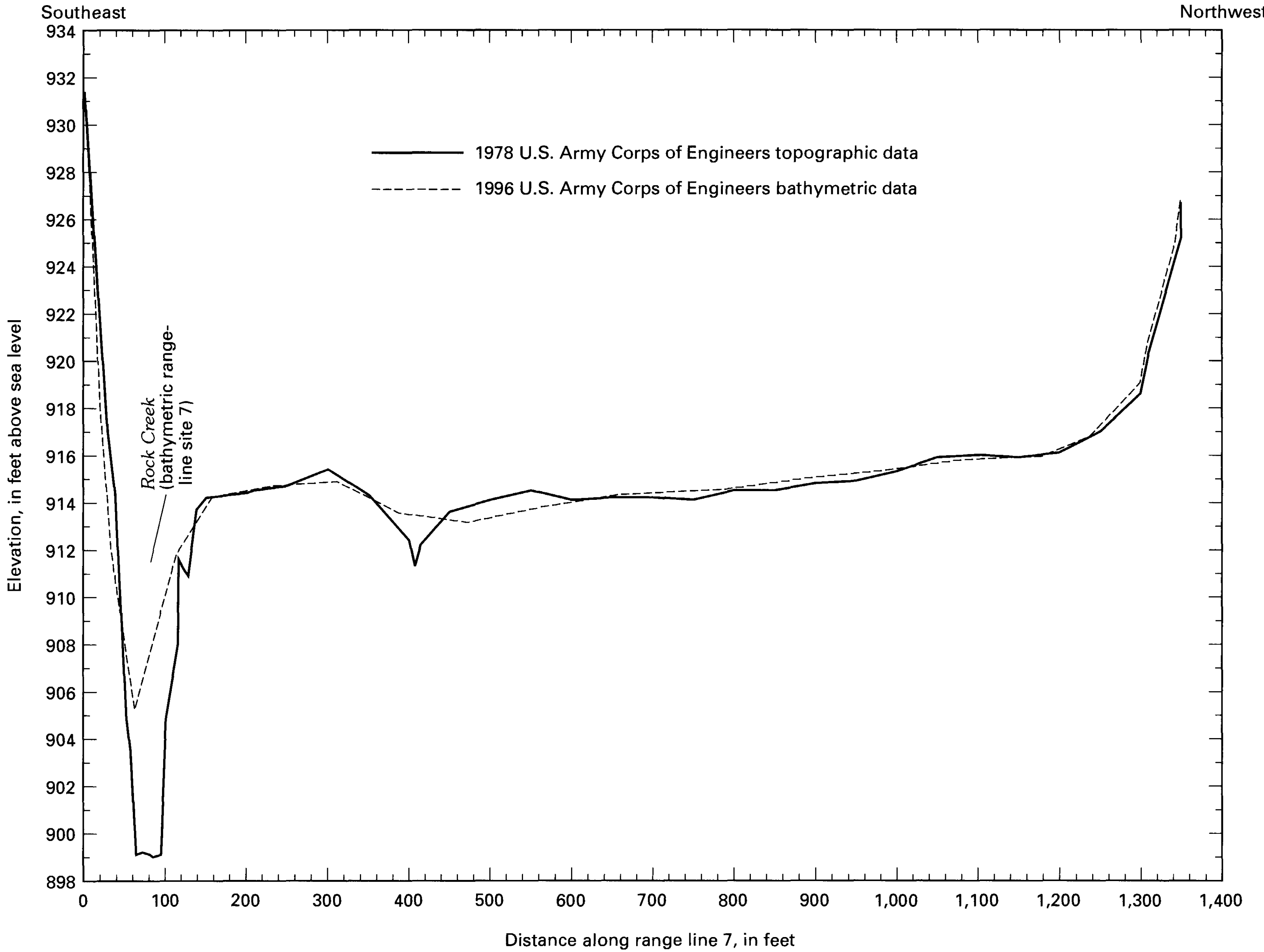

Figure 16. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 7. Location of range line shown in figure 2.

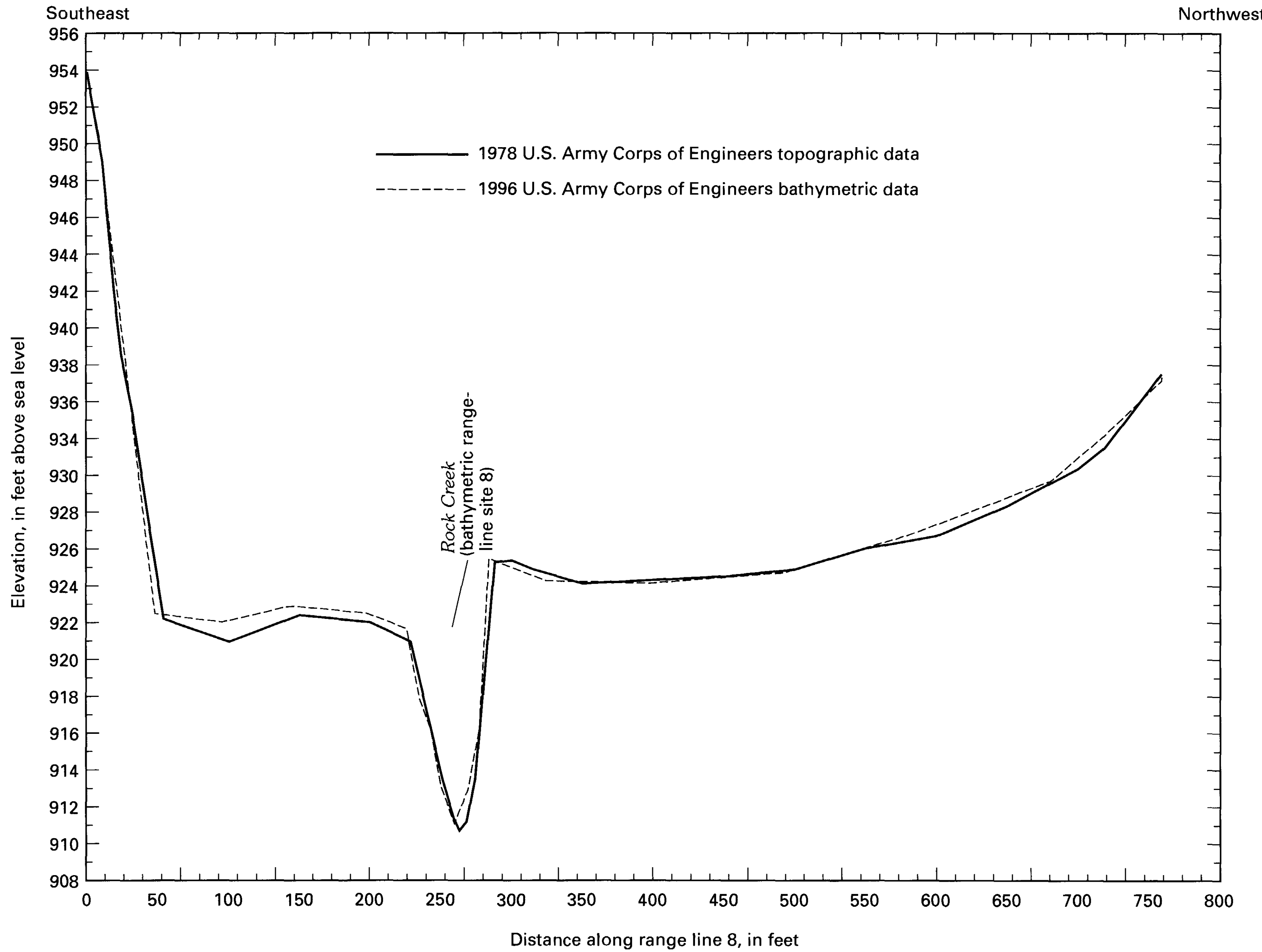

Figure 17. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 8. Location of range line shown in figure 2.

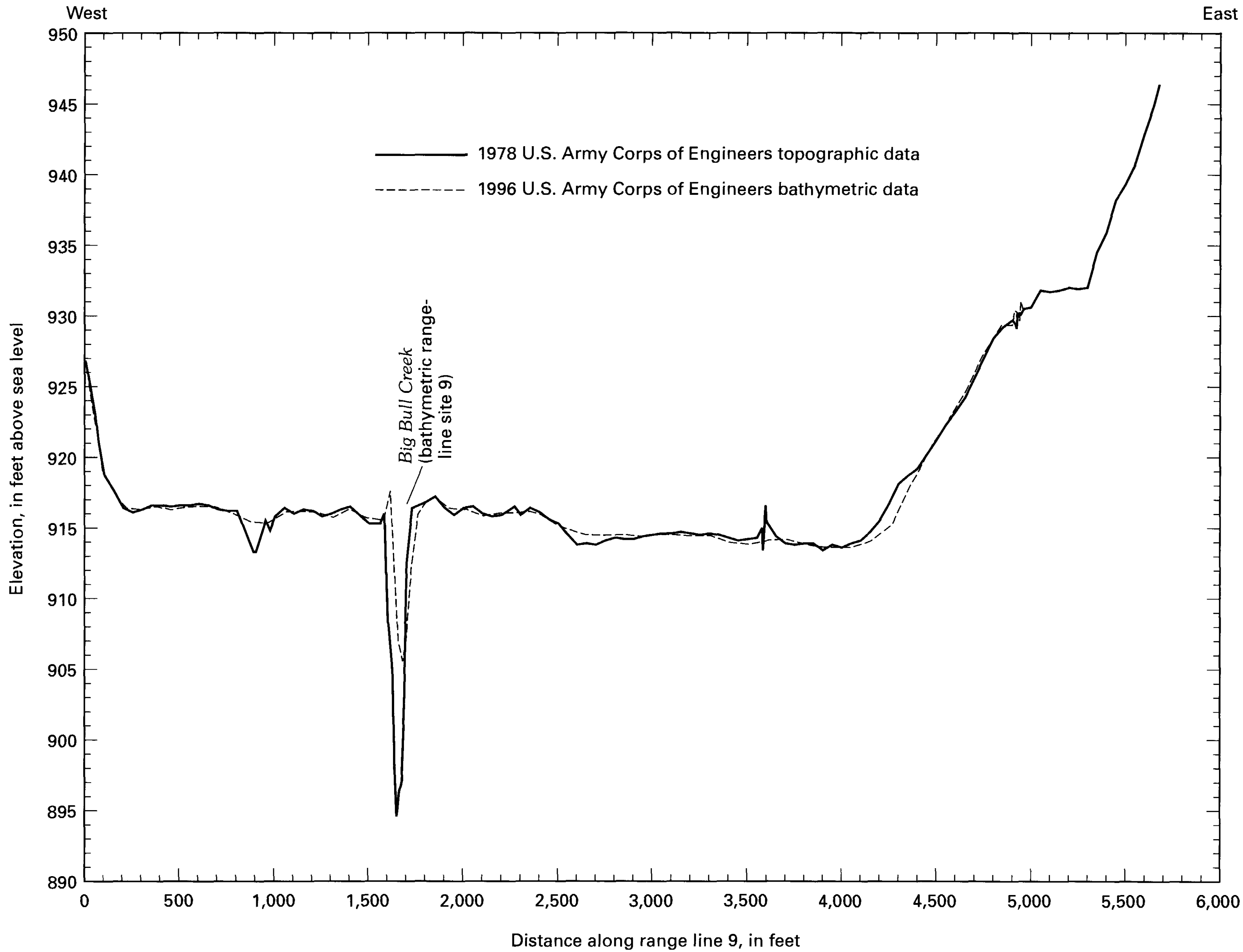

Figure 18. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 9. Location of range line shown in figure 2.

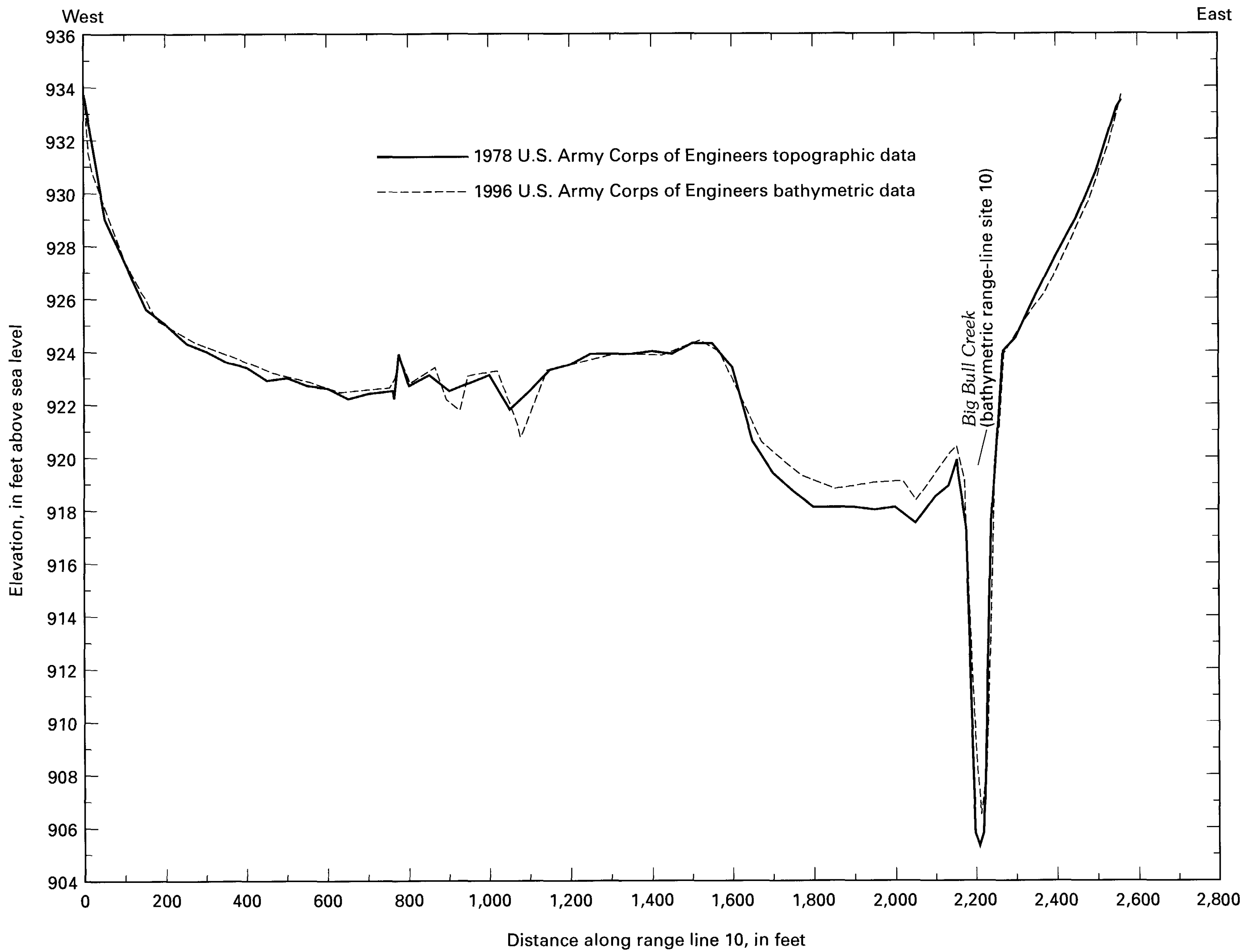

Figure 19. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 10. Location of range line shown in figure 2.

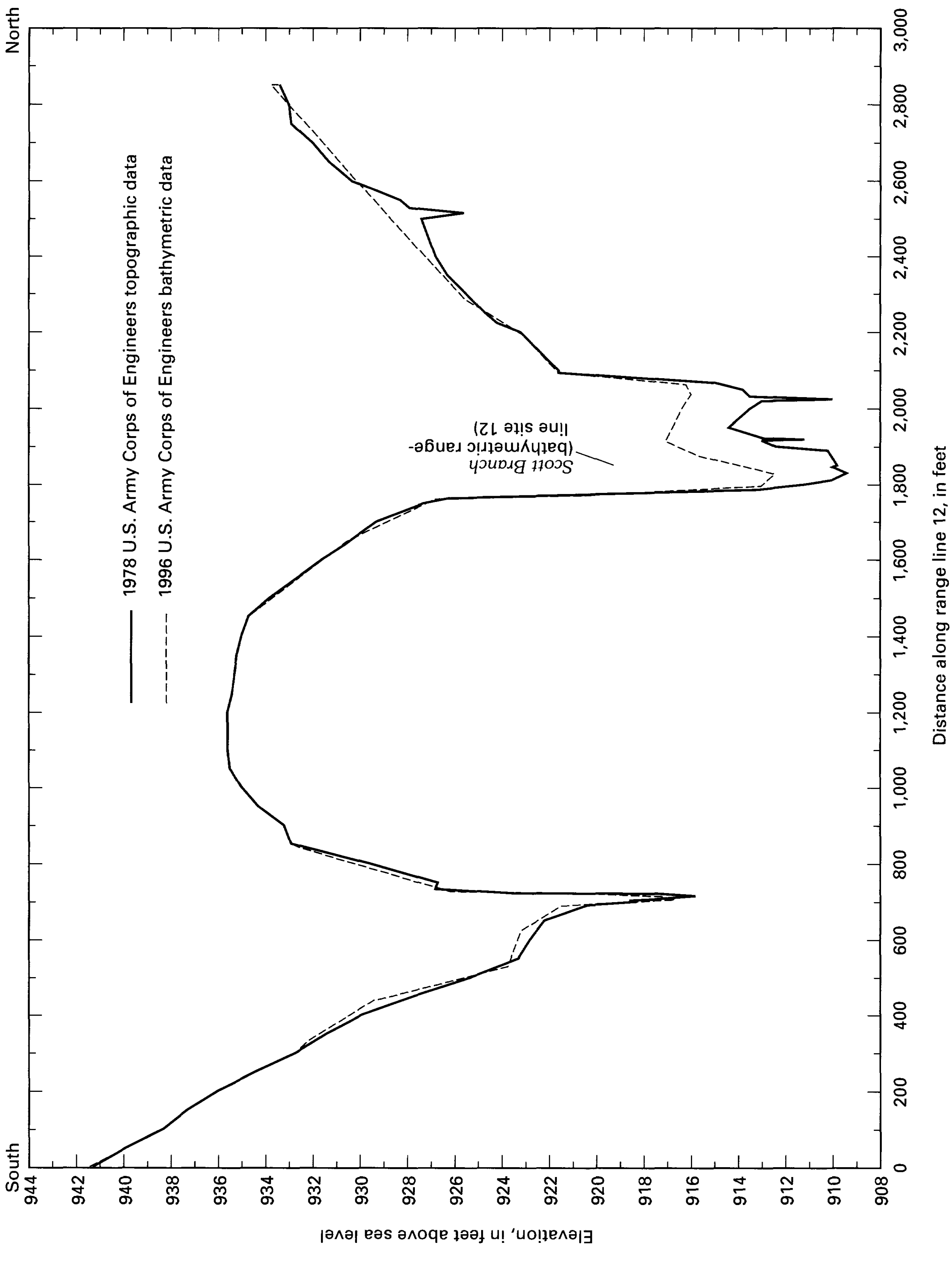

Figure 20. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 12. Location of range line shown in figure 2.

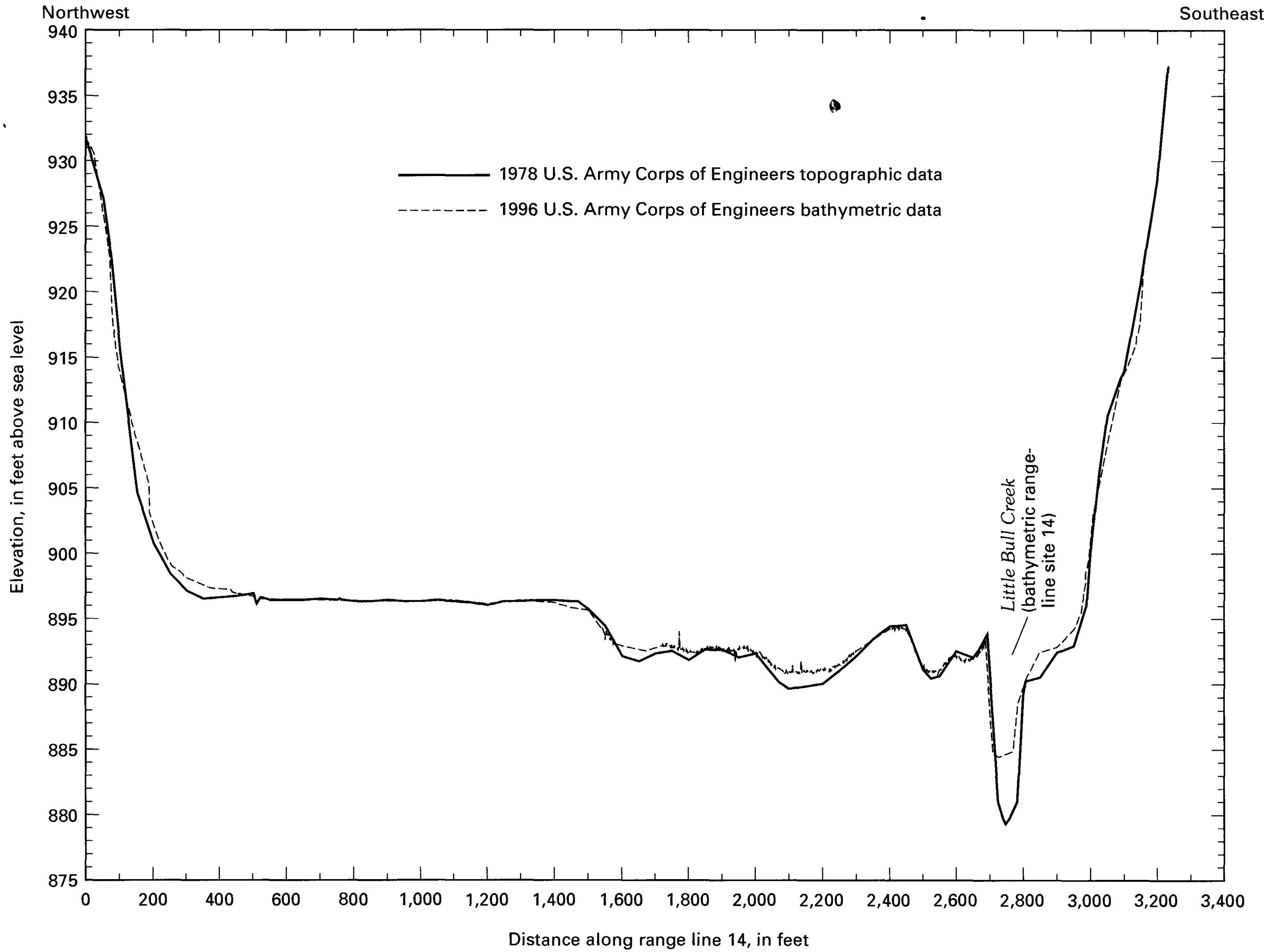

Figure 21. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 14. Location of range line shown in figure 2.

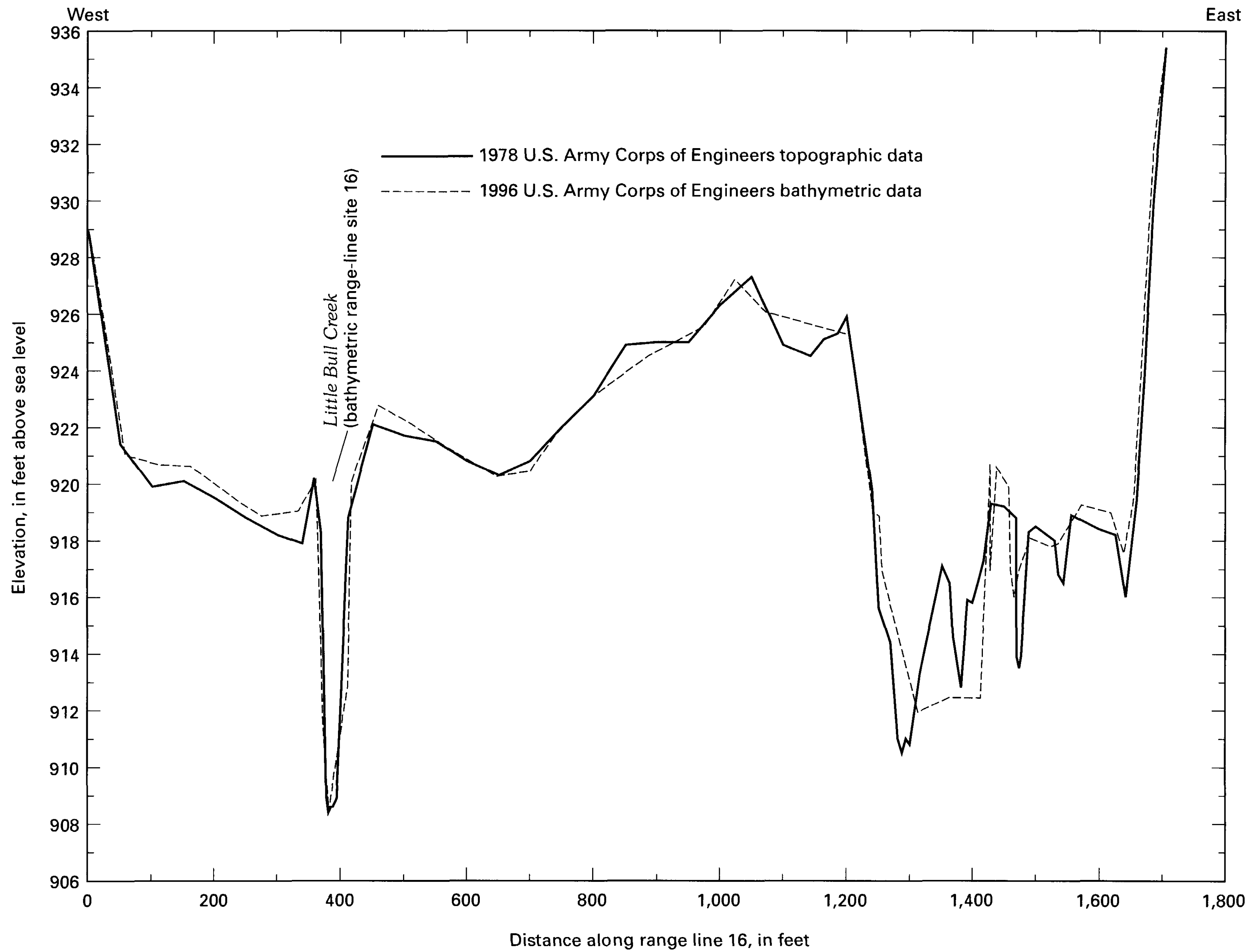

Figure 22. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 16. Location of range line shown in figure 2.

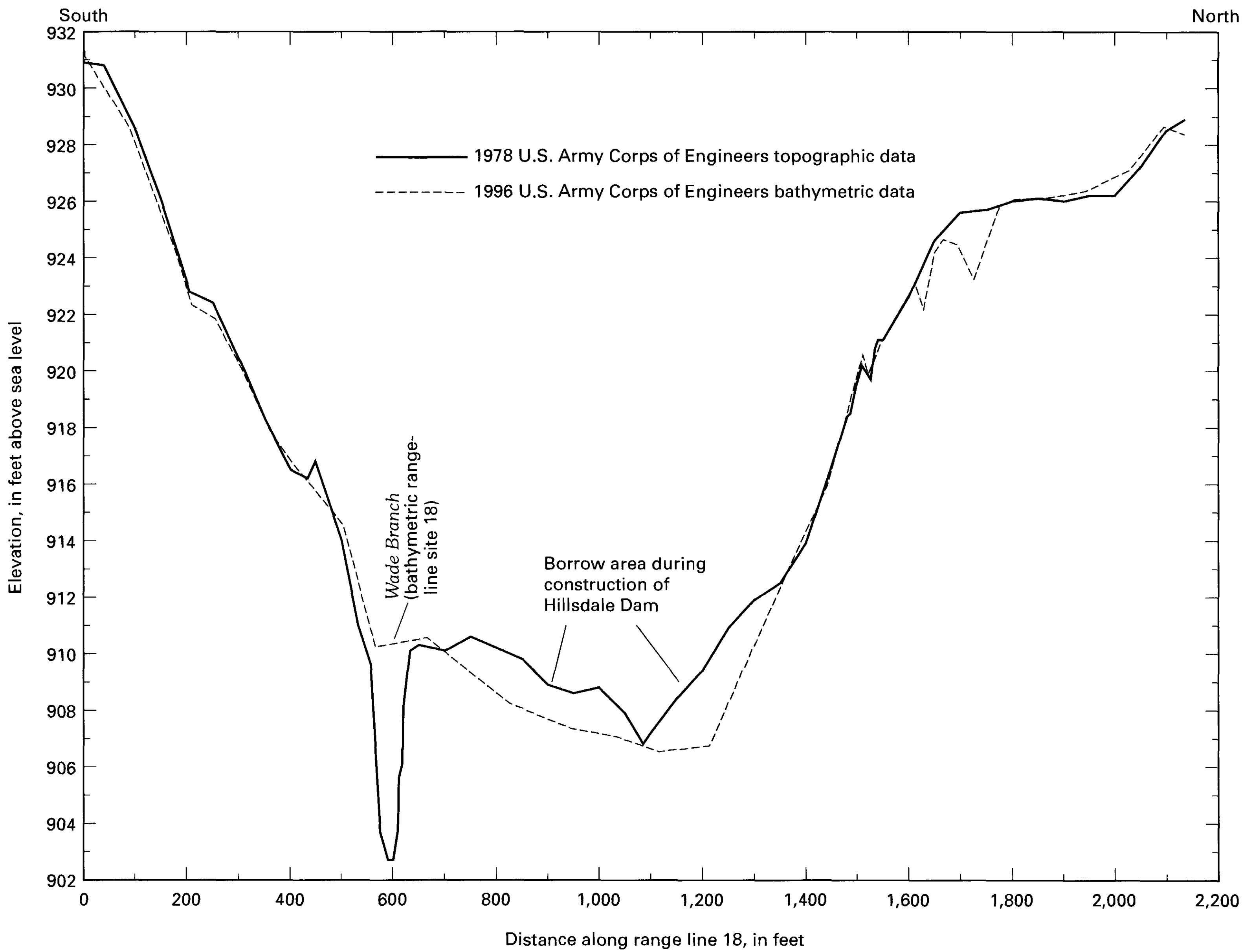

Figure 23. Comparison of 1978 U.S. Army Corps of Engineers topographic data and 1996 U.S. Army Corps of Engineers bathymetric data for Hillsdale Lake range line 18. Location of range line shown in figure 2.

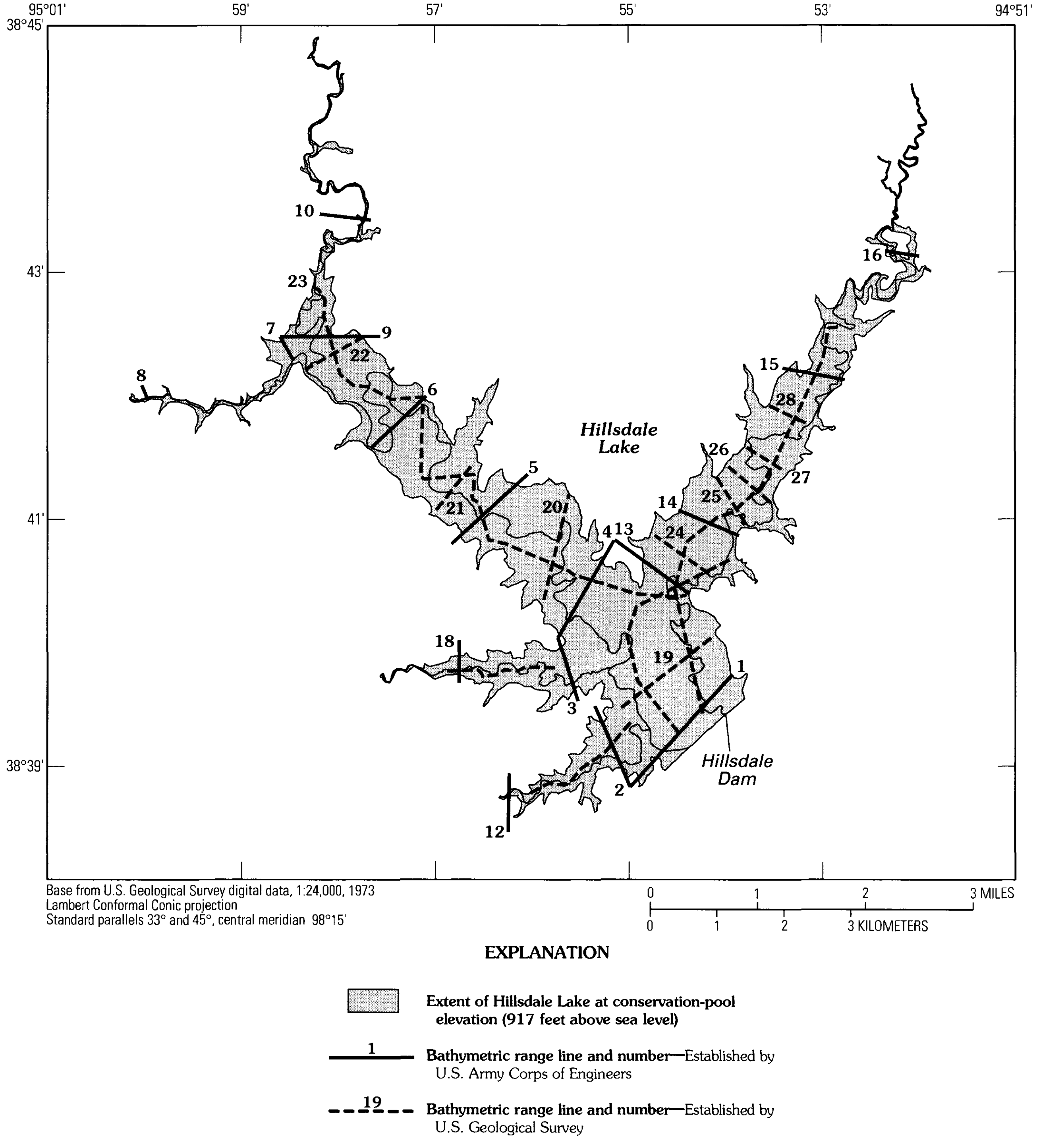

Figure 24. Additional bathymetric survey lines completed by the U.S. Geological Survey at Hillsdale Lake in 1996.

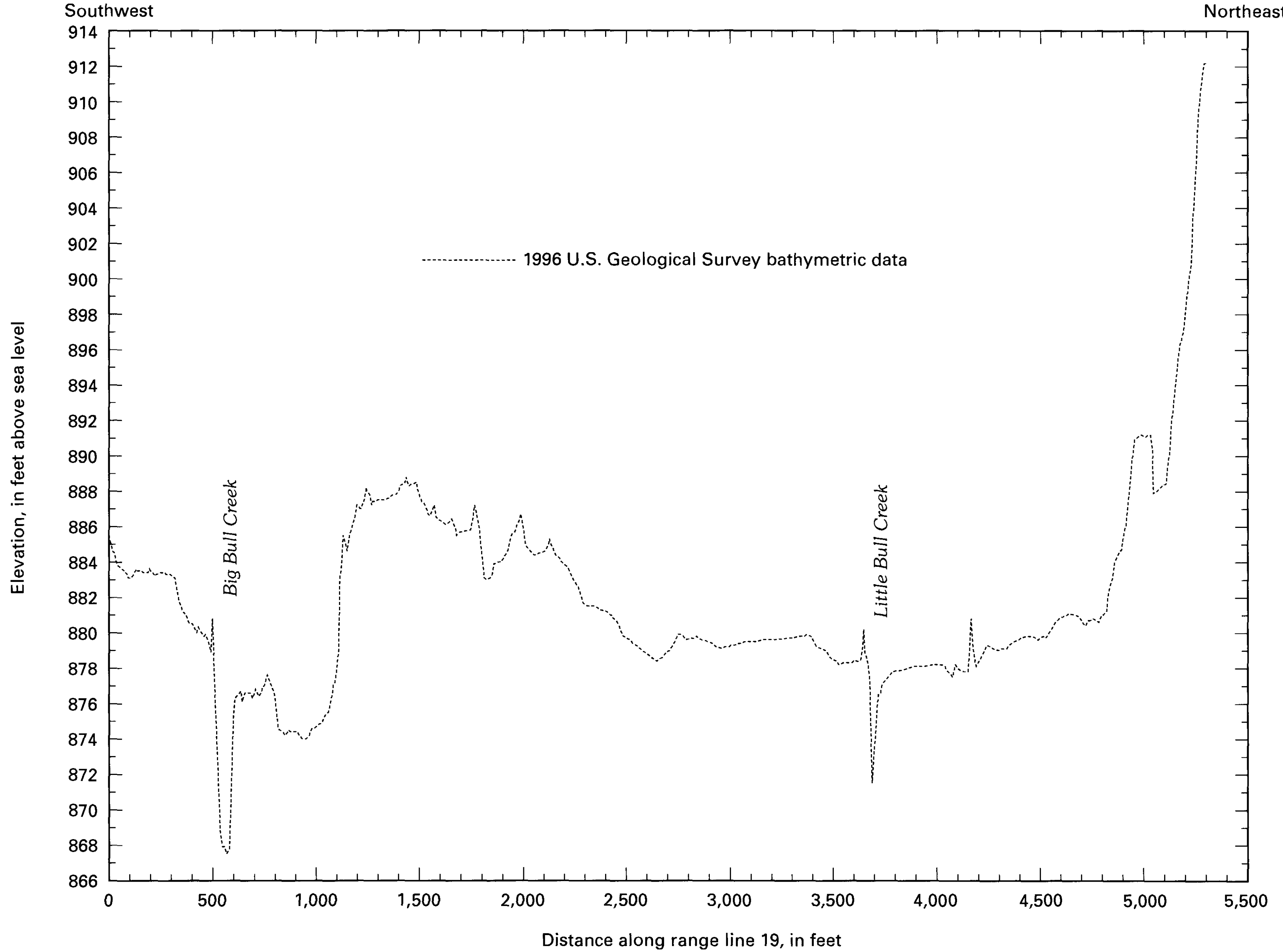

Figure 25. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 19. Location of range line shown in figure 24.

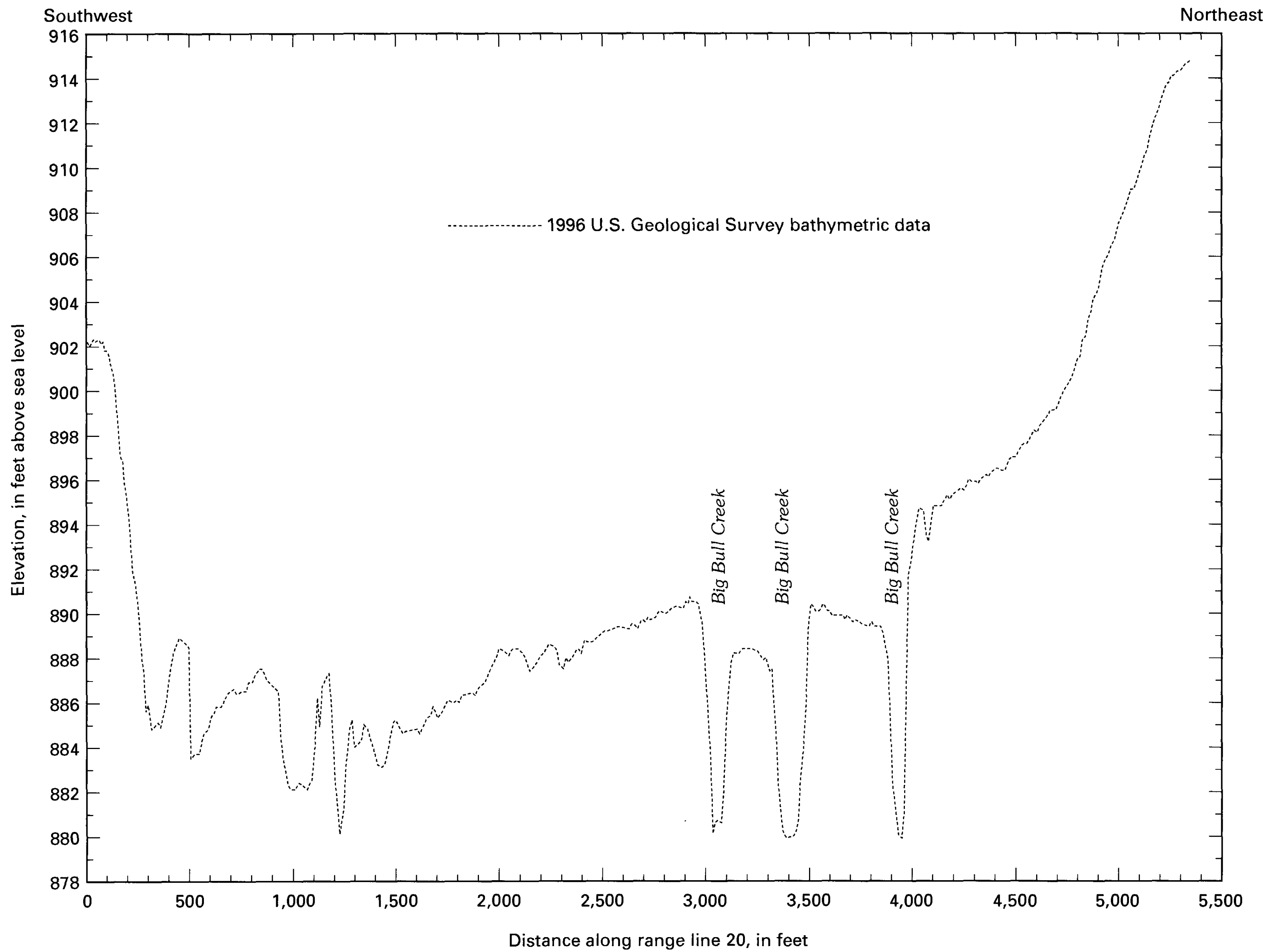

Figure 26. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 20. Location of range line shown in figure 24.

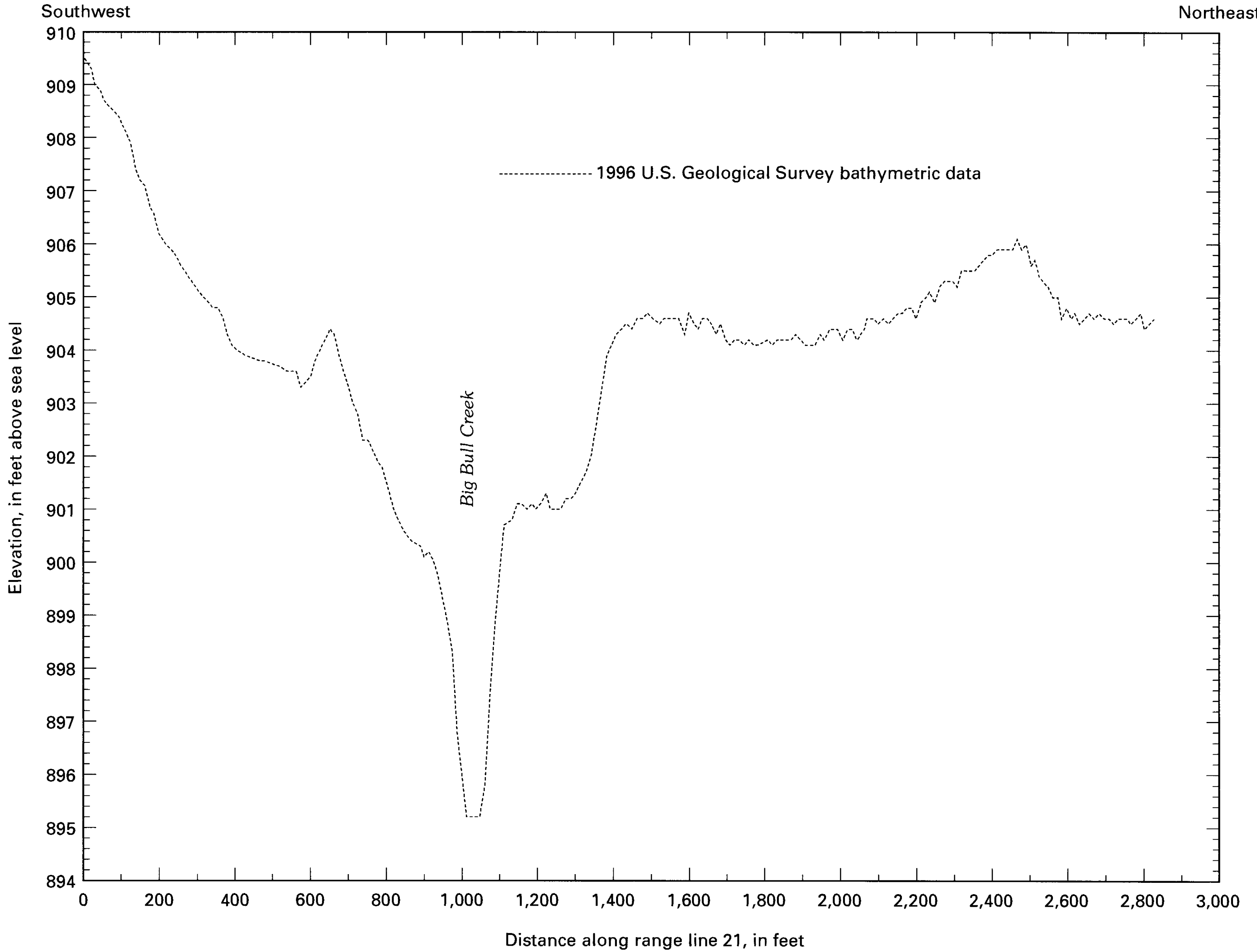

Figure 27. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 21. Location of range line shown in figure 24.

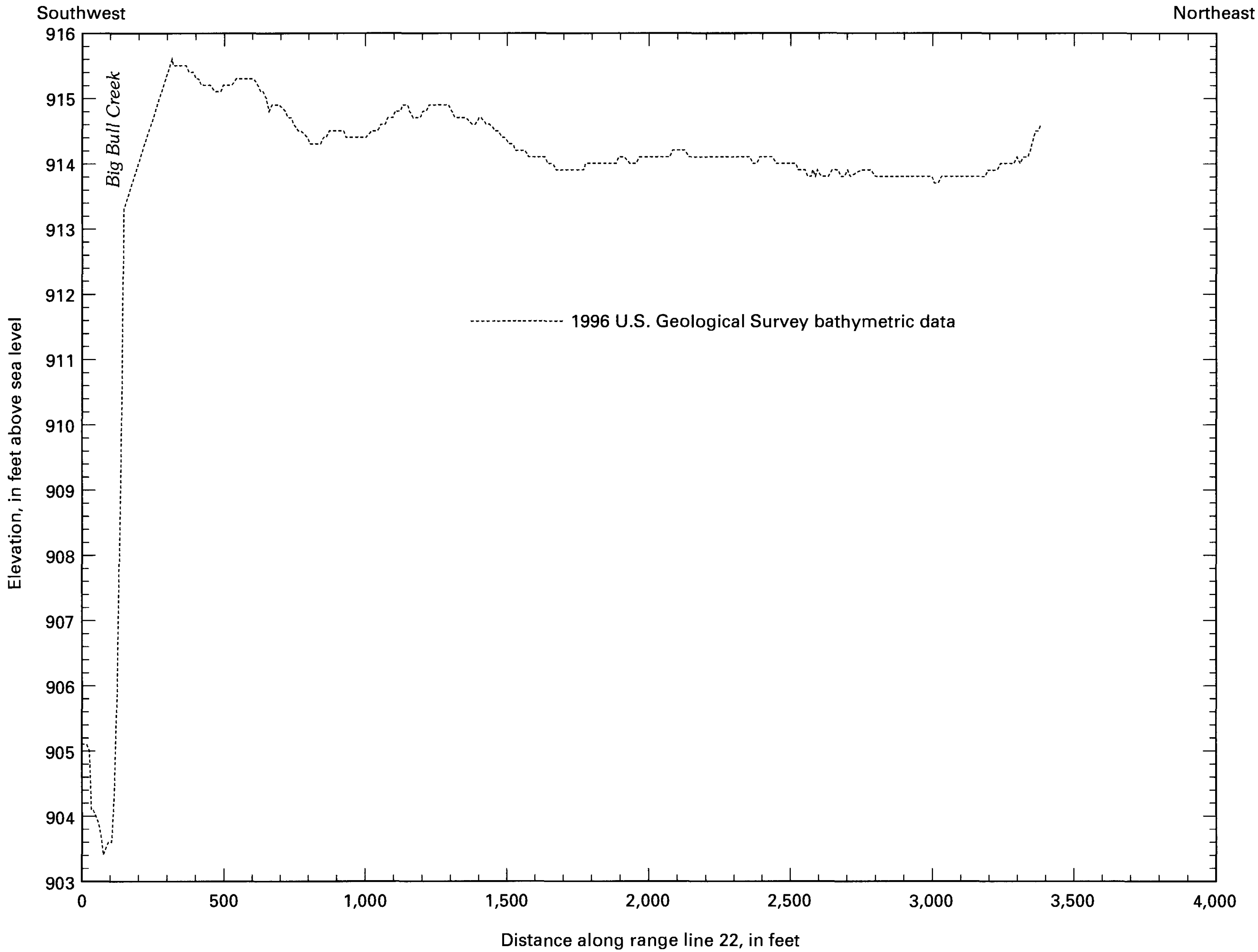

Figure 28. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 22. Location of range line shown in figure 24.

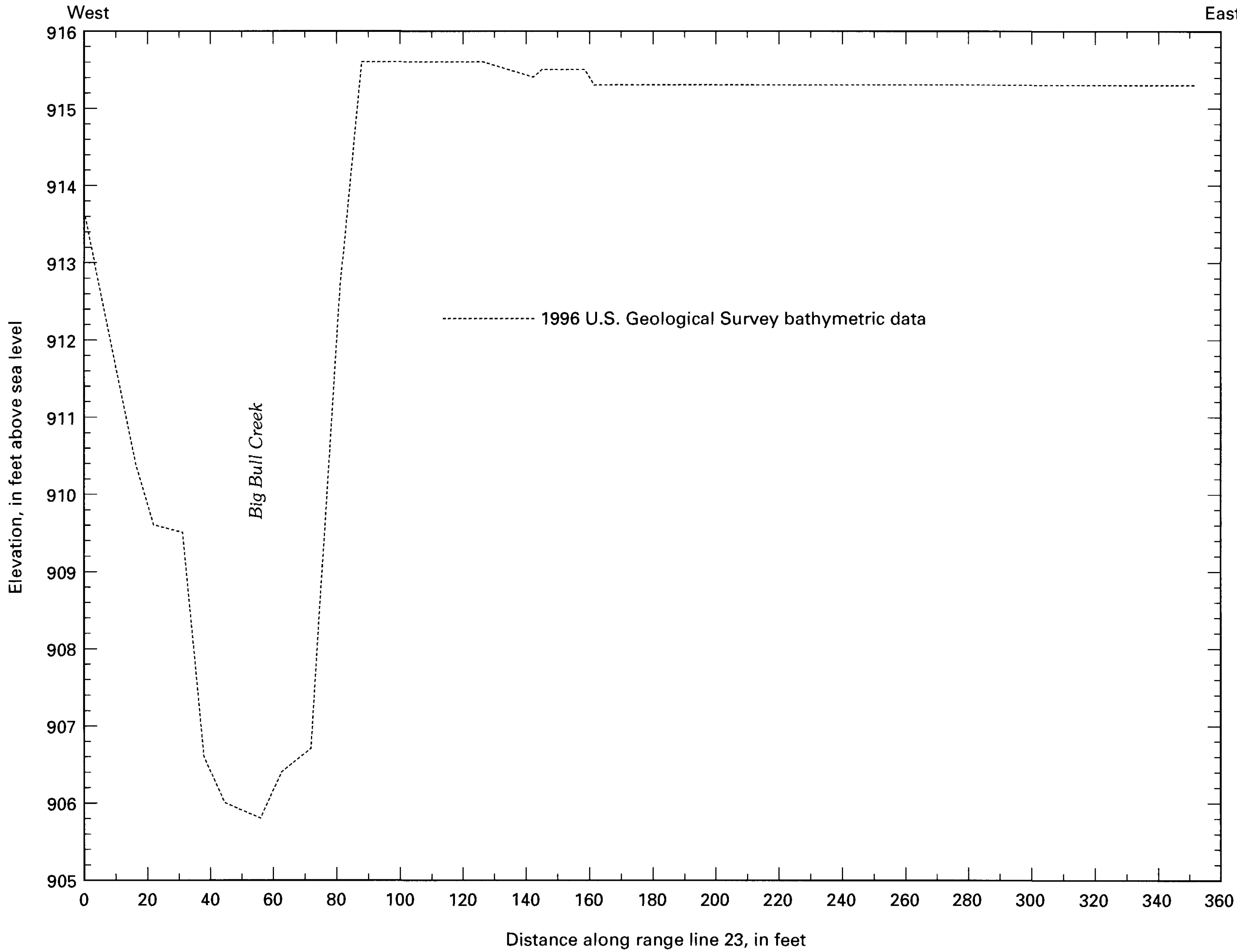

Figure 29. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 23. Location of range line shown in figure 24.

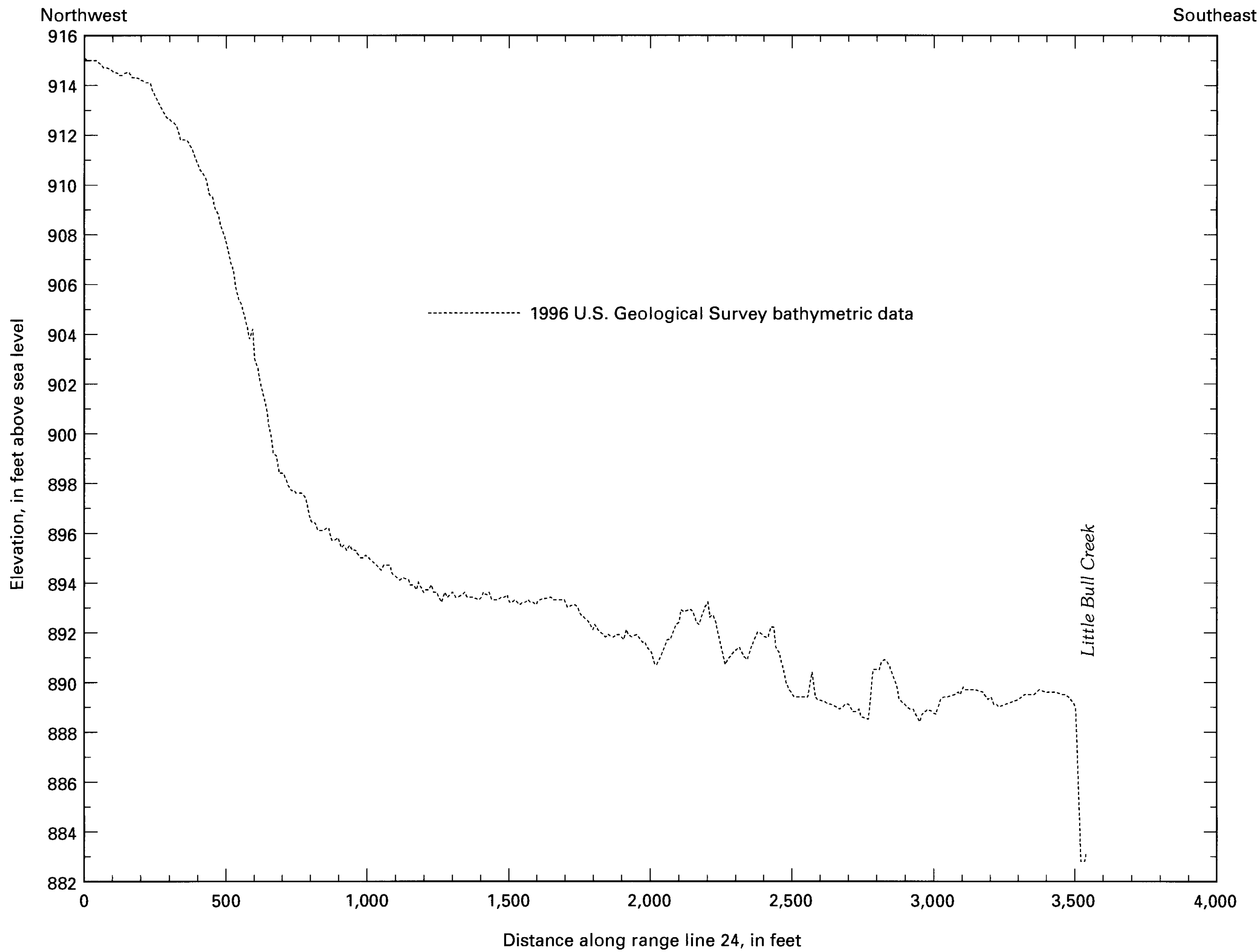

Figure 30. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 24. Location of range line shown in figure 24.

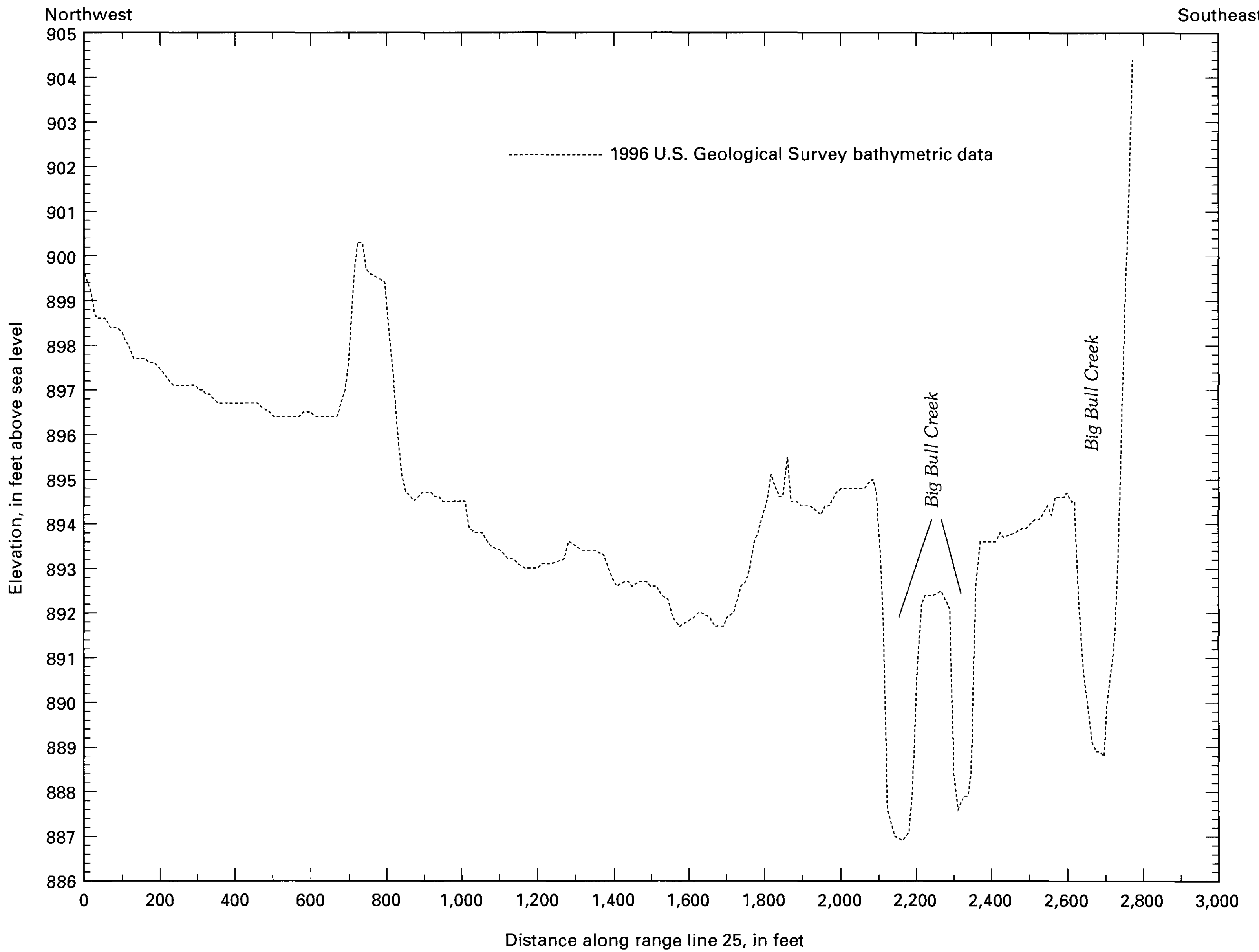

Figure 31. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 25. Location of range line shown in figure 24.

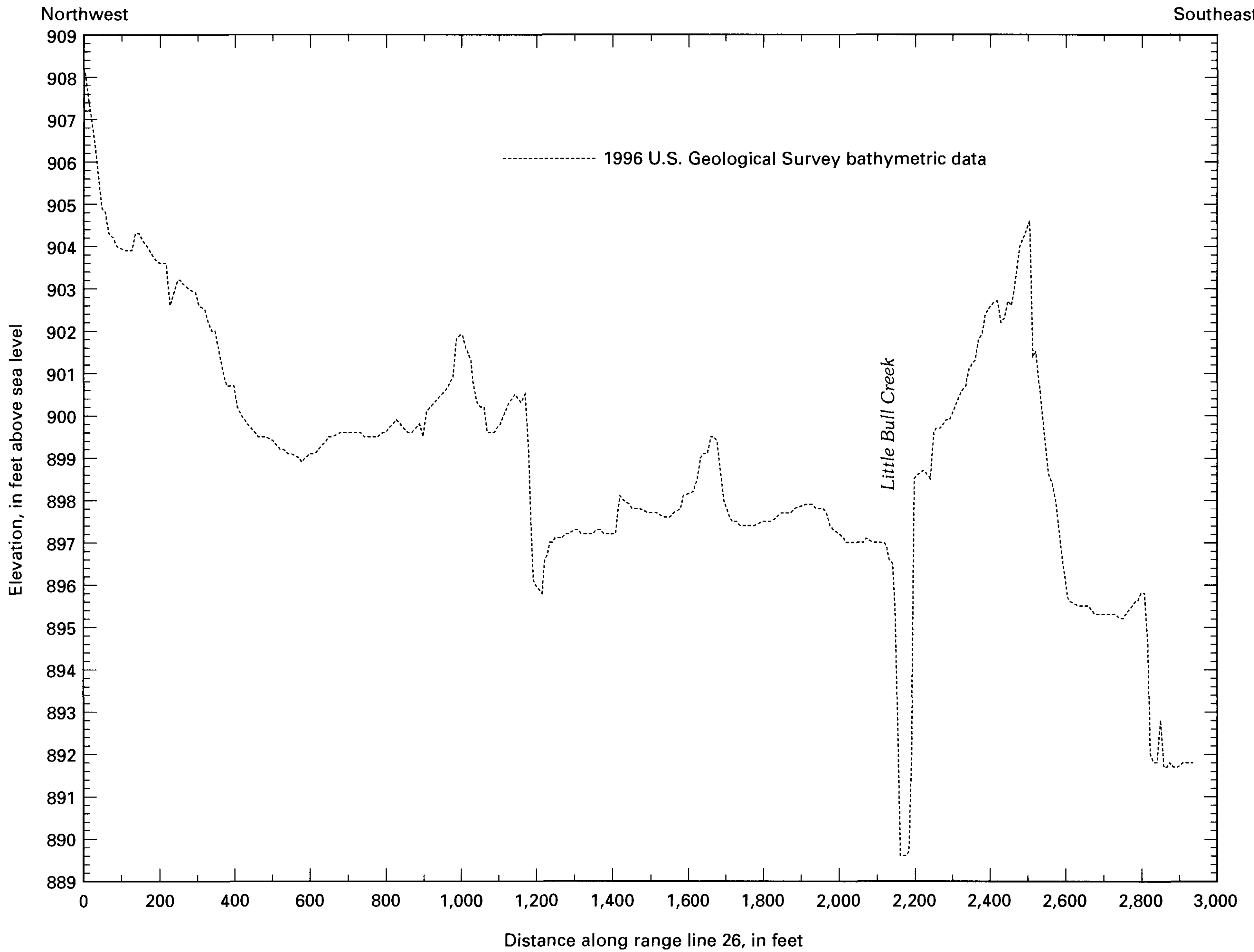

Figure 32. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 26. Location of range line shown in figure 24.

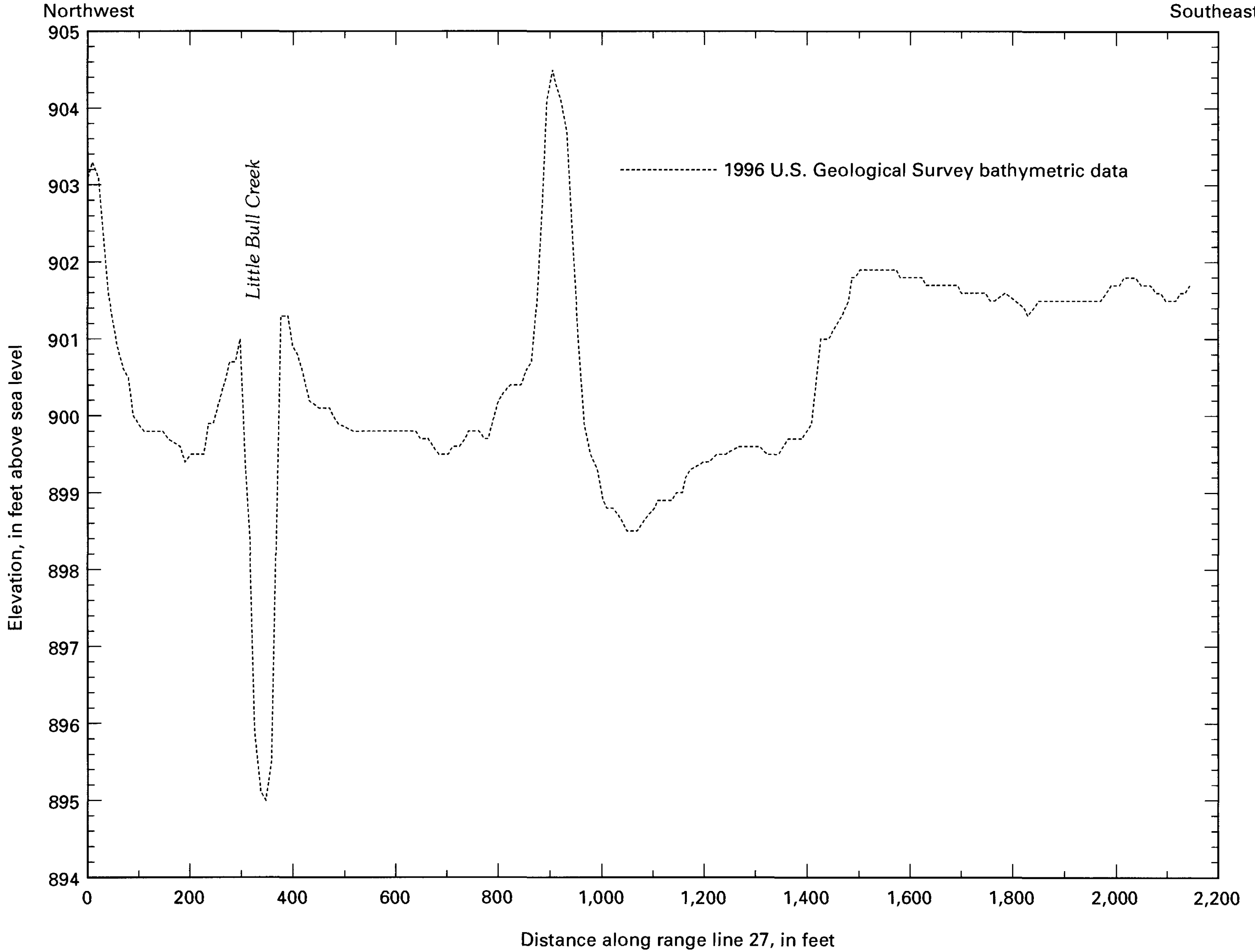

Figure 33. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 27. Location of range line shown in figure 24.

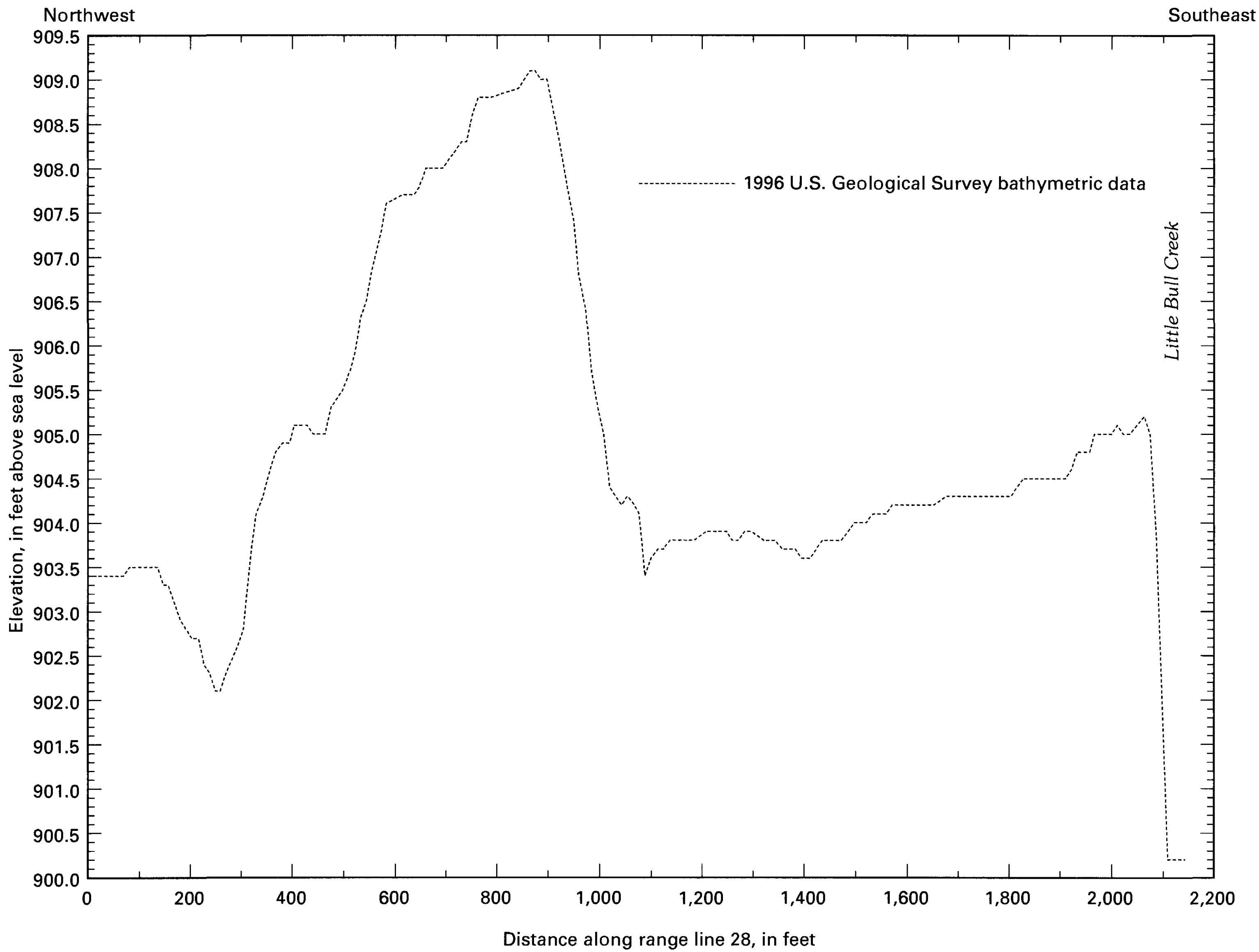

Figure 34. 1996 U.S. Geological Survey bathymetric data for Hillsdale Lake range line 28. Location of range line shown in figure 24.

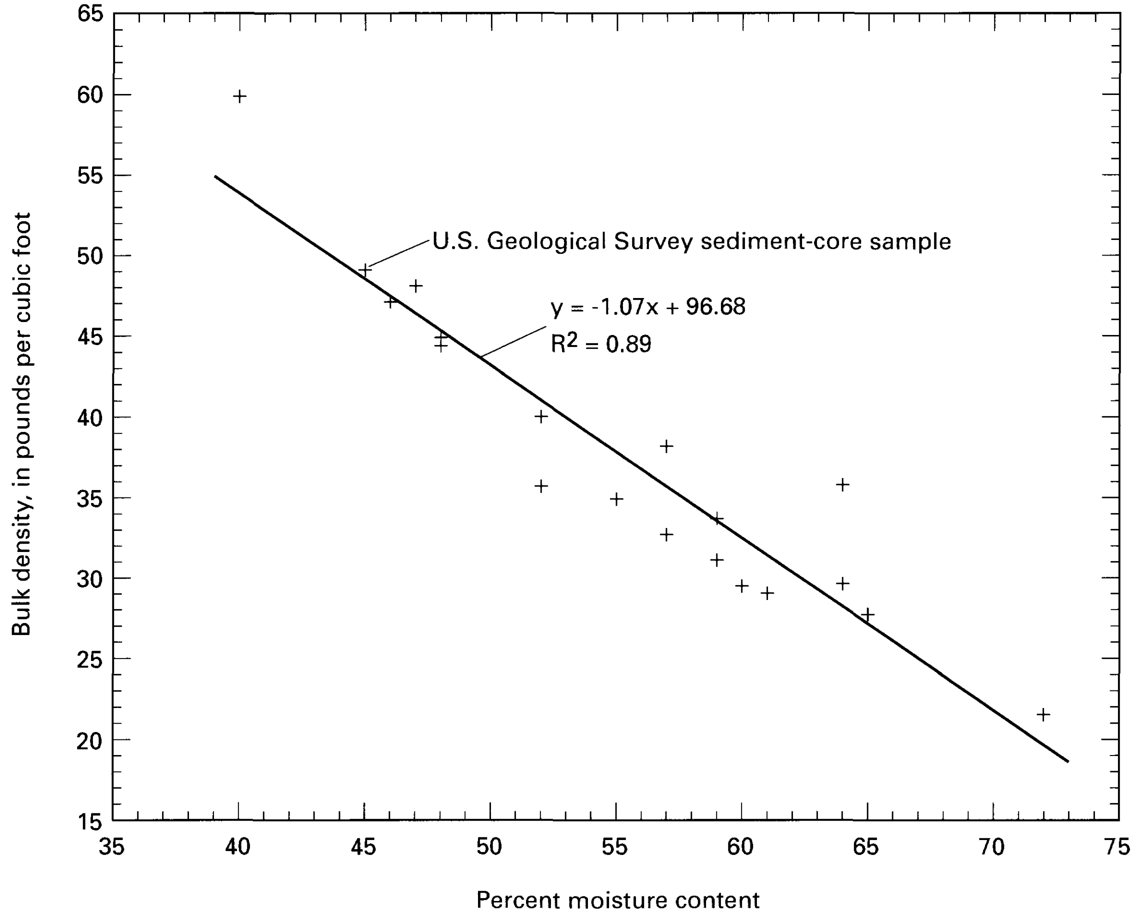

Figure 35. Relation of sediment bulk density to percent moisture content for 19 sediment-core samples from Hillsdale Lake.

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