

ESTIMATED FLOOD PEAK DISCHARGES ON TWIN, BROCK, AND LIGHTNING CREEKS, SOUTHWEST OKLAHOMA CITY, OKLAHOMA, MAY 8, 1993

By Robert L. Tortorelli

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
mile (mi)	1.609	kilometers (km)
square miles (mi ²)	2.590	square kilometers (km ²)
cubic feet per second (ft ³ /s)	0.02832	cubic meters per second (m ³ /s)
cubic feet per second per square mile [(ft ³ /s)/mi ²]	0.01093	cubic meters per second per square kilometer [(m ³ /s)/km ²]

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

Estimated Flood Peak Discharges on Twin, Brock, and Lightning Creeks, Southwest Oklahoma City, Oklahoma, May 8, 1993

By Robert L. Tortorelli

Abstract

The flash flood in southwestern Oklahoma City, Oklahoma, May 8, 1993, was the result of an intense 3-hour rainfall on saturated ground or impervious surfaces. The total precipitation of 5.28 inches was close to the 3-hour, 100-year frequency and produced extensive flooding. The most serious flooding was on Twin, Brock, and Lightning Creeks. Four people died in this flood. Over 1,900 structures were damaged along the 3 creeks. There were about \$3 million in damages to Oklahoma City public facilities, the majority of which were in the three basins.

A study was conducted to determine the magnitude of the May 8, 1993, flood peak discharge in these three creeks in southwestern Oklahoma City and compare these peaks with published flood estimates. Flood peak-discharge estimates for these creeks were determined at 11 study sites using a step-backwater analysis to match the flood water-surface profiles defined by high-water marks.

The unit discharges during peak runoff ranged from 881 cubic feet per second per square mile for Lightning Creek at SW 44th Street to 3,570 cubic feet per second per square mile for Brock Creek at SW 59th Street. The ratios of the 1993 flood peak discharges to the Federal Emergency Management Agency 100-year flood peak discharges ranged from 1.25 to 3.29. The water-surface elevations ranged from 0.2 foot to 5.9 feet above the Federal Emergency Management Agency 500-year flood water-surface elevations.

The very large flood peaks in these 3 small urban basins were the result of very intense rainfall in a short period of time, close to 100 percent runoff due to ground surfaces being essentially impervious, and the city streets acting as efficient conveyances to the main channels. The unit dis-

charges compare in magnitude to other extraordinary Oklahoma urban floods.

INTRODUCTION

One of the greatest flood disasters in the history of Oklahoma City, Oklahoma, occurred during the early evening hours from about 4 p.m. to 9 p.m. May 8, 1993. The flash flood was the result of an intense 3-hour rainfall occurring within a 12-hour rainfall event.

The southwestern part of Oklahoma City was especially hard hit. Most of the flood damage was on Twin, Brock, and Lightning Creeks, tributaries to the North Canadian River. Flood waters claimed four lives; three people died in Brock Creek, and one person died in Lightning Creek. There was an estimated \$3 million in damage to City facilities and about 1,200 homes were damaged (Brown, 1993). It is estimated to be the worst flood in the City since the June 3, 1932, flood on the North Canadian River and its tributaries that was caused, to a large extent, by Lightning Creek overflow; 3,200 people were homeless, with 5 deaths, and 7 people missing (Tortorelli, Cooter, and Schuelein, 1991).

The U.S. Geological Survey (USGS), in cooperation with the City of Oklahoma City, conducted a study to determine the magnitude of the May 8, 1993, flood peak discharge in these three creeks in southwestern Oklahoma City and compare these peaks with published flood estimates. Data presented in this report provide City officials and consultants with a technical basis to make flood-plain management decisions and assist them in deciding future courses of action on the flood-prone areas.

Purpose and Scope

The magnitudes of urban floods are seldom documented in urban areas in Oklahoma. This report pre-

sents estimates of the flood peak discharges at 11 locations on Twin, Brock, and Lightning Creeks. These locations are small stream reaches above and below major urban street bridges and culverts, which are referred to as sites in this report. The study sites were chosen at locations of interest by the cooperator, the City of Oklahoma City. Figure 1 shows the locations of the study sites: 2 sites on Twin Creek (sites 1-2), 3 sites on Brock Creek (sites 3-5), and 6 sites on Lightning Creek (sites 6-11).

The flood peak discharges and computed flood water-surface profiles are compared with those of selected frequencies used in the Federal Emergency Management Agency (FEMA) flood-insurance study for Oklahoma City (Federal Emergency Management Agency, 1990). This report also compares the estimated flood peak discharges to estimated maximum discharges in an urban environment (Tortorelli and others, 1983) and upper limits of known floods in Oklahoma (Crippen and Bue, 1977; Bingham and others, 1974; Bergman and Tortorelli, 1988).

Storm Rainfall

Rainfall was very intense for a short period of time during a longer rain event. The reported rainfall by the National Weather Service at Will Rogers Airport for the 24-hour period from 7 p.m. Friday, May 7, 1993, to 7 p.m. Saturday, May 8, 1993, was 7.04 inches (National Oceanic and Atmospheric Administration, 1993). A total rainfall of 5.28 inches fell between 3 p.m. and 6 p.m. on May 8, 1993 (figure 2). As shown in figure 2, this heavy rainfall was preceded by 0.85 inches of precipitation. Therefore, the intense rainfall fell on nearly-saturated or impervious ground surfaces, and it was assumed that almost 100 percent runoff did occur.

National Weather Service radars are capable of providing raw radar plots of cumulative rainfall. Raw radar plots are those unadjusted by surface rain gage point data. Plots of the May 8, 1993, storm were provided by the Oklahoma City Weather Forecast Office (written commun., 1993). An inspection of these raw radar plots revealed that the rainfall received by Twin and Brock Creek watersheds was nearly equal to that measured by Will Rogers Airport rain gage. The Lightning Creek study area received about 1-2 inches less.

The expected frequency of the rainfall event is usually determined by comparing the recorded rainfall

amount of a specified duration with the National Weather Service Technical Paper 40 data (Hershfield, 1961). A comparison of these data is presented in figure 3. The recorded 3-hour rainfall of 5.28 inches is only 0.10 inch less than that for the 100-year frequency, 3-hour rainfall. The concept of 100-year frequency is discussed in detail in the Estimated Flood Peak Discharges section.

Flood Damages

There were a substantial number of structures damaged in the May 8, 1993, flood in Twin, Brock, and Lightning Creeks. Table 1 shows the tally for the 3 study basins (Brown, 1993). Over 1,900 structures were damaged in the 3 basins, of which about 1,200 were homes. In addition, about \$3 million in damages to Oklahoma City public facilities were a result of the flash flood, the majority of which were in the 3 southwest urban basins.

President Clinton signed a federal disaster declaration for four counties in Oklahoma on Wednesday, May 12, 1993 (English, 1993). Oklahoma County was one of these counties, making the residents of the three study basins eligible for state and federal disaster relief.

Four people died in this flood. Three deaths were attributed to the flooding in Brock Creek, and one death occurred in Lightning Creek.

Acknowledgments

The author is indebted to many people who contributed significantly to the completion of the study. A special thanks goes to Eldon Beard of the National Weather Service, who provided rainfall data and raw radar precipitation plots. USGS personnel who assisted are: Tony Coffey and Rick Hanlon who marked the high-water marks; David Adams, Steve Smith, and Shane Hadlock who conducted the field surveys; Al Rea who provided computer expertise to generate drainage determinations and site base maps; and Lyn Osburn who provided editorial assistance. Ken Wahl, Central Region Surface-Water Specialist, provided technical expertise in the review of the hydraulic computations. This study would not have been possible without their cooperation and assistance.

Figure 1. Location of stream sites used in study, Oklahoma City, Oklahoma.

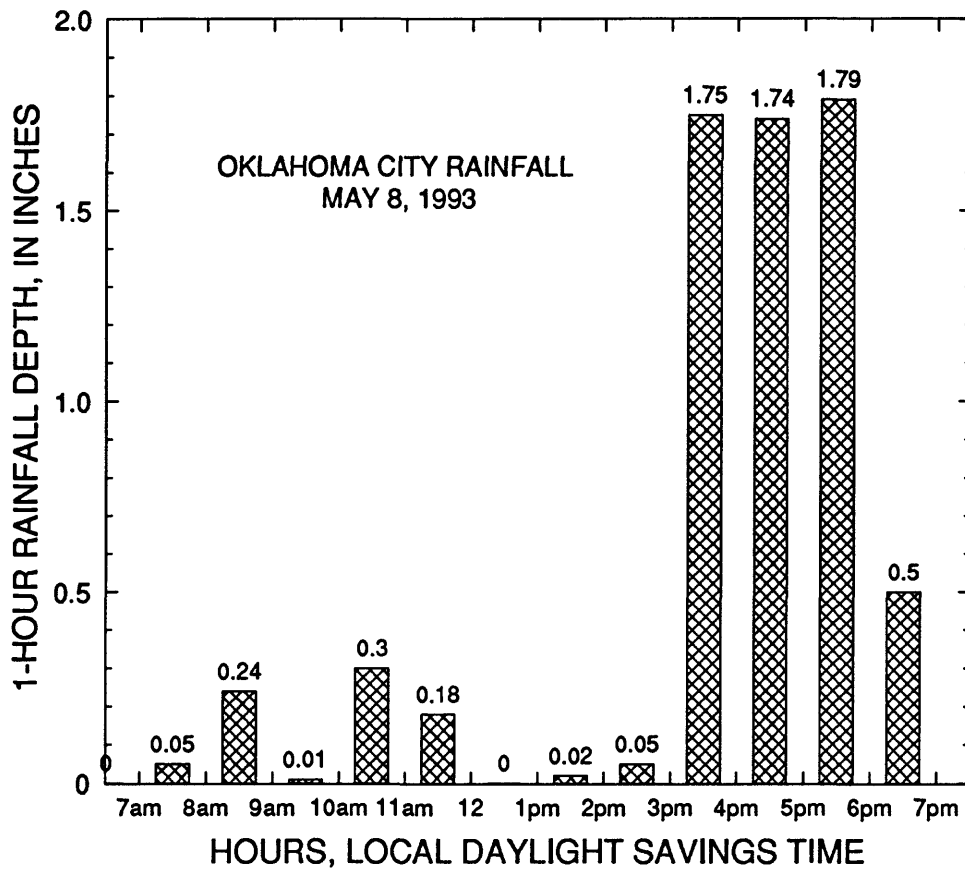


Figure 2. One-hour rainfall depths at Will Rogers Airport, Oklahoma City, Oklahoma, (data from the National Oceanic and Atmospheric Administration, 1993).

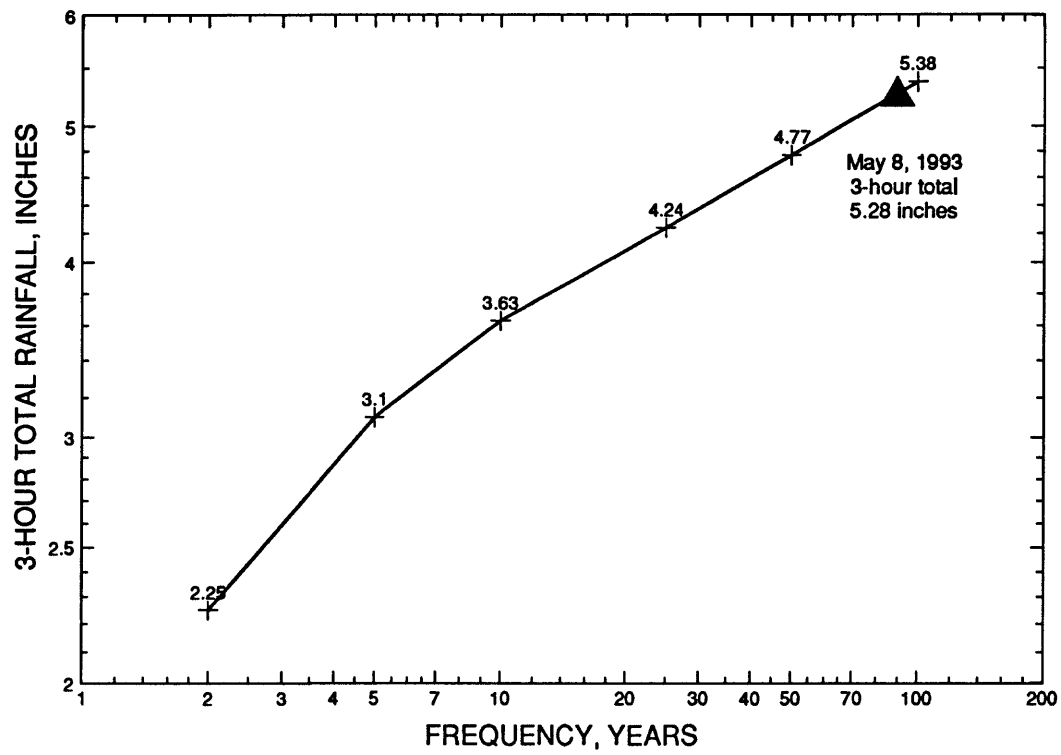


Figure 3. Three-hour storm-rainfall frequency for Oklahoma City, Oklahoma, (data from Hershfield, 1961 and National Oceanic and Atmospheric Administration, 1993).

Table 1. Summary of May 8, 1993, flood damages to private facilities in Twin, Brock, and Lightning Creek basins

Description of private facility	Number of damaged structures ¹			
	Twin Creek	Brock Creek	Lightning Creek	Total
Homes	583	359	252	1,194
Apartment Units	0	383	0	383
Motel Units	0	14	0	14
Businesses	16	22	17	55
Other ²	200	2	84	286
Total	799	780	353	1,932

¹ Data from Brown (1993).

² Includes 1 church, 1 food bank, 1 senior citizen home, 1 highway patrol office, 82 garages and outbuildings, and 200 leased storage units

METHOD OF INVESTIGATION

Many peak discharges must be determined after the passage of the flood by indirect methods (Benson and Dalrymple, 1967). This study used step-backwater analysis to match the flood water-surface profiles defined by high-water marks.

Streamflow volume or discharge is usually measured by means of a current meter. Techniques of making current-meter or direct measurements are standardized and well known (Carter and Davidian, 1968). During floods, however, it is frequently impossible or impractical to measure the peak discharges when they occur. Roads may be impassable; knowledge of the flood rise may not be available in advance to permit reaching the site near the time of the peak; structures from which current-meter measurements might have been made may be nonexistent or impassable; personnel may not be available to obtain direct measurements at numerous locations; or the peak may be of such short duration that a satisfactory current-meter measurement could not be made.

Indirect measurements use the energy equation to estimate discharge. The specific equations used dif-

fer for specific flow situations, but all methods involve these general factors (Benson and Dalrymple, 1967):

1. Physical characteristics of the channel: dimensions and conformation of the channel within the reach studied.

2. Water-surface elevations at the time of peak stage to define the upper limit of the cross-sectional areas and the fall of the water surface between two adjacent cross sections.

3. Hydraulic factors based on physical characteristics, water-surface elevations, and discharge, such as roughness coefficients and discharge coefficients.

The data required for computation of discharge by indirect methods are obtained by a field survey of a reach of channel. This includes the elevation and location of high-water marks corresponding to the peak water-surface elevation, cross sections of the channel along the reach, selection of the roughness coefficients, and description of the geometry of any culverts or bridges in the reach.

Field Survey

The field survey was conducted by U.S. Geological Survey personnel using a Geodimeter 440 total sta-

tion¹. The vertical and horizontal control for the survey of the study sites was based on the FEMA reference mark RM 12-30A, Twin Creek at SW 44th Street (Federal Emergency Management Agency, 1990). All other FEMA reference marks near the study sites were destroyed prior to May 8, 1993. A baseline traverse was surveyed along SW 44th Street. Additional traverse lines were surveyed from this baseline to the other sites. Additional vertical elevation reference marks were established and are listed in table 2. A check with 1990 Oklahoma City Global Positioning System survey control monuments revealed a difference of about 0.5 foot with the original FEMA reference mark (table 3). The horizontal control was based on an arbitrary datum of 10,000 feet northing and 10,000 feet easting and a magnetic azimuth of 262° down SW 44th Street at RM 12-30A. The entire study was completely integrated both vertically and horizontally.

High-Water Marks

High-water marks are evidence of the highest elevation reached by the flood. There are many different types of marks including seed lines and mud lines on fences, trees, posts, and buildings; and drift on bushes, and stream banks. The proper identification of the marks requires experience, and should be accomplished as quickly as possible after the flood so as not to be lost to subsequent rains.

There are two labels on the high-water marks identified in this study. A field crew dispatched two weeks after the flood marked high-water marks with nails, lumber crayons, paint, stakes, and flagging. These were recorded in site notes and are referred to as flagged high-water marks. The survey crew, which surveyed from July through October 1993, noted and surveyed several additional high-water marks while in the process of surveying the study sites. These were high-quality marks of seed or mud lines on buildings, or were elevations pointed out by local residents. These are referred to as unflagged high-water marks.

Several high-water marks on both banks were identified throughout the study reaches for a considerable distance upstream and downstream from the

bridge or culvert at the major urban street at each site to assist in the interpretation of the profiles. Plan views were plotted of each study site to assign stream stationing locations of all high-water marks on the stream profile. Stream stationing is the longitudinal distance along the stream channel from a reference point, in this study the distance upstream from the stream mouth. As was expected, there was a certain amount of scatter in the high-water mark profile. The slope determined by these high-water marks is probably very nearly parallel to that of the water-surface elevation at the time of the flood peak (Benson and Dalrymple, 1967).

Cross Sections

Cross sections were surveyed at each study site, including the geometry of bridges and culverts. Several cross sections were used at each study site to properly represent the cross-sectional geometry of the reach and thus ensure a good definition of the water-surface profile. There were two to three times as many cross sections used in this study than were used in the FEMA flood-insurance study (1990), and each cross section had at least two times as many points defining the cross section. The cross sections also are believed to be more accurate since they were all ground-surveyed instead of defined by aerial photographs as was done in the original FEMA flood-insurance study. Care was taken to locate the cross sections as nearly as possible at right angles to the direction of flow. Since many of the study sites were highly urbanized, the location of buildings were modeled on several cross sections so that the buildings could be included in the hydraulic models.

Photographs were taken at the time of the field survey at cross-sectional locations to aid in the determination of roughness coefficients. Recent digital aerial photographs were utilized to ensure average conditions were modeled when choosing roughness coefficients.

Plan views of each study site were plotted to determine the stream stationing locations of the cross sections on the stream profiles. Care was taken to match stream stationing used in the FEMA flood-insurance study to allow later comparisons. Appendices contain the plan view of each study site showing

¹. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Table 2. Elevation reference marks established during the study

[ft, feet; NGVD, National Geodetic Vertical Datum of 1929]

Site number	Stream name and location	Reference mark	Elevation (ft, NGVD) ¹	Description of location
Twin Creek				
1	SW 29th Street	RM 93-TN01	1,219.77	Chiseled "□" on the top of the southeast wingwall next to south (upstream) headwall of the Twin Creek SW 29th Street culvert.
2	SW 44th Street	RM 12-30A ²	1,235.85	Chiseled "X" on the center of the north (downstream) headwall of the Twin Creek SW 44th Street culvert.
Brock Creek				
3	SW 29th Street	RM 93-BK02	1,204.22	Chiseled "□" 10 feet east of the west end of the south (upstream) headwall of the Brock Creek SW 29th Street culvert.
		RM 93-BK04	1,204.10	Chiseled "□" on the east end of the north (downstream) headwall of the Brock Creek SW 29th Street culvert.
		RM 93-BK05	1,203.93	Chiseled "X" on the center of the north (downstream) headwall of the Brock Creek SW 29th Street culvert.
4	SW 44th Street	RM 93-BK01	1,221.63	Chiseled "X" on the center of the south (upstream) headwall of the Brock Creek SW 44th Street culvert.
5	SW 59th Street	RM 93-BK03	1,243.68	Chiseled "X" on the center of the south (upstream) headwall of the Brock Creek SW 59th Street culvert.
Lightning Creek				
6	SE 25th Street	RM 93-LG07	1,186.12	Chiseled "X" on the south wingwall 7 feet east of the east (downstream) headwall of 4-opening exit of the Lightning Creek SE 25th Street culvert.
7	SW 29th Street	RM 93-LG06	1,196.32	Chiseled "□" on the northeast corner of the north (downstream) walkway of the Lightning Creek SW 29th Street bridge.
8	Grand Avenue	RM 93-LG05	1,199.64	Chiseled "□" on the top of the northeast corner of the north (downstream) curb of the Lightning Creek Grand Boulevard bridge.
9	SW 44th Street	RM 93-LG01	1,206.34	Chiseled "□" on the northeast corner of the north (downstream) walkway of the Lightning Creek SW 44th Street bridge.
		RM 93-LG02	1,197.90	Chiseled "□" on the southeast corner of the east (upstream) walkway of the Lightning Creek Santa Fe Avenue bridge at SW 41st Street.
10	Sage Street	RM 93-LG03	1,206.12	Chiseled "□" on the northeast corner of the east (downstream) walkway of the Lightning Creek Sage Street bridge.
11	SW 51st Street	RM 93-LG04	1,207.25	Chiseled "□" on the southwest corner of the south (upstream) walkway of the Lightning Creek SW 51st Street bridge.

¹ NGVD is used to be consistent with previous flood-insurance study data.² Original flood study reference mark, study elevations based on this mark.

Table 3. Vertical control elevations established during the study and two 1990 City of Oklahoma City Global Positioning System control monuments

[ft, feet; GPS, Global Positioning System; NGVD, National Geodetic Vertical Datum of 1929]

City of Oklahoma City GPS control monuments	GPS elevation (ft, NGVD) ¹	Study elevation (ft, NGVD) ¹	Description of location
Station no.			
260	1,234.09	1,233.50	Monument cap 2,250 ft east of the intersection of Western Avenue and SW 44th Street 11.31 feet north of north SW 44th Street curb.
285	1,249.91	1,249.44	Monument cap 1,050 ft east of the intersection of May Avenue and SW 44th Street about 2 feet north of south end of private drive island in line with north SW 44th Street curb.

¹- NGVD is used to be consistent with previous flood-insurance study data.

cross sectional stream stationing followed by cross-sectional plots. Appendices 1 and 2 have Twin Creek sites (site 1-2), appendices 3-5 have Brock Creek sites (sites 3-5) and appendices 6-10 have Lightning Creek sites (sites 6-11).

Step-Backwater Analysis

The peak discharges on the study sites were determined by using step-backwater analysis to match the water-surface profile defined by the high-water marks, essentially a curve-fitting technique. The technique is an iterative process where several stage-discharges are modeled until the best fit is achieved.

Almost all open-channel flows are both unsteady (depth at a point varies with time) and nonuniform (depth changes from point to point along a channel). Steady, uniform flow is assumed for step-backwater analysis. The assumption of steadiness is justified by the fact that at peak flows the discharge hydrograph flattens out and flow approximates steady conditions even though these peak flows were of short duration (less than 1 hour). High-water marks are left along the channel by these relatively steady, peak flows. Uniformity of flow is achieved by dividing the channels into shorter lengths that are considered reasonably uniform between cross sections, both on the basis of high-water marks and on channel geometry (Davidian, 1984).

Step-backwater analysis has been long recognized as a valid method in estimating stage-discharge relations in natural channels (Bailey and Ray, 1966; Druse, 1982). Davidian (1984) recognized that it is an acceptable technique for indirect measurements in natural channels. The study sites have all or part of the reach in heavily urbanized areas, including frequent bridges or culverts. Step-backwater analysis was used to conduct the FEMA (1990) City of Oklahoma City flood-insurance study and has the capability to model bridges and culverts. Therefore, it is reasonable to use the method to estimate the discharge associated with the water-surface profile of the May 8, 1993, flood.

The step-backwater computer program used for the study is WSPRO (a computer model for Water Surface PROfile computations, Shearman, 1990). Several cross sections were used at each study site to ensure a good definition of the tailwater downstream of the culverts or bridges at the major urban street locations of the study sites and a good definition of the headwater in the ponded conditions upstream of these structures. Emphasis was placed on matching the computed water-surface profile to the high-water marks upstream of the structures, because the structures probably provide the most reliable control of the urban stage-discharge relations.

Care was taken in the subdivision of roughness coefficients in cross-sectional subsections as recommended by Davidian (1984). There was an extreme

variance in roughness in most of the study cross sections, ranging from smooth concrete to dense trees and underbrush. This requires a large number of subsections, and these conditions produce very large velocity head coefficients (alphas) if left uncorrected in the computer model. Large velocity head coefficients result in a lower than reasonable water-surface profile or higher estimated flood discharge. Where this was a concern, the roughness coefficients of the main channel subsections were composited, or weighted by cross-sectional area at flood elevation, to produce a single roughness coefficient and subsection. This method also was used in the overbank subsections, if deemed necessary.

The buildings were coded into the geometry of several of the study cross sections to accurately model the urban cross-sectional conditions. The buildings were thus superimposed on the basic shape of the cross sections. This was done to ensure that both the reduced cross-sectional areas and the very large wetted perimeters actually present would be modeled. The plots of the cross sections used in the study are presented in the appendices.

To ensure that the cross-section stationing of the cross-sectional points was the most accurate possible, a computer program written by David Dunn (written commun., 1994) was used. Cross-section stationing is the horizontal distance along the cross-section line from an arbitrary reference point. The program converts the cross-sectional point output from the Geodimeter 440 total station to a WSPRO format and trigonometrically fits all points to a straight line defined by the end points of the cross section. This ensures accurate cross-sectional area computation.

The starting discharge for each high-water mark water-surface elevation at the furthest downstream cross section was computed by the slope-conveyance method (Shearman, 1990) at all study sites in Twin and Brock Creeks (sites 1-5). The FEMA flood insurance study streambed slope was used (Federal Emergency Management Agency, 1990). The sites were too far apart to run each creek as a single reach.

The Lightning Creek study sites (sites 6-11) were run essentially as a continuous reach since they were close enough together to model in sufficient detail, but discharge was permitted to change within the overall reach. The starting discharge for the high-water mark water-surface elevation at the furthest downstream cross section of the furthest downstream study site (site 6) was computed by the slope-convey-

ance method. Then each site upstream (sites 7-11) utilized the last cross section of the study site downstream as the starting water-surface elevation. A slope-conveyance computation was run on sites 7-11 as a check to ensure this water-surface elevation was reasonable.

At each of the culvert sites (sites 1-6), WSPRO culvert routines were run separately using the high-water marks as tailwater and headwater elevations and then those discharges were subtracted from total discharge to obtain over-the-road flows. Bridge routines were tried at those sites with bridges (sites 6-11). If excessive road overflow warning messages were given in the WSPRO output (at all sites except site 9), road and bridges were treated as a composite section (Shearman, 1990).

Maximum Urban Discharge Estimates

The maximum urban discharge estimates that were compared with the May 8, 1993, peak discharge estimates were derived by using the urban regression equations described in Thomas and Corley (1977). The urban peak discharge estimates can be interpolated between the rural peak discharge estimates (lower limiting discharges) and the peak discharge estimates for a completely developed urban basin (upper limiting discharges). This interpolation for intermediate stages of development is based on an urban adjustment factor, R_L , defined by Leopold (1968) as a ratio of the urban 2-year peak discharge to the rural 2-year peak discharge. Figure 4, adapted from Leopold (1968) by Sauer (1974), illustrates the relationship between R_L and the percentage of the basin that is: (1) impervious and (2) served by storm sewers.

The rural or undeveloped flood peak discharge estimates ($R_L=1$) can be estimated from Thomas and Corley (1977). Full urban development discharges in Oklahoma City stream basins were previously estimated using $R_L=4.1$ (Tortorelli and others, 1983). The completely developed urban flood discharges may be computed using $R_L=7$, which assumes 100-percent runoff (Tortorelli and others, 1983).

Figure 4. Relationship of Leopold Urban Adjustment Factor, R_L , to the percentage of the area impervious, and served by storm sewer (Adapted from Leopold, 1968).

ESTIMATED FLOOD PEAK DISCHARGES

The rate of discharge of a stream is the volume of water that passes a given location in a specific period of time. The peak discharge rates at the selected study locations are expressed in cubic feet per second (ft^3/s) and represent the discharge occurring at the time of maximum flood stage (water-surface elevation).

Flood peak discharges for the May 8, 1993, flood estimated for the 11 study sites along Twin, Brock, and Lightning Creeks by indirect methods using step-backwater analysis ranged from 6,000 ft^3/s for Twin Creek at SW 44th Street (site 2) to 15,000 ft^3/s for Lightning Creek from SE 25th Street to Grand Avenue (sites 6-8). Unit discharge, which generally is expressed in cubic feet per second per square mile [$(\text{ft}^3/\text{s})/\text{mi}^2$], is an indication of runoff intensity. Unit discharges during peak runoff ranged from 881 $(\text{ft}^3/\text{s})/\text{mi}^2$ for Lightning Creek at SW 44th Street (site 9) to 3,570 $(\text{ft}^3/\text{s})/\text{mi}^2$ for Brock Creek at SW 59th Street (site 5). Flood peak discharges, with corresponding unit discharges for each of the 11 sites, are listed in table 4.

Recurrence interval, as applied to floods, is the average interval of time a given flood magnitude will be equaled or exceeded once. For example, a flood with a 100-year recurrence interval has a 1 in 100 chance, on the average, of occurring in any given year, or an average frequency of 1 in 100 years. The fact that a major flood occurs in one year does not decrease the probability of a flood as great or greater occurring within the same year. Similarly, if a 100-year flood occurs in a given year, there is still a 1 in 100 chance that a similar flood will occur in subsequent years. Peak discharges and flood profiles for the 100-year flood have been developed and published in the Flood Insurance Study for the City of Oklahoma City (Federal Emergency Management Agency, 1990).

Flood peak discharges for the May 8, 1993, flood determined for the 11 study sites were compared by ratio to those discharges used to develop the FEMA 100-year flood profiles. At all sites the peak discharges exceeded the FEMA 100-year flood discharges. The 100-year flood peak discharge comparisons (table 4) ranged from 1.25 (site 9) to 3.29 (site 1).

The water-surface elevations for the May 8, 1993, flood for the 11 study sites were compared to those of the FEMA 100- and 500-year flood profiles (table 5). The May 8, 1993, flood water-surface eleva-

tions ranged from 0.2 ft (site 4) to 5.9 feet (site 8) above the FEMA 500-year flood water-surface elevations. At all sites the flood water-surface elevations exceeded the FEMA 500-year water-surface elevations.

The flood peak discharges for the May 8, 1993, flood determined for the 11 study sites were compared to the maximum urban discharge estimates (table 5). At all sites the peak discharges exceeded that of the 100-year flood with a $R_L=4.1$, except at site 9. At 7 of the 11 sites the peak discharges exceeded or equaled that of the 100-year flood with a $R_L=7.0$. This suggests that the very large flood peaks were the result of close to 100-percent runoff in the study stream basins. Not only were the ground surfaces essentially impervious, but the city streets acted as efficient conveyances to the main channel (similar to storm sewers or tributary channels).

Crippen and Bue (1977) developed an envelope curve on the basis of maximum floods in the Oklahoma, Texas, Missouri, and Kansas region (Region 9, p. 11). Unit peak discharges of the May 8, 1993, Oklahoma City, Oklahoma, flood and other extraordinary urban floods that have occurred in Oklahoma are compared to a modified maximum flood envelope curve (figure 5). Unit peak discharges from the Enid, Oklahoma, flood (Bingham and others, 1974) and Tulsa, Oklahoma, flood (Bergman and Tortorelli, 1988) were shown to illustrate that high unit peak discharges of similar magnitudes have occurred.

Another comparison (table 6) shows that at sites where culverts pass the flow under a major city street, the culverts were overwhelmed by the flood flows (sites 1-6). In all cases, the culverts were drowned out with submerged outlets (type 4 flow, Bodhaine, 1968). These structures had less than normal flow efficiency, forcing an even greater flow into street overflow.

The very large flood peaks in these 3 small urban creeks were the result of very intense rainfall in a short period of time, close to 100-percent runoff in the study stream basins, essentially impervious ground surfaces, and the city streets acting as efficient conveyances to the main channels. All drainage structures, culverts, and bridges were assumed to be free and unobstructed in the computation of the flood peak discharges. The high-water marks defined the flood water-surface profile and elevations; however, it is unknown to what degree the drainage structures were obstructed by such things as sections of stockade

Table 4. Summary of flood peak discharge for the flood of May 8, 1993[mi², square mile; ft³/s, cubic feet per second; (ft³/s)/mi², cubic feet per second per square mile]

Indirect discharge measurements					Oklahoma City flood-insurance study ¹		Ratio of flood peak discharge to 100-year flood-insurance study peak discharge
Site number	Stream name and location	Drainage area ² (mi ²)	May 8, 1993, flood		100-year		
			Peak discharge (ft ³ /s)	Unit discharge [(ft ³ /s)/mi ²]	Peak discharge (ft ³ /s)	Unit discharge [(ft ³ /s)/mi ²]	
Twin Creek							
1	SW 29th Street	3.23	10,000	3,100	3,040	941	3.29
2	SW 44th Street	2.73	6,000	2,200	3,040	1,110	1.97
Brock Creek							
3	SW 29th Street	4.74	12,000	2,530	5,210	1,100	2.30
4	SW 44th Street	3.24	10,000	3,090	4,040	1,250	2.48
5	SW 59th Street	2.24	8,000	3,570	2,460	1,100	3.25
Lightning Creek ³							
6	SE 25th Street	13.90	15,000	1,080	8,020	577	1.87
7	SW 29th Street	13.60	15,000	1,100	8,020	590	1.87
8	Grand Avenue	12.70	15,000	1,180	8,020	631	1.87
9	SW 44th Street	11.35	10,000	881	8,020	707	1.25
10	Sage Street	8.42	10,000	1,190	5,420	644	1.85
11	SW 51st Street	8.12	10,000	1,230	5,420	667	1.85

¹. Federal Emergency Management Agency (1990)². Determined from 7.5 minute quadrangle Digital Elevation Models, U.S. Geological Survey (1990)³. Discharges are reduced by detention ponds.

Table 5. Hydraulic data for the May 1993 flood, Oklahoma City flood-insurance study floods, and maximum urbanization 100-year floods[mi²: square mile; ft, feet; ft³/s, cubic feet per second; NGVD, National Geodetic Vertical Datum of 1929; R_L, Leopold Urban Adjustment Factor]

Site number	Stream name and location	Drainage area ³ (mi ²)	Distance ⁴ (ft)	May 8, 1993, flood			Oklahoma City flood-insurance study flood ¹				Maximum urbanization ² 100-year flood		
				Peak discharge (ft ³ /s)	Water-surface elevation (ft, NGVD) ⁵	Distance ⁴ (ft)	100-year		500-year		R _L =4.1	R _L =7.0	
							Peak discharge (ft ³ /s)	Water-surface elevation (ft, NGVD) ⁵	Peak discharge (ft ³ /s)	Water-surface elevation (ft, NGVD) ⁵			
Twin Creek													
1	SW 29th Street	3.23	17,185	10,000	1,223.3	3,040	1,221.5	4,220	1,223.0	4,370	6,210		
2	SW 44th Street	2.73	22,580	6,000	1,237.5	3,040	1,235.5	4,220	1,235.9	4,370	6,210		
Brock Creek													
3	SW 29th Street	4.74	4,440	12,000	1,206.1	5,210	1,205.0	7,000	1,205.3	6,290	8,880		
4	SW 44th Street	3.24	10,020	10,000	1,224.2	4,040	1,222.2	5,460	1,224.0	5,060	7,160		
5	SW 59th Street	2.24	16,020	8,000	1,243.8	2,460	1,239.3	3,420	1,242.9	3,530	5,020		
Lightning Creek ⁶													
6	SE 25th Street	13.90	5,150	15,000	1,194.8	8,020	1,187.2	11,200	1,192.3	10,600	15,000		
7	SW 29th Street	13.60	6,960	15,000	1,199.3	8,020	1,191.8	11,200	1,194.2	10,600	15,000		
8	Grand Avenue	12.70	9,610	15,000	1,200.5	8,020	1,192.3	11,200	1,194.6	10,600	15,000		
9	SW 44th Street	11.35	12,760	10,000	1,205.8	8,020	1,199.1	11,200	1,201.6	10,600	15,000		
10	Sage Street	8.42	14,655	10,000	1,208.9	5,420	1,201.3	7,050	1,205.0	7,760	11,000		
11	SW 51st Street	8.12	16,000	10,000	1,210.1	5,420	1,202.5	7,050	1,206.4	7,760	11,000		

1. Federal Emergency Management Agency (1990)

2. As defined in USGS Open-File Report 83-26 (Tortorelli and others, 1983)

3. From 7.5 minute quadrangle Digital Elevation Models, U.S. Geological Survey (1990)

4. Distance above mouth of stream.

5. NGVD is used to be consistent with previous flood-insurance study data.

6. Discharges are reduced by detention ponds.

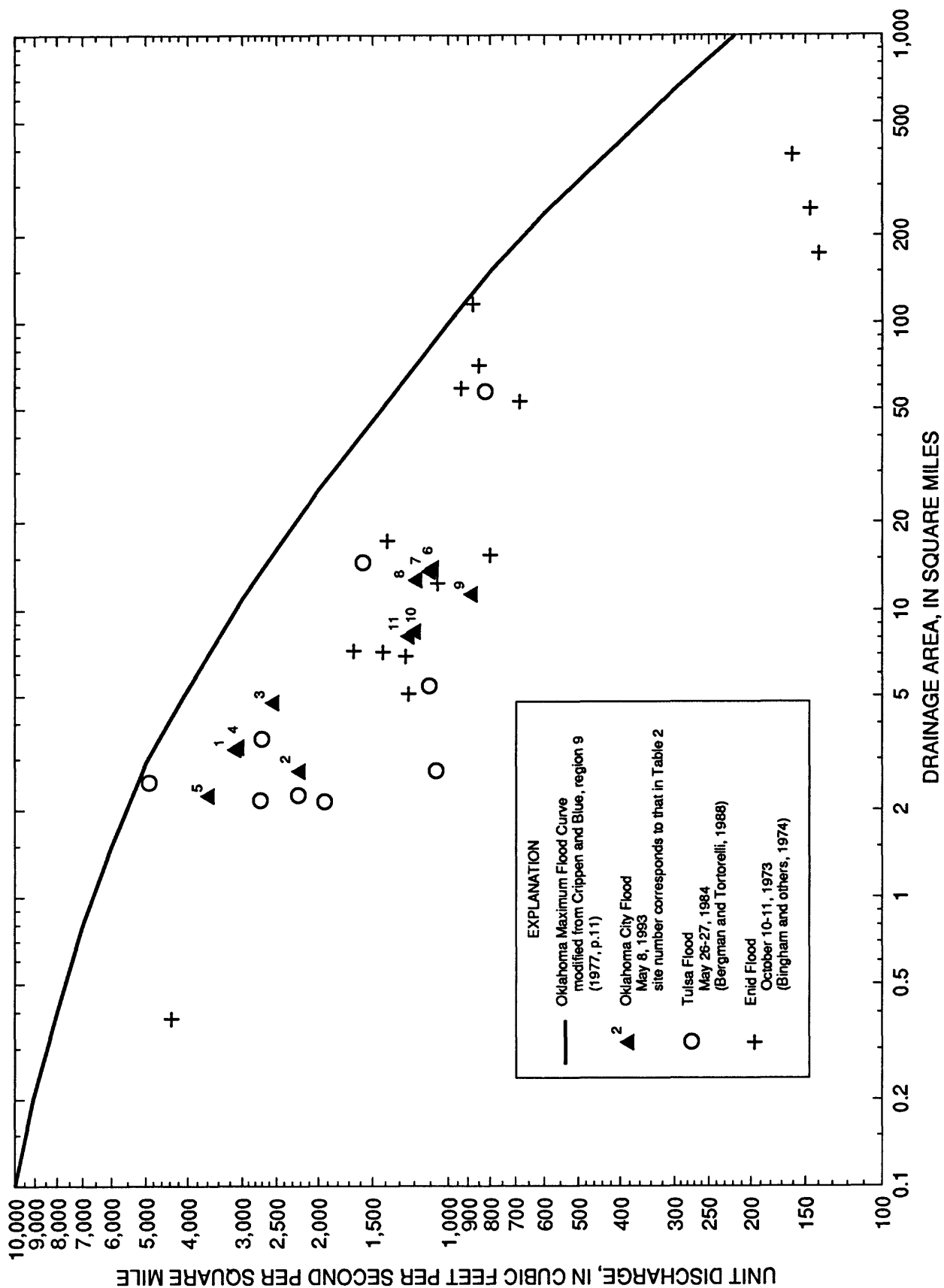


Figure 5. Relation of the May 8, 1993, unit discharge to the upper limits of measured floods in Oklahoma.

Table 6. Culvert flows and peak discharge in Oklahoma City May 1993 flood[ft, feet; ft³/s, cubic feet per second]

Site number	Stream name and location	Distance ¹ (ft)	May 8, 1993, flood	
			Culvert flows ² (ft ³ /s)	Peak discharge (ft ³ /s)
Twin Creek				
1	SW 29th Street	15,985	1,700	10,000
2	SW 44th Street	22,590	1,000	6,000
Brock Creek				
3	SW 29th Street	4,250	4,500	12,000
4	SW 44th Street			10,000
	SW 43rd Street	9,675	750	
	SW 44th Street	9,955	750	
5	SW 59th Street	15,895	1,250	8,000
Lightning Creek				
6	SE 25th Street			15,000
	Short 4-Opening	4,675	6,800	
	Long 2-Opening	3,550	3,800	
	Total		10,600	

¹. Distance above mouth of stream². Submerged outlet, Type 4 flow (Bodhaine, 1968)

fences, automobiles, and other debris that were observed floating down the creeks by local residents.

The May 8, 1993, flood water-surface profiles and the FEMA flood water-surface profiles (Federal Emergency Management Agency, 1990) differ in two aspects: the slope of the profile and the elevation of the profile. The differences can be attributed to differences in cross-sectional geometry, roughness coefficients, and number of cross sections used to define the FEMA step-backwater model. The FEMA cross sections were fewer per stream mile and were defined using aerial photography rather than land surveys.

There was no discernible pattern in the profile slope differences between the May 8, 1993, flood and the FEMA floods among the sites. The FEMA discharges for the 100-year flood were substantially less than the May 8, 1993, discharges (table 5). Along Twin Creek (figs. 6-7) and Brock Creek (figs. 8-10) the FEMA flood profiles were very close to and sometimes higher than the May 8, 1993, flood profiles. Along Lightning Creek (figs. 11-15) the FEMA flood profiles were much lower than the May 8, 1993, flood profiles.

Twin Creek

There are 2 study sites on Twin Creek: SW 29th Street (site 1), and SW 44th Street (site 2). The SW 29th Street study site was substituted for a proposed study site at Grand Avenue due to lack of high-water marks. The May 8, 1993, flood peak discharge was estimated to be 10,000 ft³/s at site 1 and 6,000 ft³/s at site 2 (table 4). The ratio of the peak discharge to that of the 100-year flood-insurance study peak ranged from 1.97 to 3.29 (table 4).

The water-surface profiles of these sites are presented in figure 6 (site 1) and figure 7 (site 2). The difference between the FEMA 500-year water-surface profiles and the May 8, 1993, flood ranged from 0.3 to 1.6 feet (table 5). Both sites have long underground culverts and had a considerable amount of overland flow in streets and buildings. Most of the flood flow at site 1 was overland between SW 27th and SW 29th Streets, and most the flood flow at site 2 was overland between SW 44th and SW 51st Streets. There is a dip in the high-water marks at site 2 above SW 44th Street that is probably due to high-water marks being identified on the fences along the alley above the concrete-capped culvert in this part of the profile. The local

velocity in this subsection was probably higher than the average profile velocity. Natural water surfaces are not level across a cross section, but step-backwater computations assume a level average water surface across a cross section.

Brock Creek

There are 3 study sites on Brock Creek: SW 29th Street (site 3), SW 44th Street (site 4), and SW 59th Street (site 5). The May 8, 1993, flood peak discharge was estimated to be 12,000 ft³/s at site 3, 10,000 ft³/s at site 4, and 8,000 ft³/s at site 5 (table 4). The ratio of the peak discharge to that of the 100-year flood-insurance study peak ranged from 2.30 to 3.25 (table 4). According to a local resident on Binkley Street, this was the highest flood in about 48 years. Another local resident, on SW 43rd Street, said this was the highest flood since 1937, when it reached Youngs Boulevard west of the channel.

The water-surface profiles of these sites are presented in figure 8 (site 3), figure 9 (site 4), and figure 10 (site 5). The difference between the FEMA 500-year water-surface elevations and the May 8, 1993, flood ranged from 0.2 to 0.9 feet (table 5). The flood flow at site 3 was mostly confined to the main channel, park land, and adjacent streets. Sites 4 and 5 had a considerable amount of overland flow in streets and buildings. Site 4 had a large amount of damage to apartment units in addition to homes downstream from SW 44th Street.

Lightning Creek

There are 6 study sites on Lightning Creek: SE 25th Street (site 6), SW 29th Street (site 7), Grand Avenue (site 8), SW 44th Street (site 9), Sage Street (site 10), and SW 51st Street (site 11). The May 8, 1993, flood peak discharge was estimated to be 15,000 ft³/s at sites 6-8, and 10,000 ft³/s at sites 9-11 (table 4). The ratio of the peak discharge to that of the 100-year flood-insurance study peak ranged from 1.25 to 1.87 (table 4). Local residents in the lower part of Lightning Creek said this was the worst flooding they had seen in 37 years. Another local resident, on SW 43rd Street, said this was the highest flood since 1945.

The flood was relatively less severe than in Twin and Brock Creeks due to less rainfall; large, improved, and well-maintained main channels (espe-

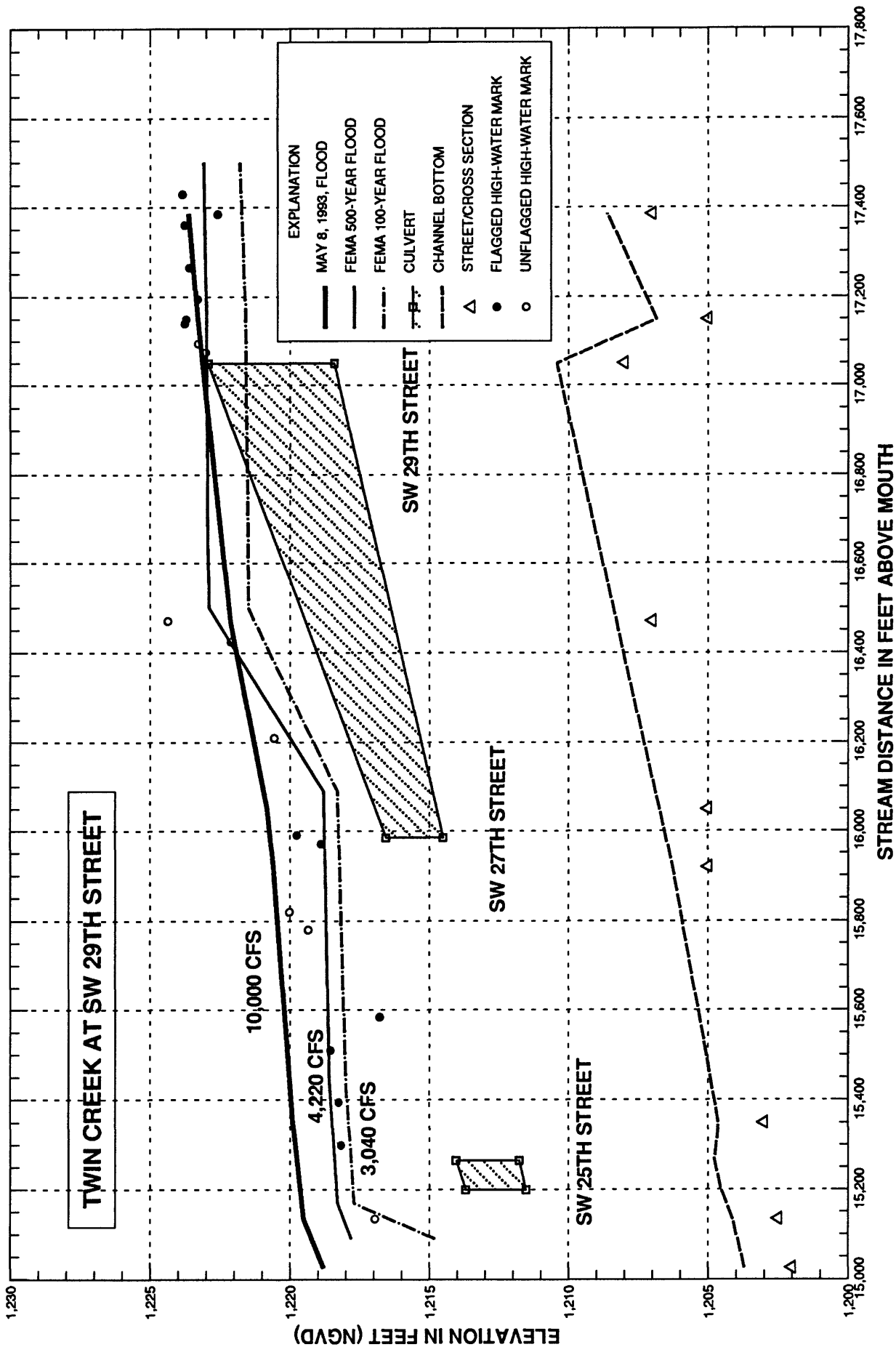


Figure 6. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Twin Creek at SW 29th Street (site 1).

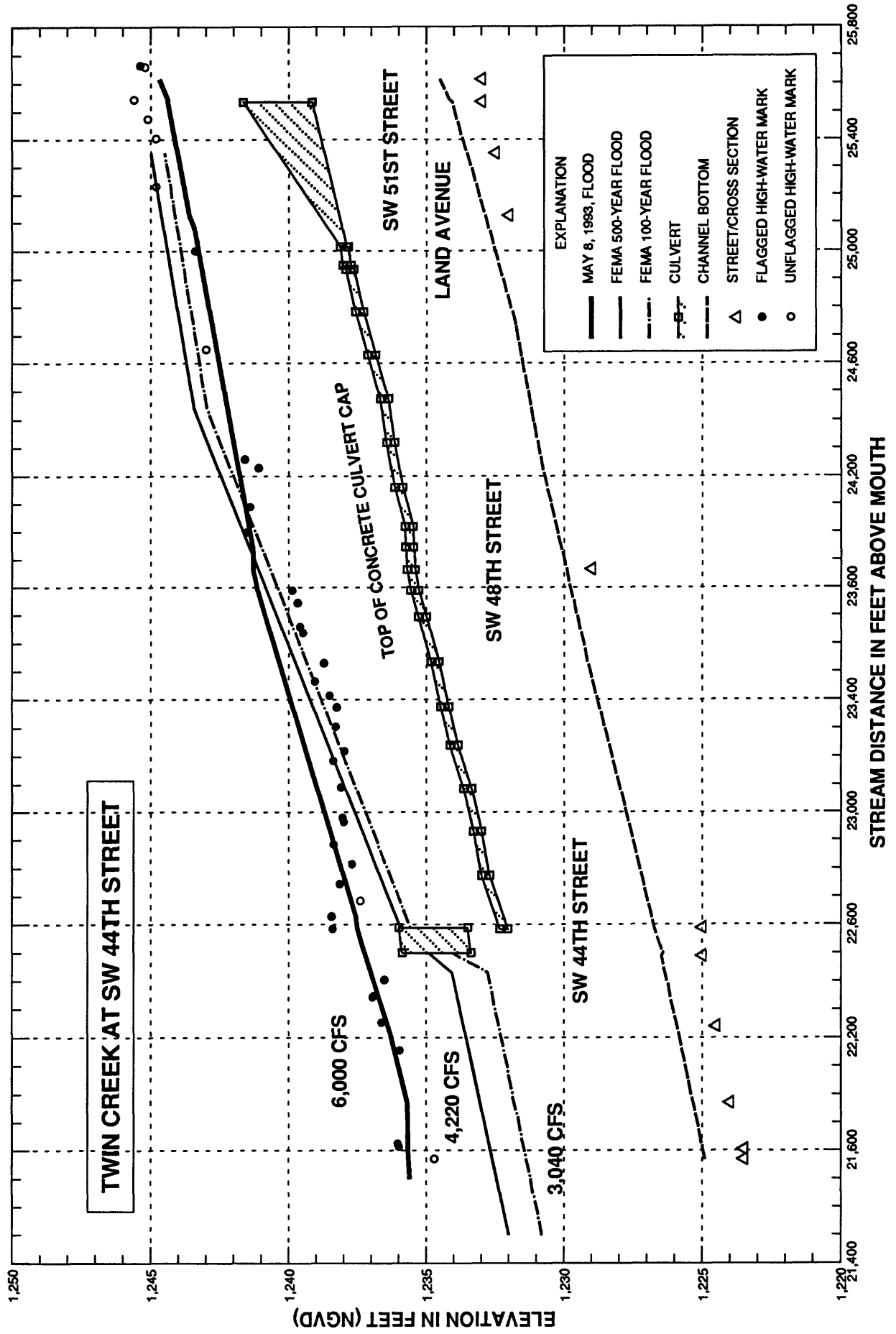


Figure 7. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Twin Creek at SW 44th and SW 51st Street (site 2).

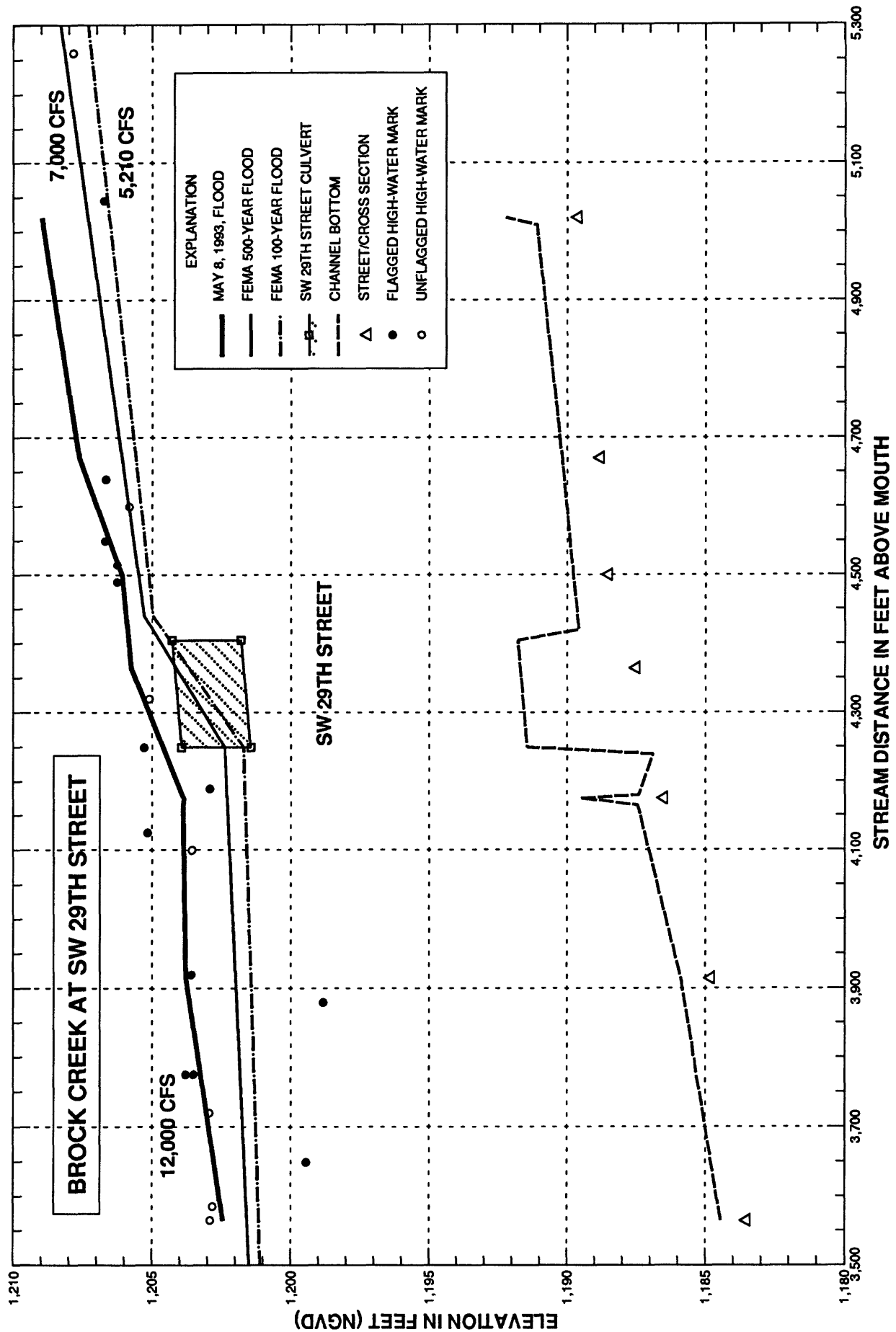


Figure 8. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Brock Creek at SW 29th Street (site 3).

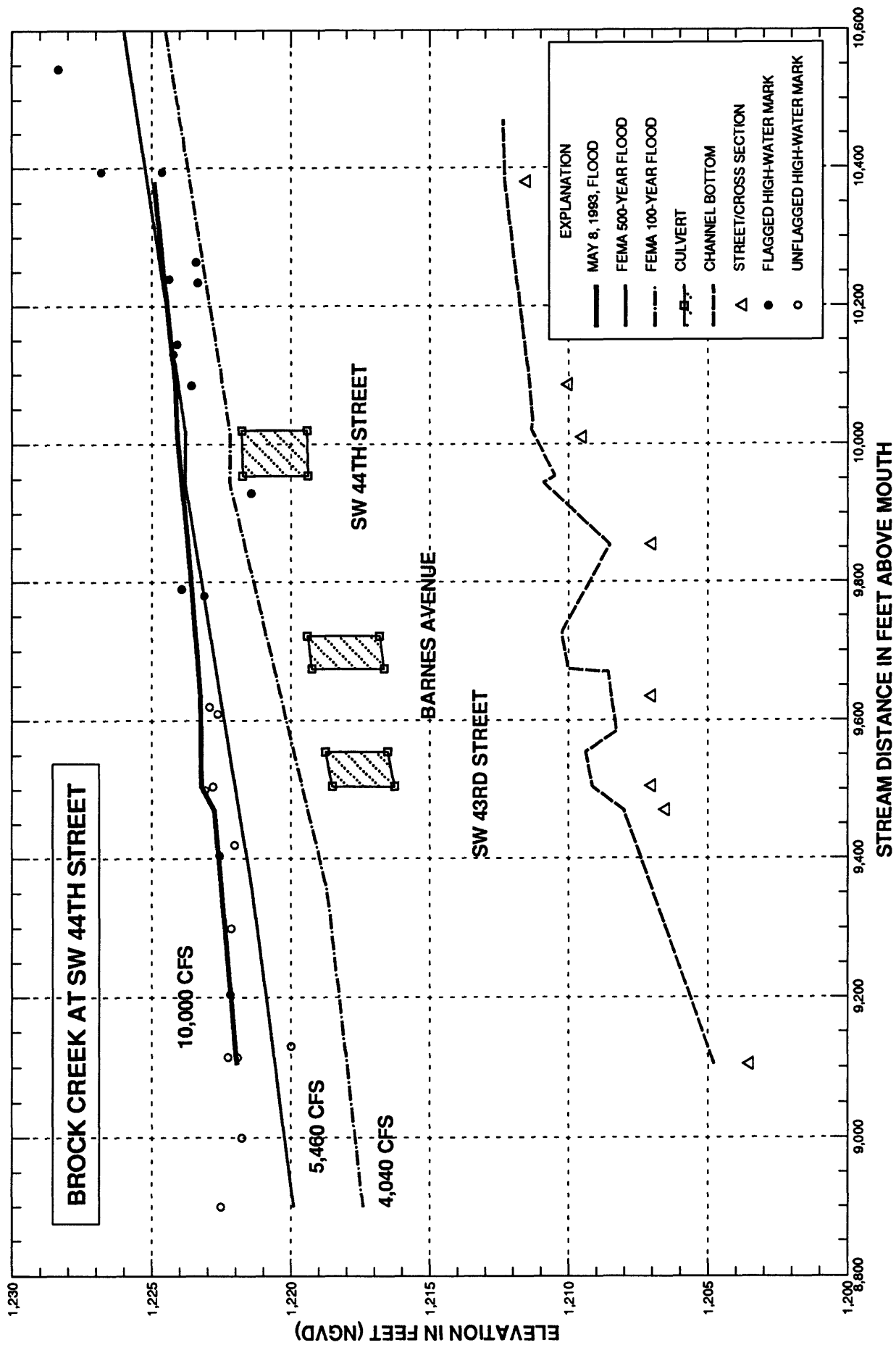


Figure 9. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Brock Creek at SW 44th Street (site 4).

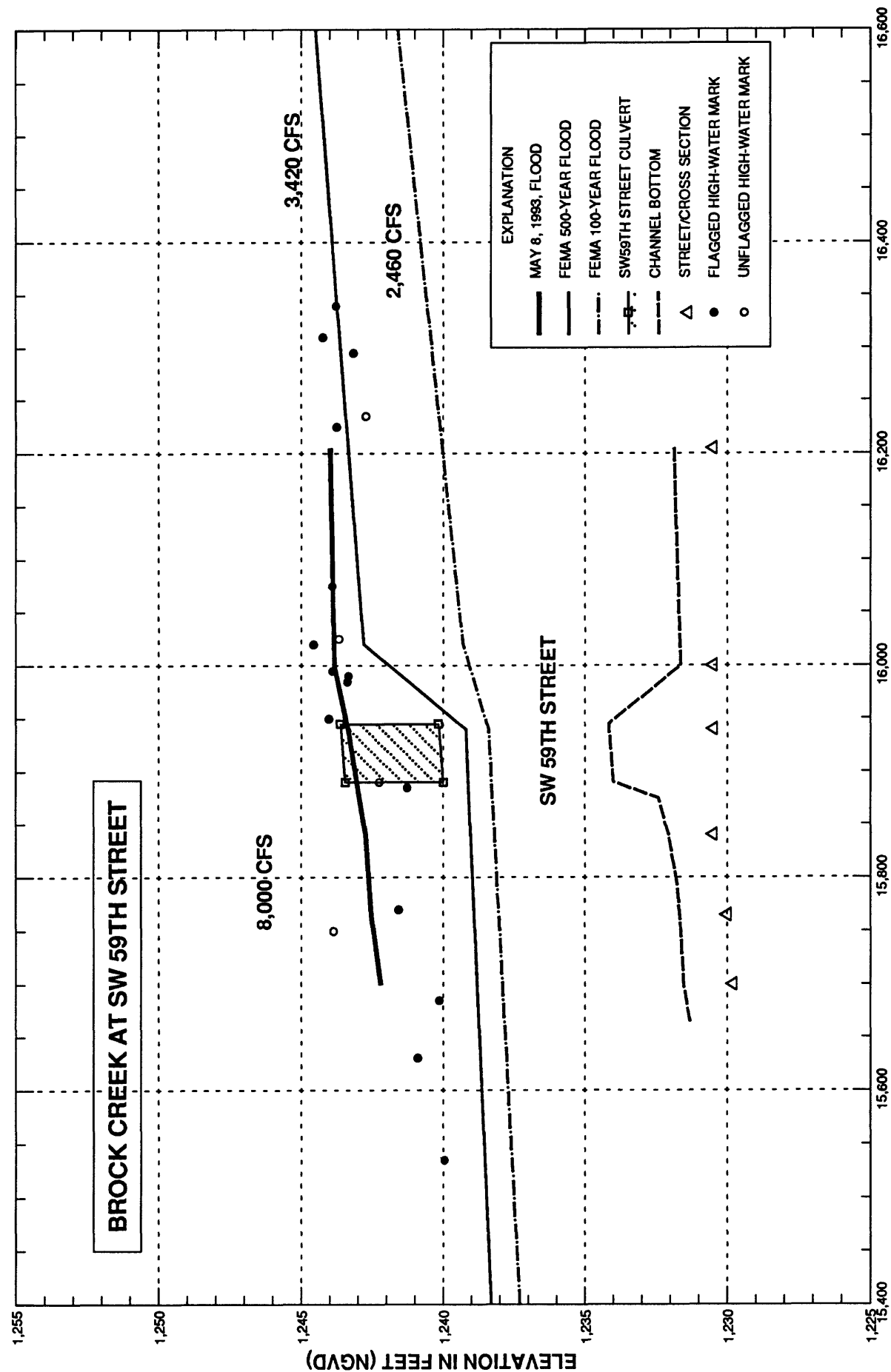


Figure 10. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Brock Creek at SW 59th Street (site 5).

cially above SW 29th Street); and detention ponds in the upper end of the drainage basin. However, there is a large constriction due to the encroachment of commercial buildings just below SW 29th Street and dense growths of trees and brush line the main channel banks starting downstream from SW 29th Street.

The water-surface profiles of these sites are presented in figure 11 (site 6), figure 12 (site 7), figure 13 (site 8), figure 14 (site 9), and figure 15 (sites 10 and 11). The difference between the FEMA 500-year water-surface profiles and the May 8, 1993, flood ranged from 2.5 to 5.9 feet (table 5). Site 6 had a large, long underground culvert with four openings that exit east of the railroad downstream from SE 25th Street and two openings that exit downstream from SE 23rd Street. Other study sites on Lightning Creek had bridges. Sites 6-8 had a considerable amount of overland flow in streets and buildings. Sites 9-11 had some overland flow in streets and buildings.

There was a major reduction of discharge between site 8 (Grand Avenue) and site 9 (SW 44th Street) from 15,000 ft³/s to 10,000 ft³/s. This was modeled by reducing the peak to 12,000 ft³/s at the last upstream cross section of site 8 and then reducing the peak to 10,000 ft³/s at the first cross section of site 9. This apparent discharge reduction shown by high-water mark data may be attributed to 3 factors: (1) there are 3 small tributaries (or large storm sewers) that enter the main channel between Grand Avenue and SW 44th Street; (2) rainfall was greater north of SW 44th Street; (3) detention structures are located on the upper end of Lightning Creek.

SUMMARY

The flash flood in southwestern Oklahoma City, Oklahoma, May 8, 1993, was the result of an intense 3-hour rainfall occurring within a 12-hour rainfall event. A total rainfall of 5.28 inches fell between 3 p.m. and 6 p.m. at Will Rogers Airport. The recorded rainfall was close to the 100-year frequency, 3-hour rainfall. This intense rainfall that fell on nearly saturated ground or impervious surfaces, was assumed to result in almost 100-percent runoff, and produced extensive flooding.

The most serious flooding was on Twin, Brock, and Lightning Creeks, tributaries to the North Canadian River. A study was conducted to determine the

magnitude of the May 8, 1993, flood peak discharge in these three creeks in southwestern Oklahoma City and compare these peaks with published flood estimates. Flood peak-discharge estimates for the May 8, 1993, flood were determined for 11 study sites along these creeks. These were determined by an indirect method using step-backwater analysis to match the flood water-surface profiles defined by high-water marks.

Four people died in this flood. Three deaths were attributed to the flooding in Brock Creek, and one death occurred on Lightning Creek. Over 1,900 structures were damaged in the 3 basins, of which about 1,200 were homes. In addition, there were about \$3 million in damages to Oklahoma City public facilities, the majority of which were in the three basins. Oklahoma County was declared a federal disaster area.

The unit discharge during peak runoff at the indirect-measurement sites ranged from 881 cubic feet per second per square mile [(ft³/s)/mi²] for Lightning Creek at SW 44th Street (site 9) to 3,570 (ft³/s)/mi² for Brock Creek at SW 59th Street (site 5). The ratios of the 1993 flood peak-discharges determined for the 11 study sites to those discharges used to develop the FEMA flood-insurance study 100-year flood profiles ranged from 1.25 (site 9) to 3.29 (site 1). At all sites the peak discharges exceeded the FEMA 100-year flood discharges, and the flood water-surface elevations at the study sites ranged from 0.2 ft (site 4) to 5.9 feet (site 8) above the FEMA 500-year flood water-surface elevations.

The flood peak discharges for the 11 study sites were compared to the maximum urban discharge estimates, and to extraordinary urban floods in Oklahoma. The peak discharges at 7 of the 11 sites exceeded or equaled that of the 100-year flood with a $R_L=7.0$. This suggests that the very large flood peaks were the result of close to 100 percent runoff in the study stream basins. Unit peak discharges for the 1993 flood were comparable to those for other extraordinary urban floods in Oklahoma.

The differences in profile slope and water-surface elevation between May 8, 1993, flood water-surface profiles and the FEMA flood water-surface profiles can be attributed to differences in cross-sectional geometry, roughness coefficients, and number of cross sections used to define the FEMA step-backwater model. In addition, it is unknown to what degree the drainage structures were obstructed.

The very large flood peaks in these 3 small urban basins were the result of very intense rainfall in

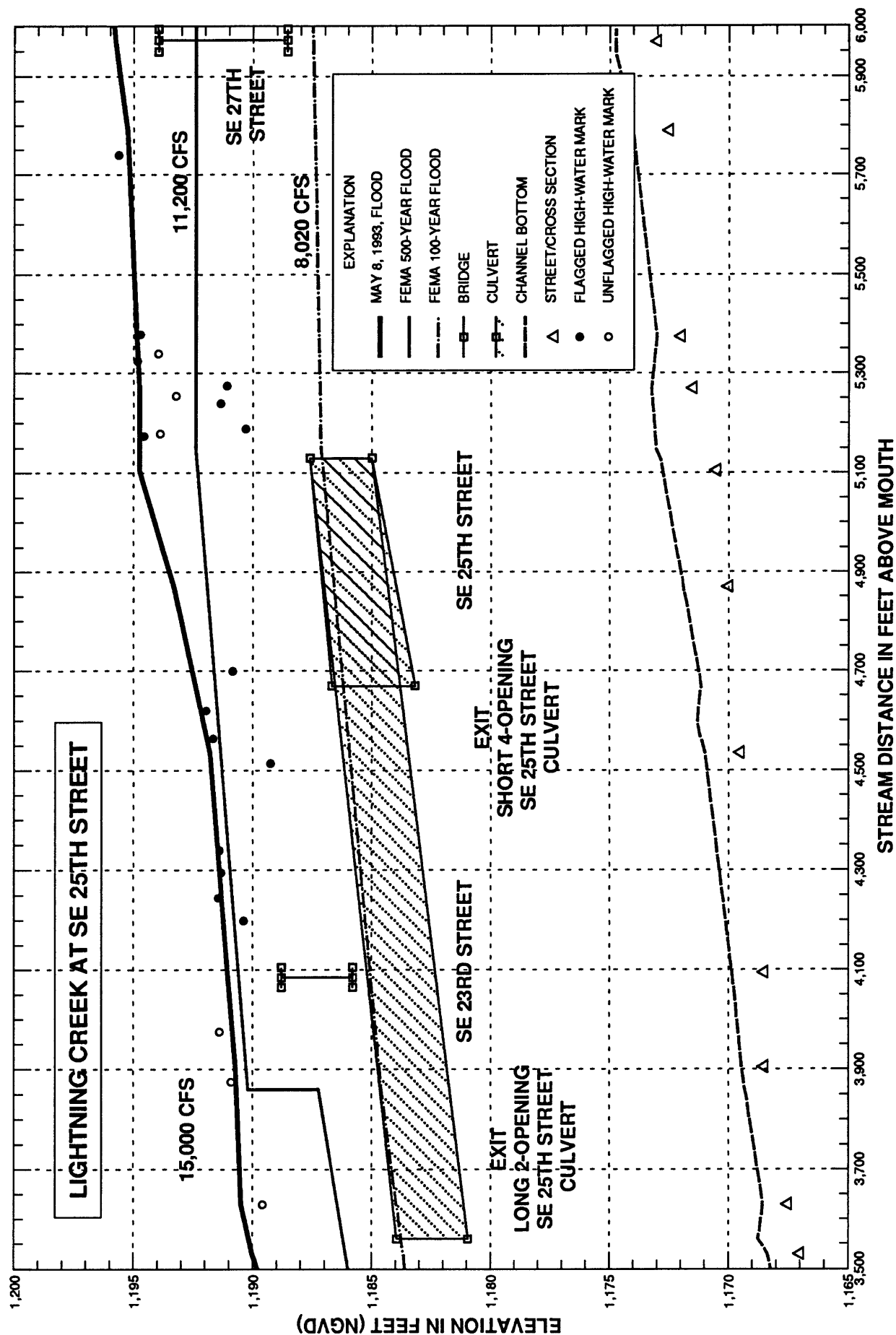


Figure 11. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Lightning Creek at SE 25th Street (site 6).

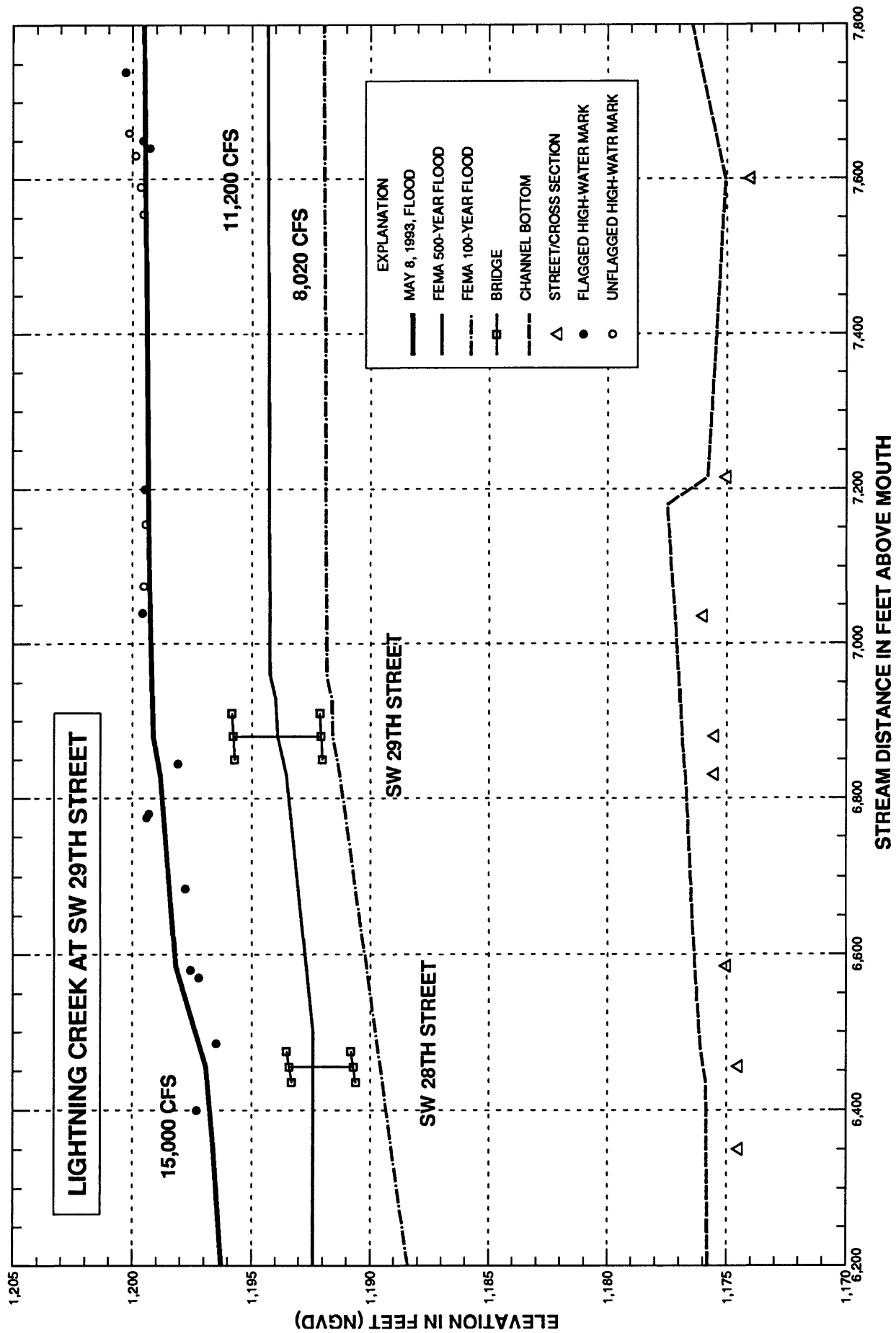


Figure 12. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Lightning Creek at SW 29th Street (site 7).

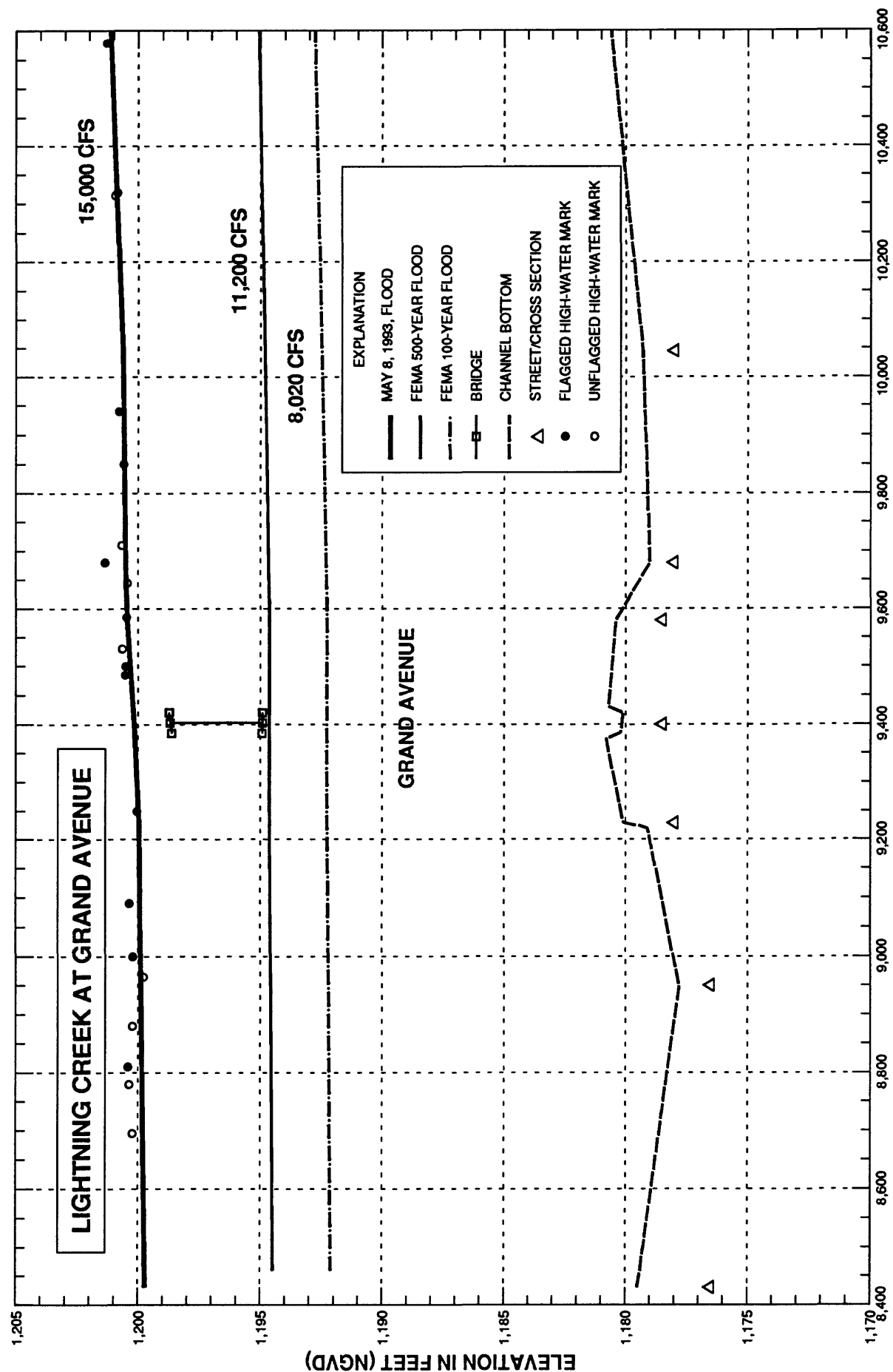


Figure 13. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Lightning Creek at Grand Avenue (site 8).

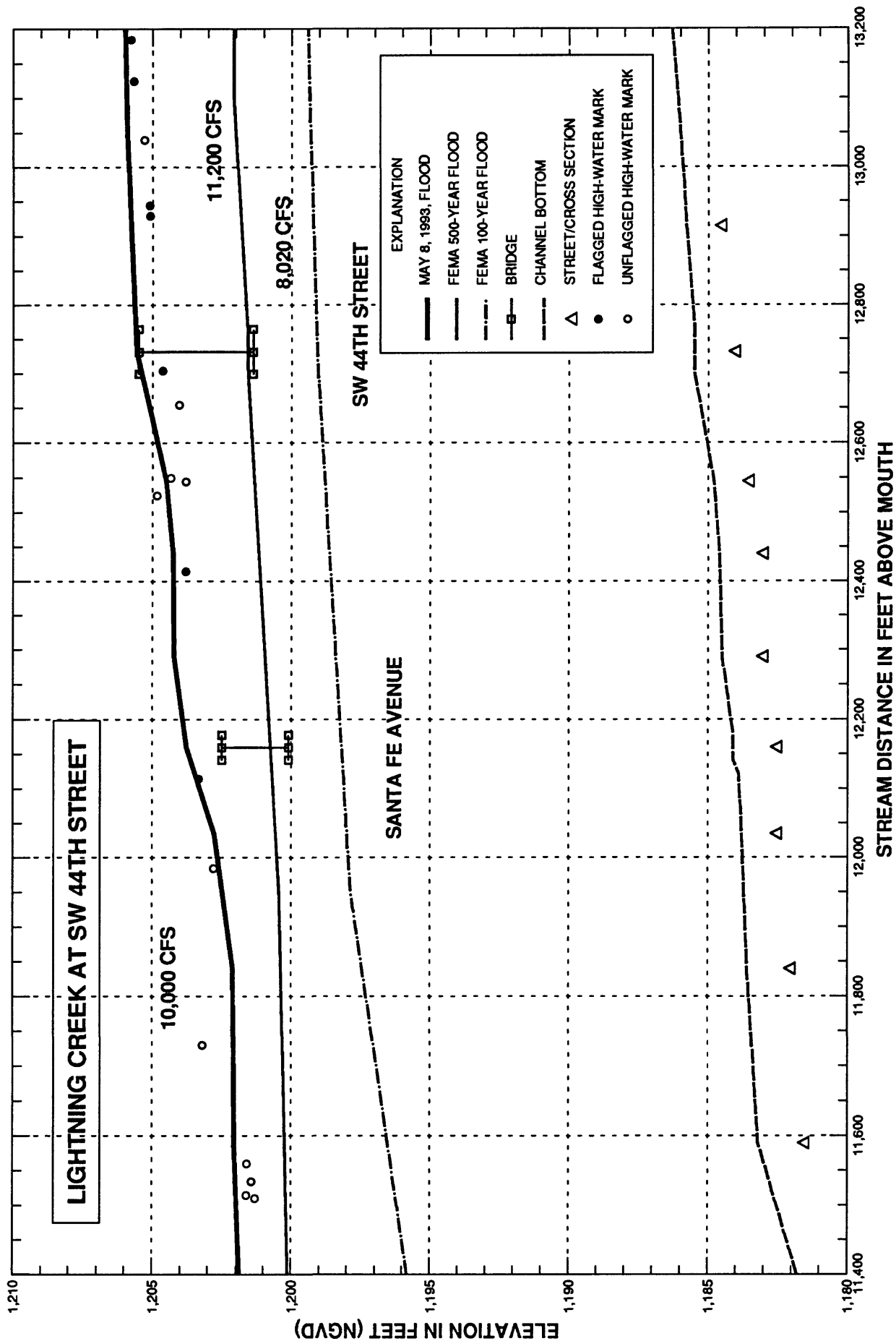


Figure 14. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Lightning Creek at SW 44th Street (site 9).

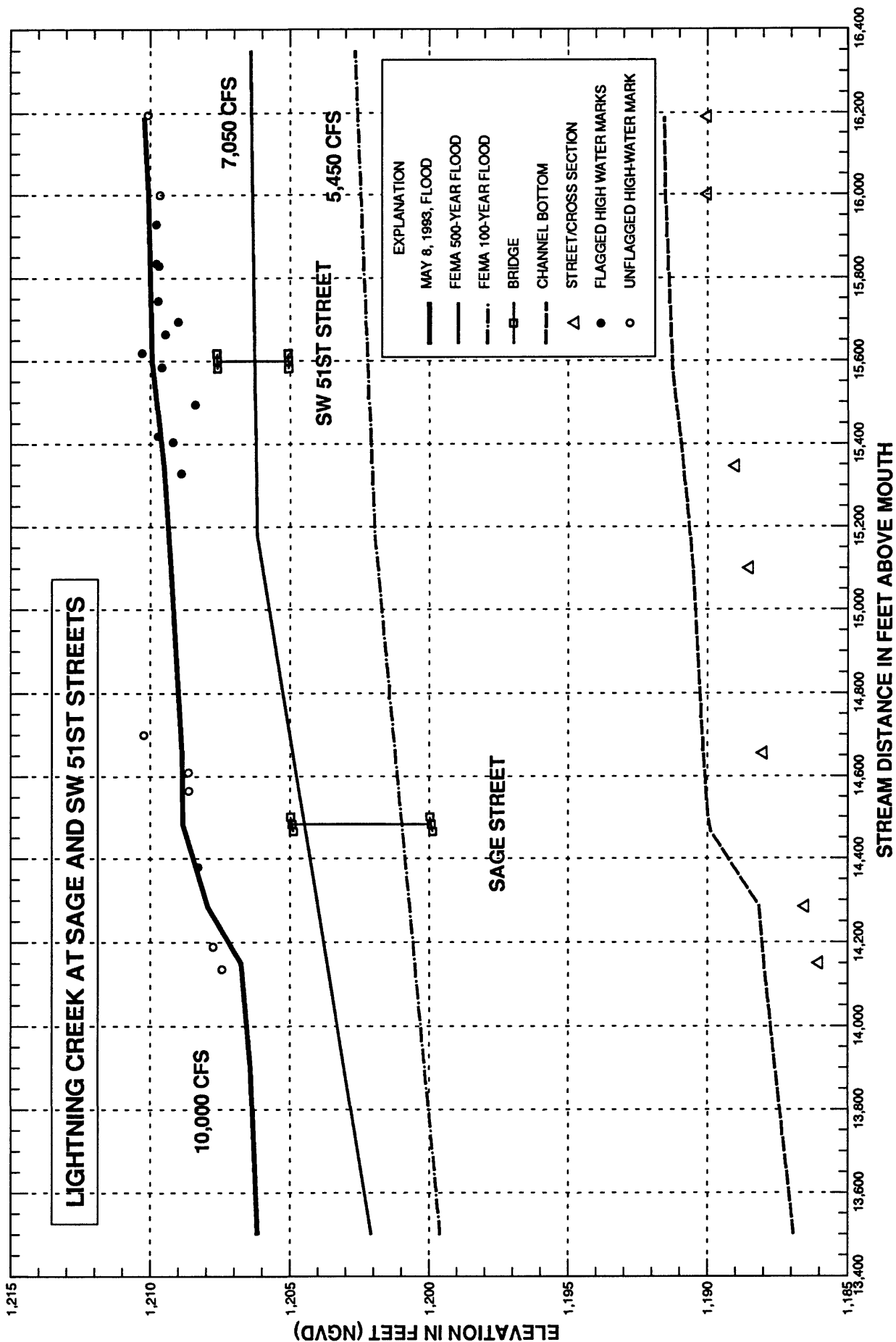


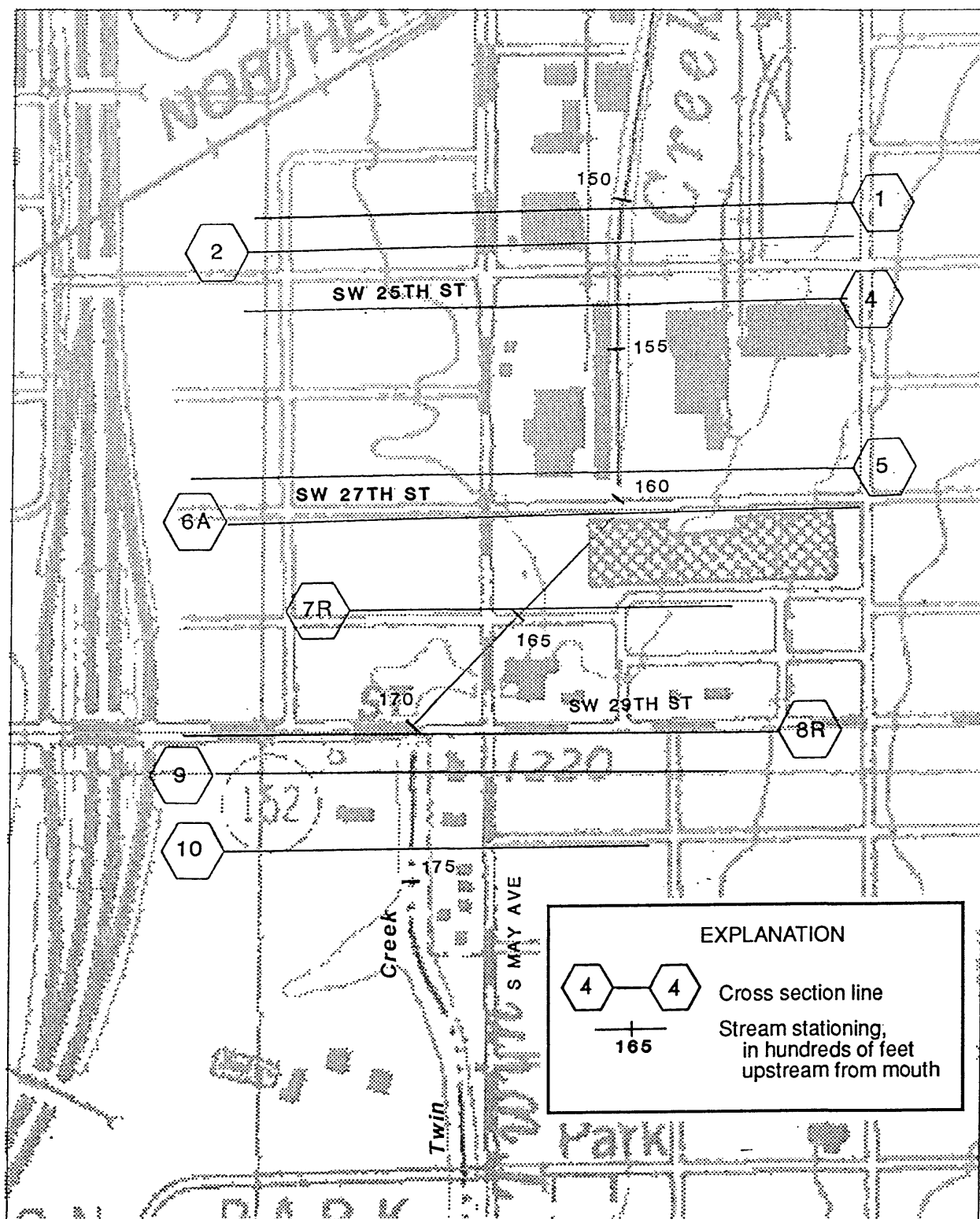
Figure 15. Oklahoma City flood-insurance study floods and May 1993 flood water-surface profiles of Lightning Creek at Sage Street (site 10) and SW 51st Street (site 11).

a short period of time, close to 100-percent runoff due to ground surfaces being essentially impervious, and the city streets acting as efficient conveyances to the main channel.

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APPENDICES

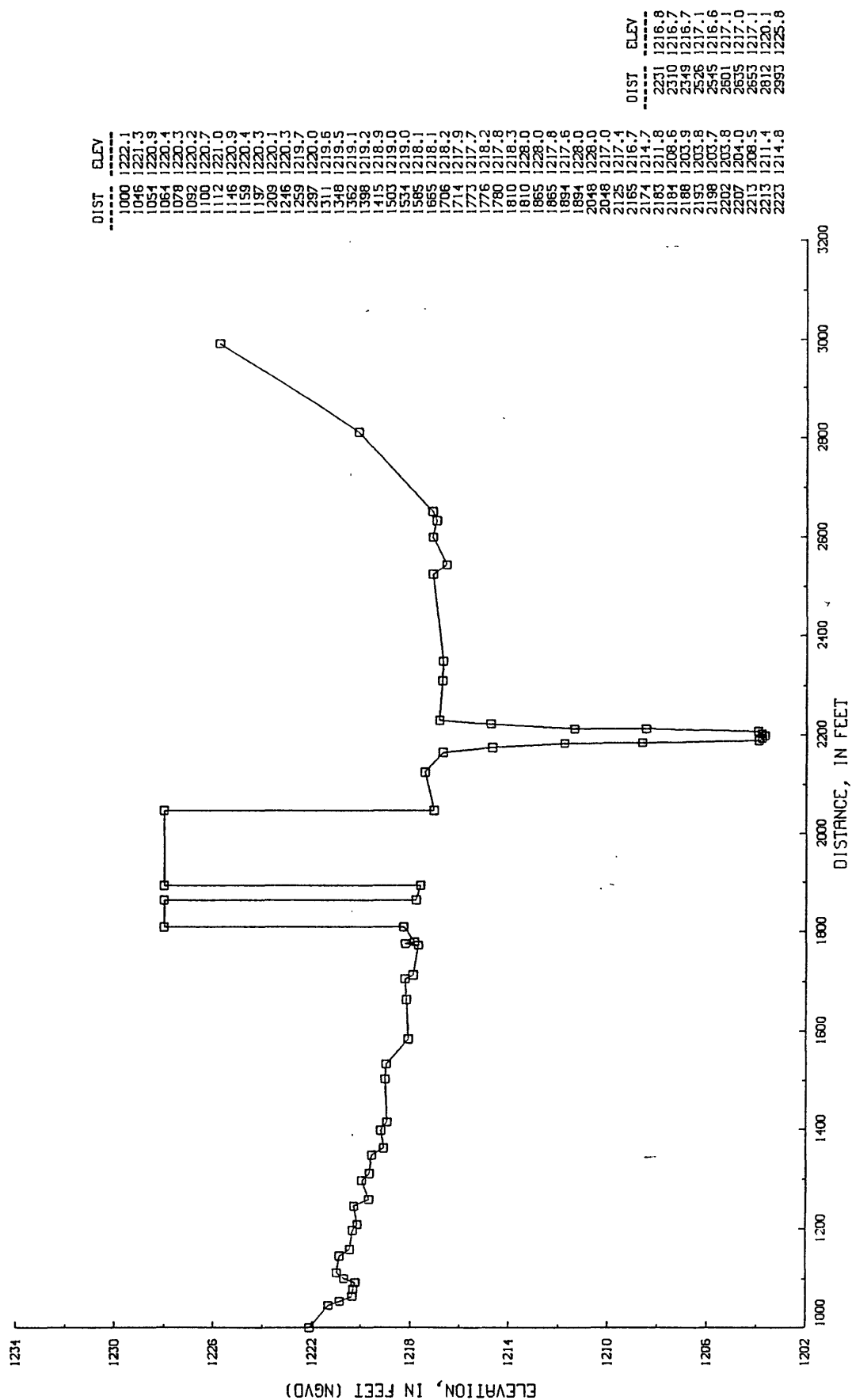


Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 1-1. Location of study cross sections on Twin Creek at SW 29th Street (site 1).

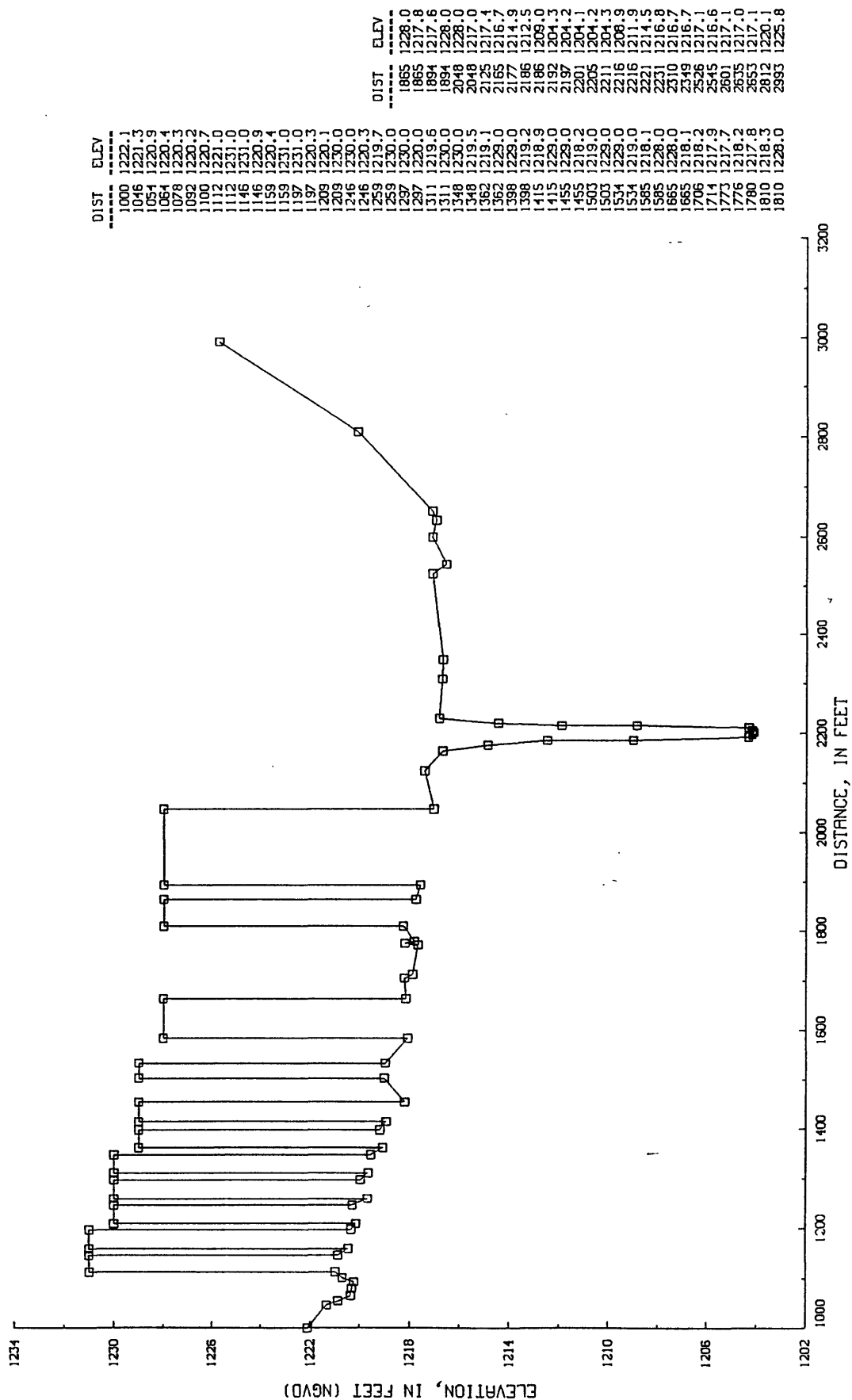
CROSS SECTION TN1, DOWNSTREAM FOOT BRIDGE - STATION - 15025



Appendix 1-2. Plot of cross section 1, Twin Creek at SW 29th Street (site 1).

TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

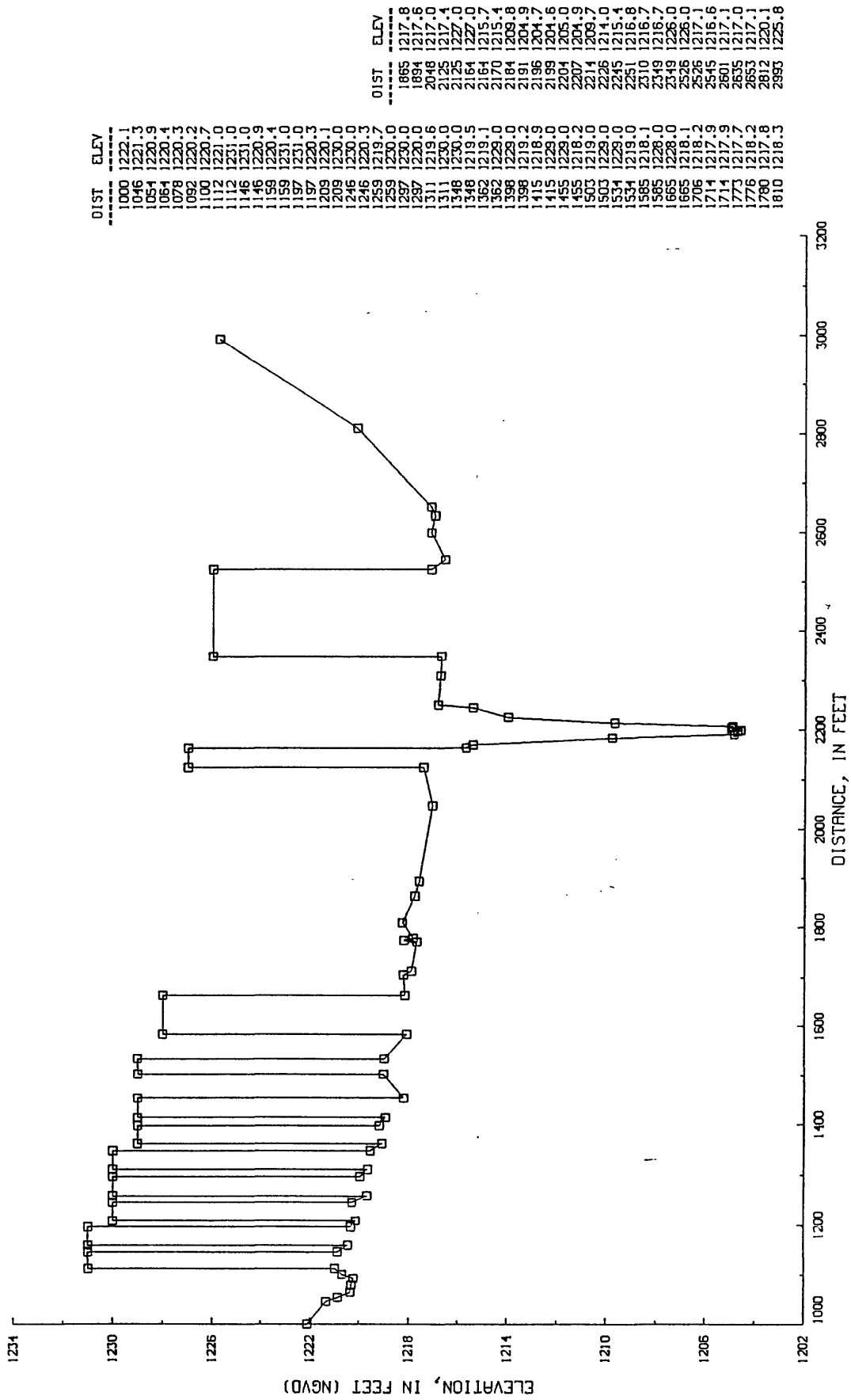
CROSS SECTION TN2, DOWNSTREAM SW 25TH - STATION - 15135



Appendix 1-3. Plot of cross section 2, Twin Creek at SW 29th Street (site 1).

TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

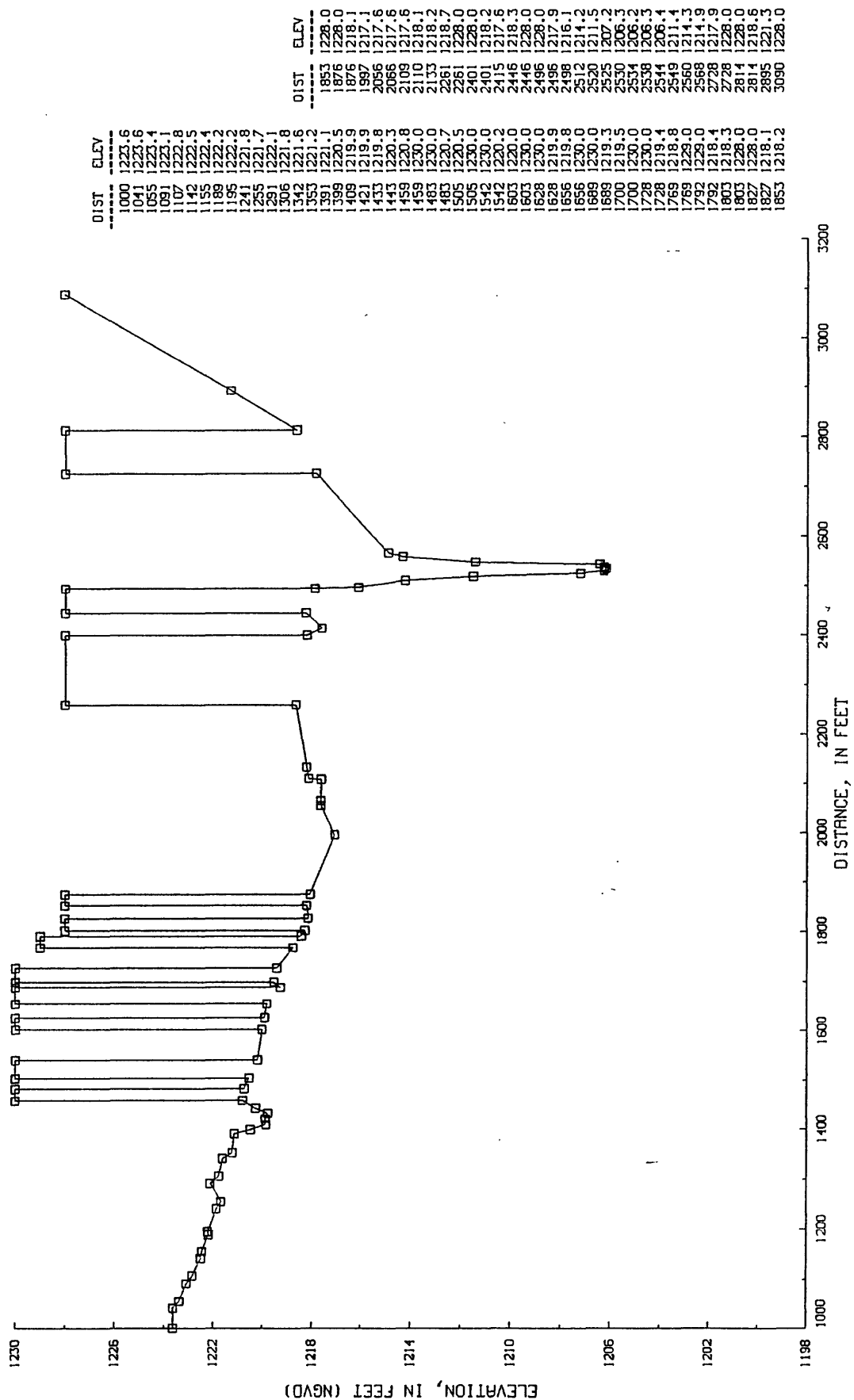
CROSS SECTION TN4, UPSTREAM SW 25TH - STATION - 15350



Appendix 1-4. Plot of cross section 4, Twin Creek at SW 29th Street (site 1).

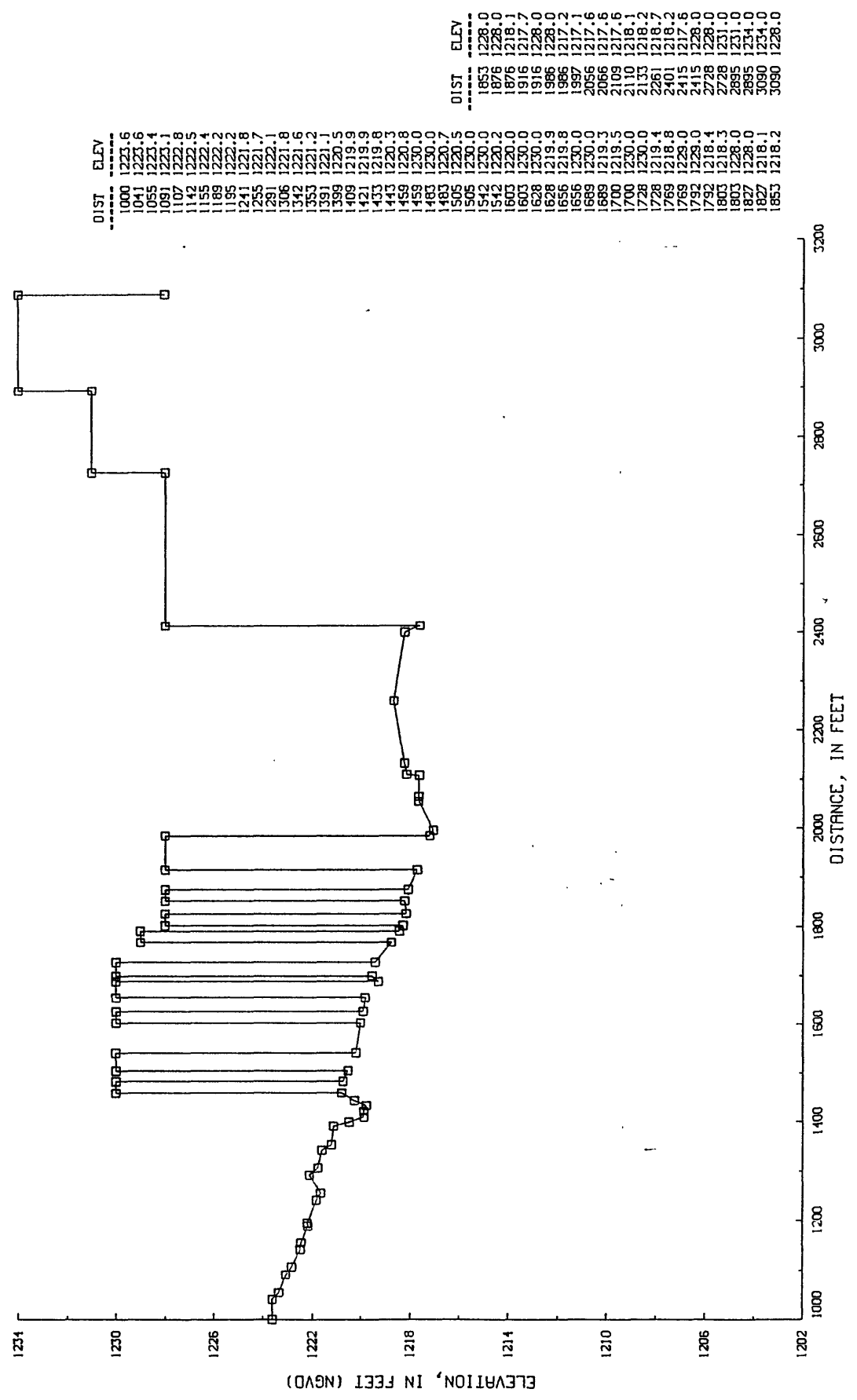
TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION TMS, DOWNSTREAM SW 27TH - STATION - 15920



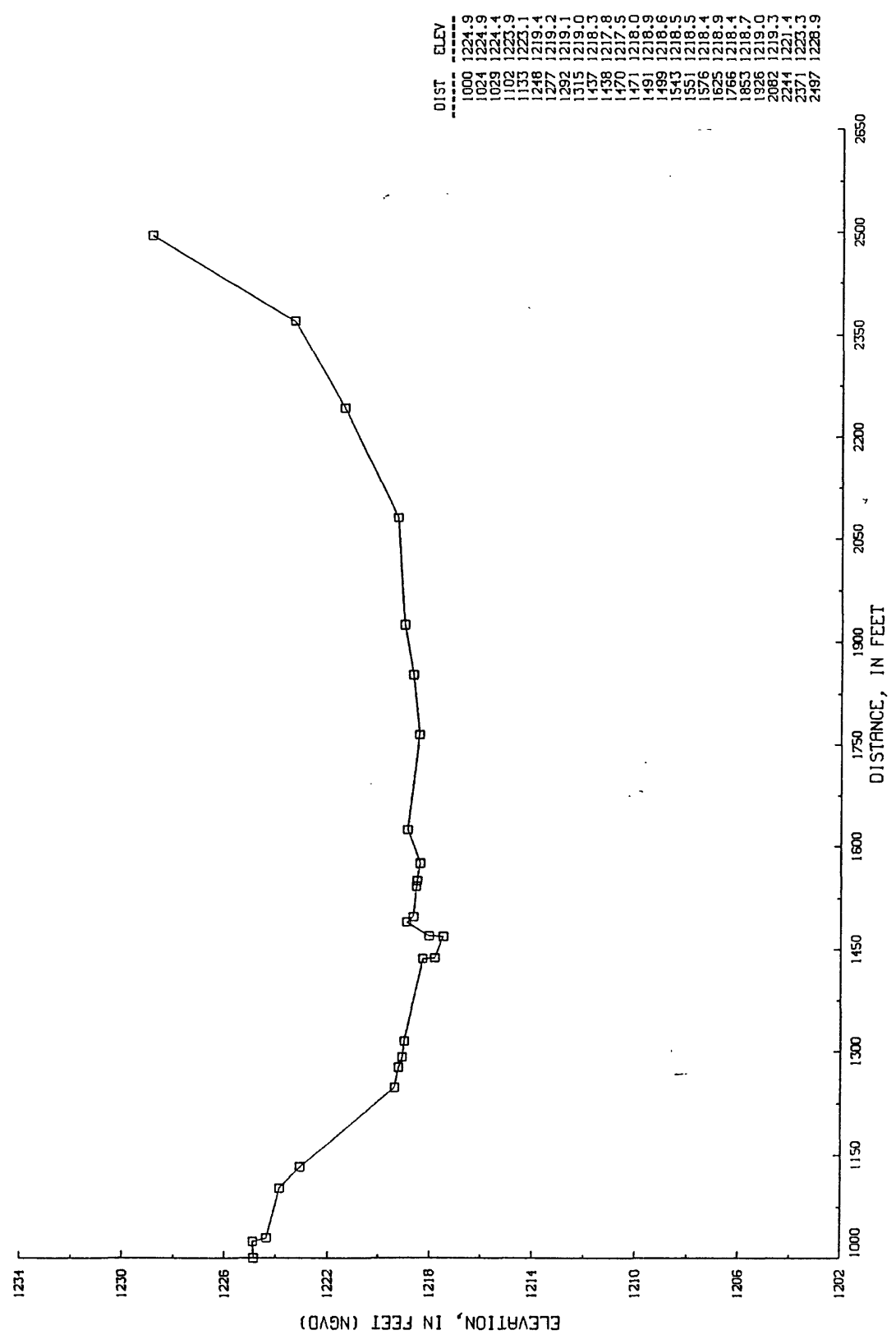
Appendix 1-5. Plot of cross section 5, Twin Creek at SW 29th Street (site 1).

TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION TN6A, SOUTH SIDE SW 27TH - STATION - 16050



Appendix 1-6. Plot of cross section 6A, Twin Creek at SW 29th Street (site 1).

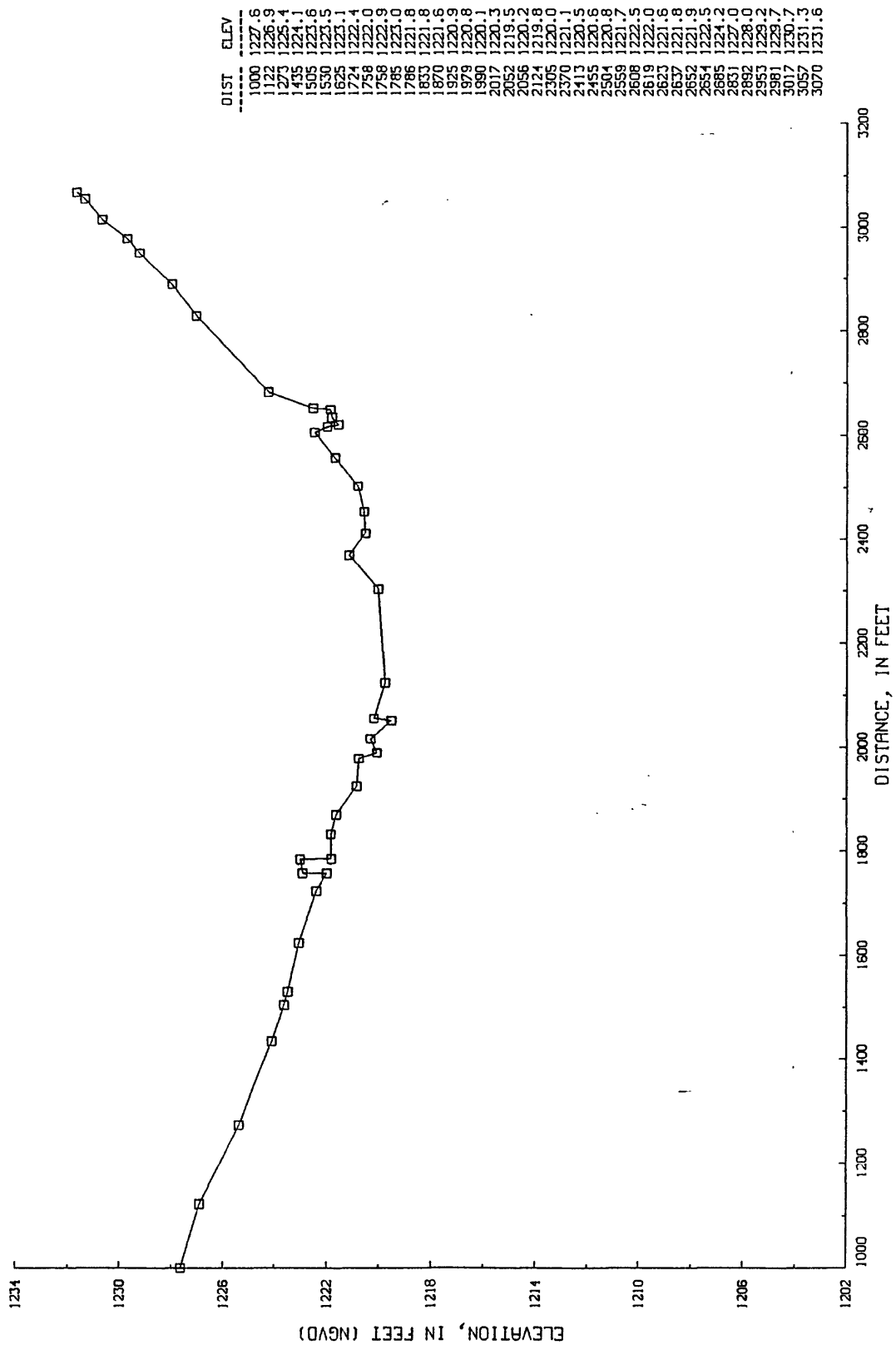
TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION TN7R, NORTH SIDE SW 28TH - STATION - 16470



Appendix 1-7. Plot of cross section 7R, Twin Creek at SW 29th Street (site 1).

TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

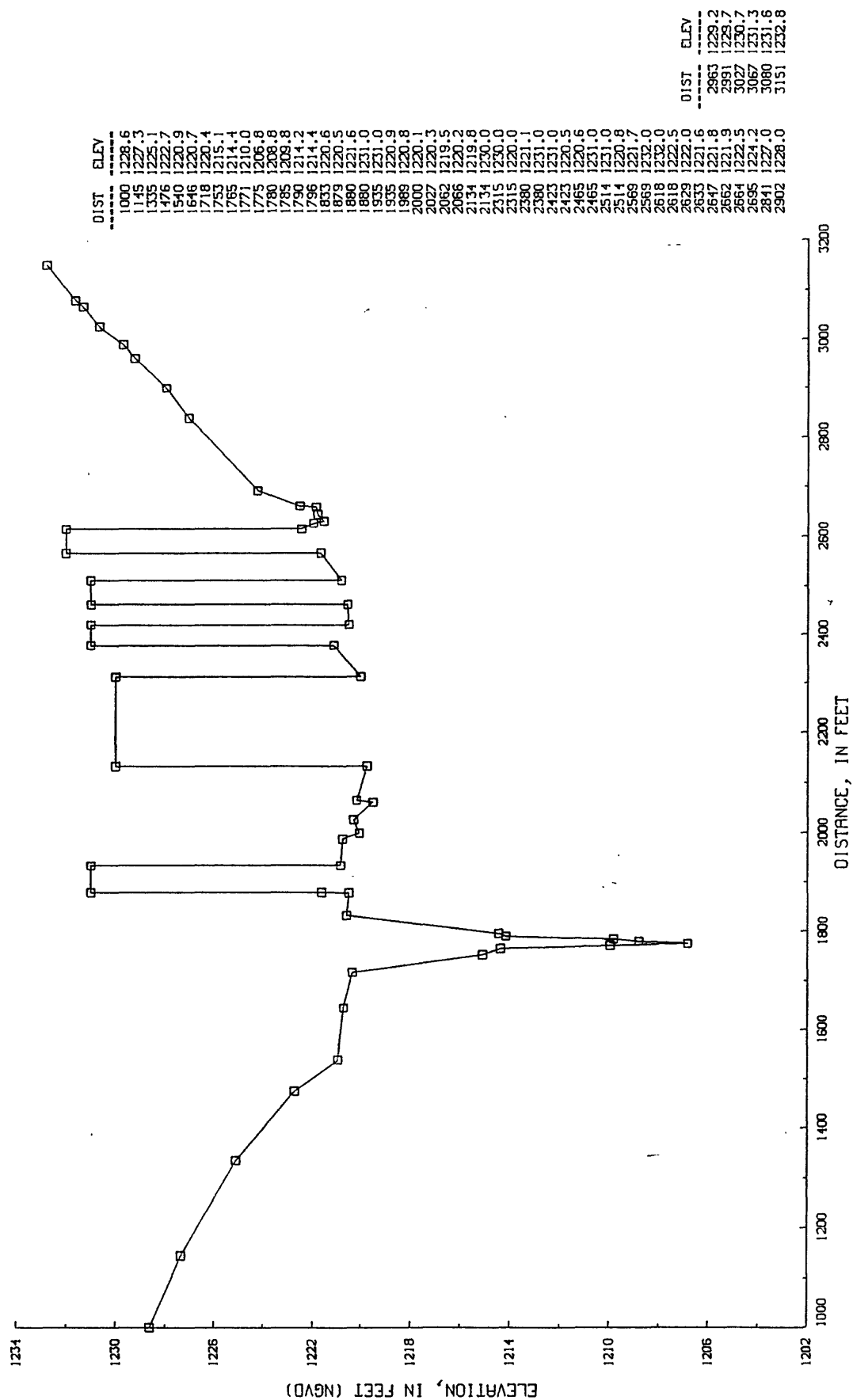
CROSS SECTION TN8R, SOUTH SIDE SW 29TH - STATION - 17050



Appendix 1-8. Plot of cross section 8R, Twin Creek at SW 29th Street (site 1).

TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

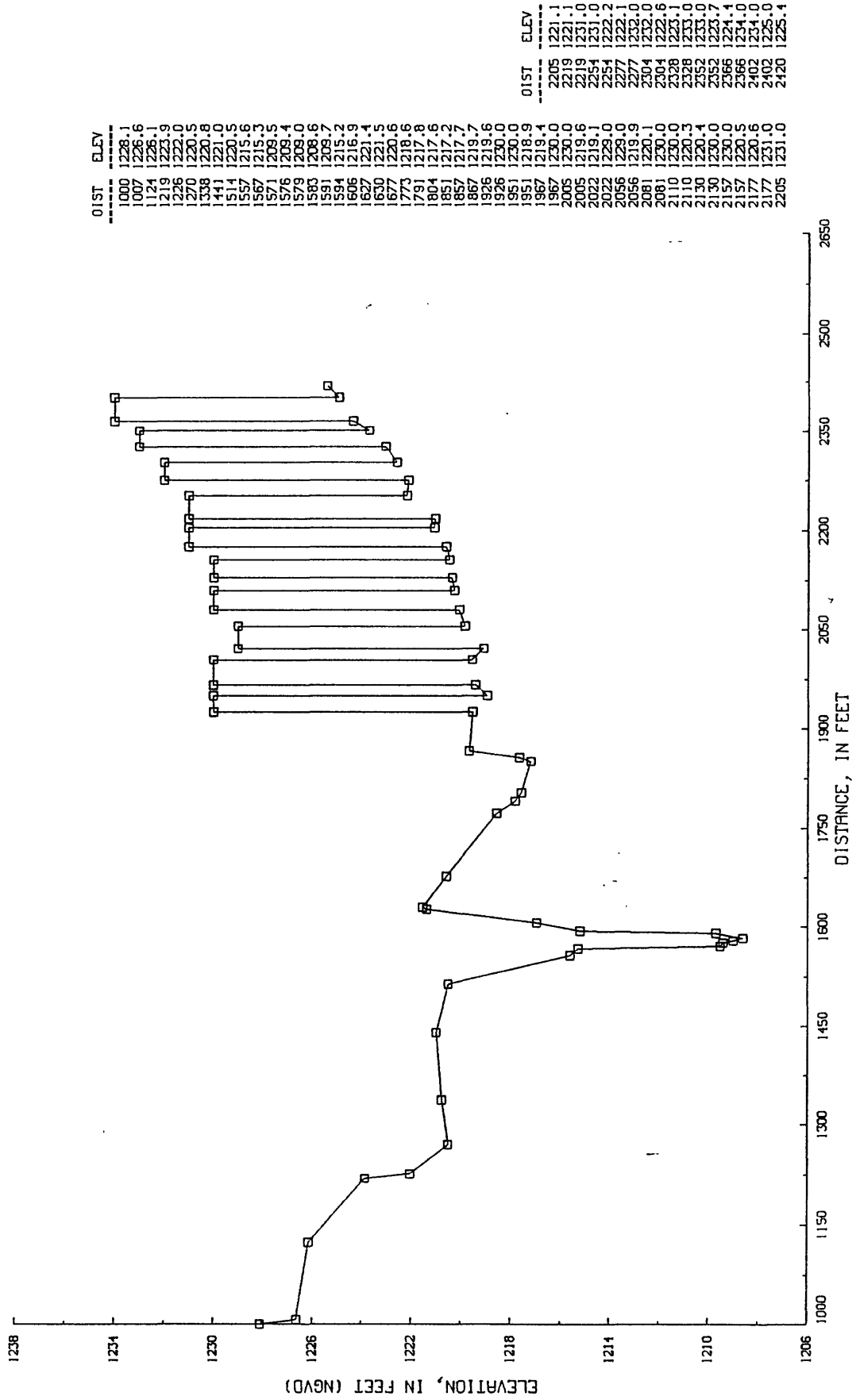
CROSS SECTION TN9, UPSTREAM SW 29TH - STATION - 17150



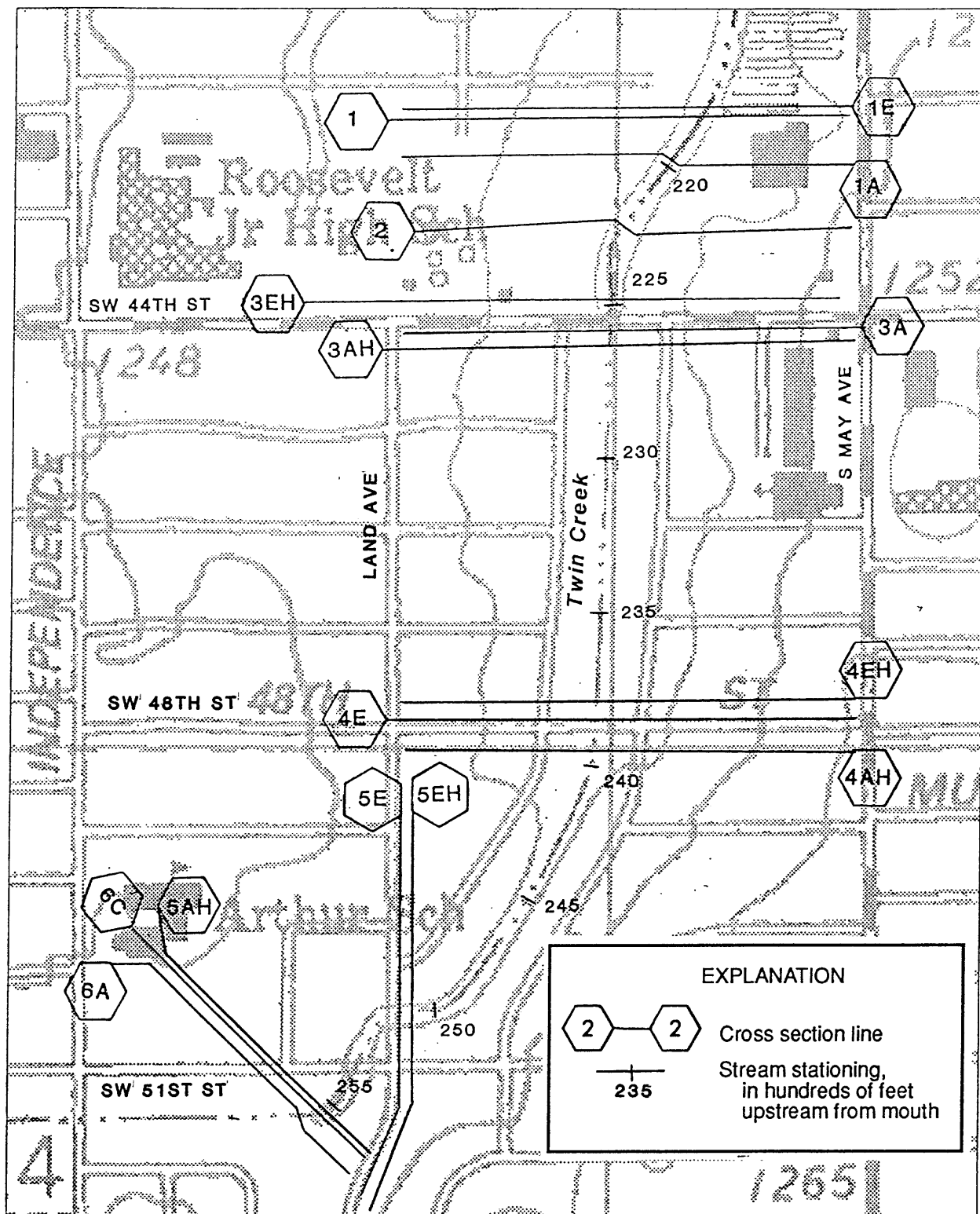
Appendix 1-9. Plot of cross section 9, Twin Creek at SW 29th Street (site 1)

TWIN CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION TN10, SOUTH SIDE SW 30TH - STATION - 17385



Appendix 1-10. Plot of cross section 10, Twin Creek at SW 29th Street (site 1).



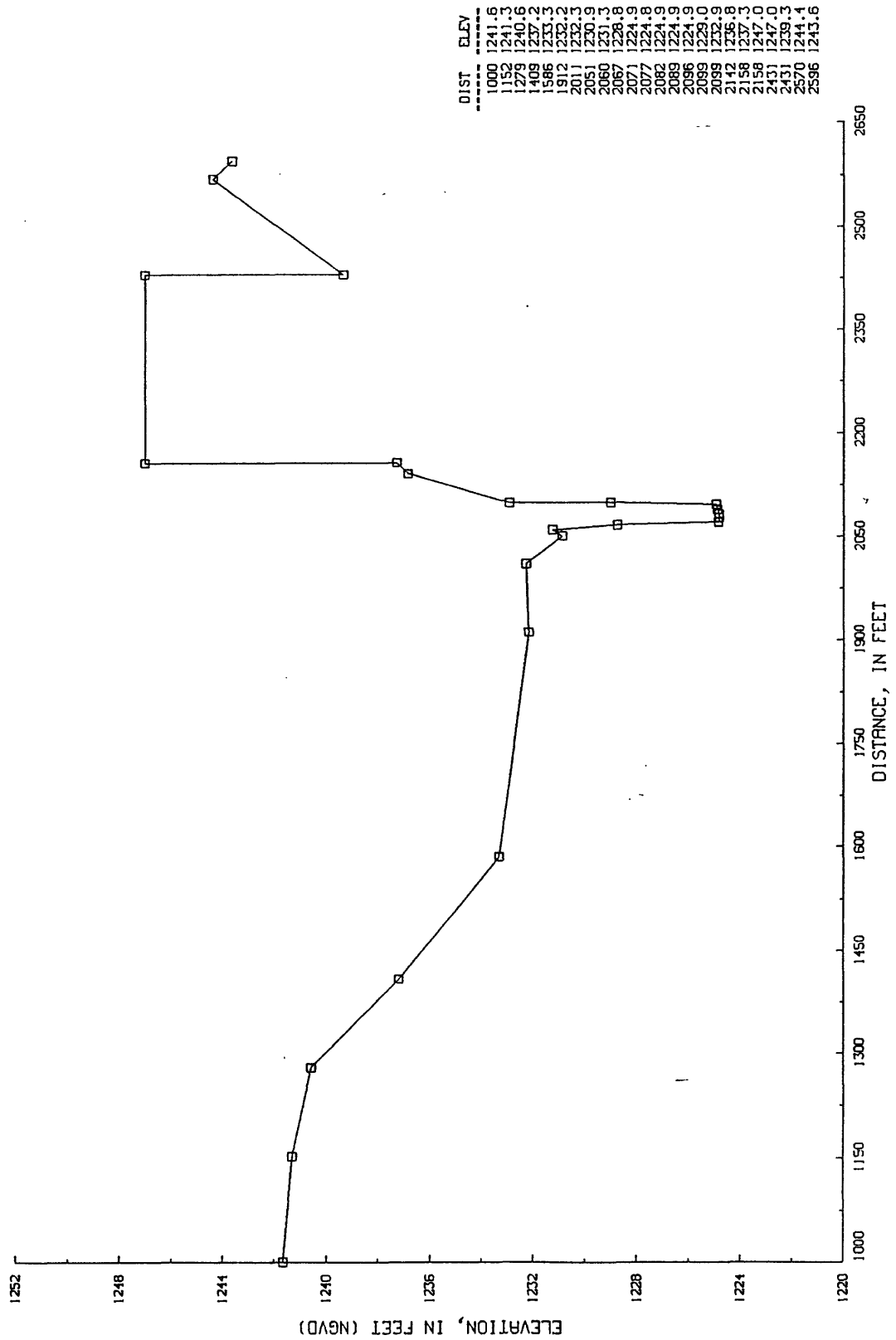
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 2-1. Location of study cross sections on Twin Creek at SW 44th Street (site 2).

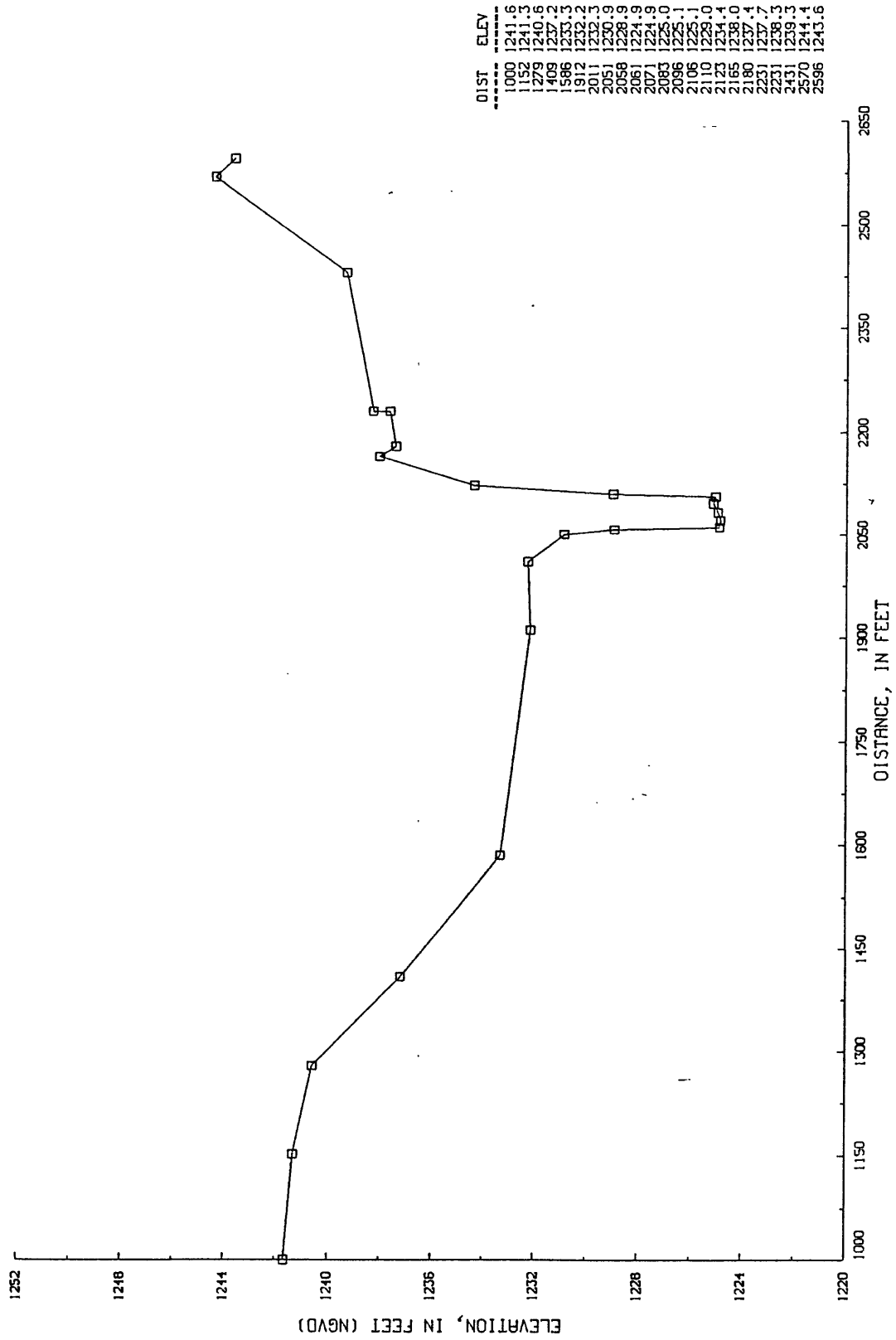
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION T1E, SOUTH SIDE STORAGE CLOSET - STATION-21770



Appendix 2-2. Plot of cross section 1E, Twin Creek at SW 44th Street (site 2).

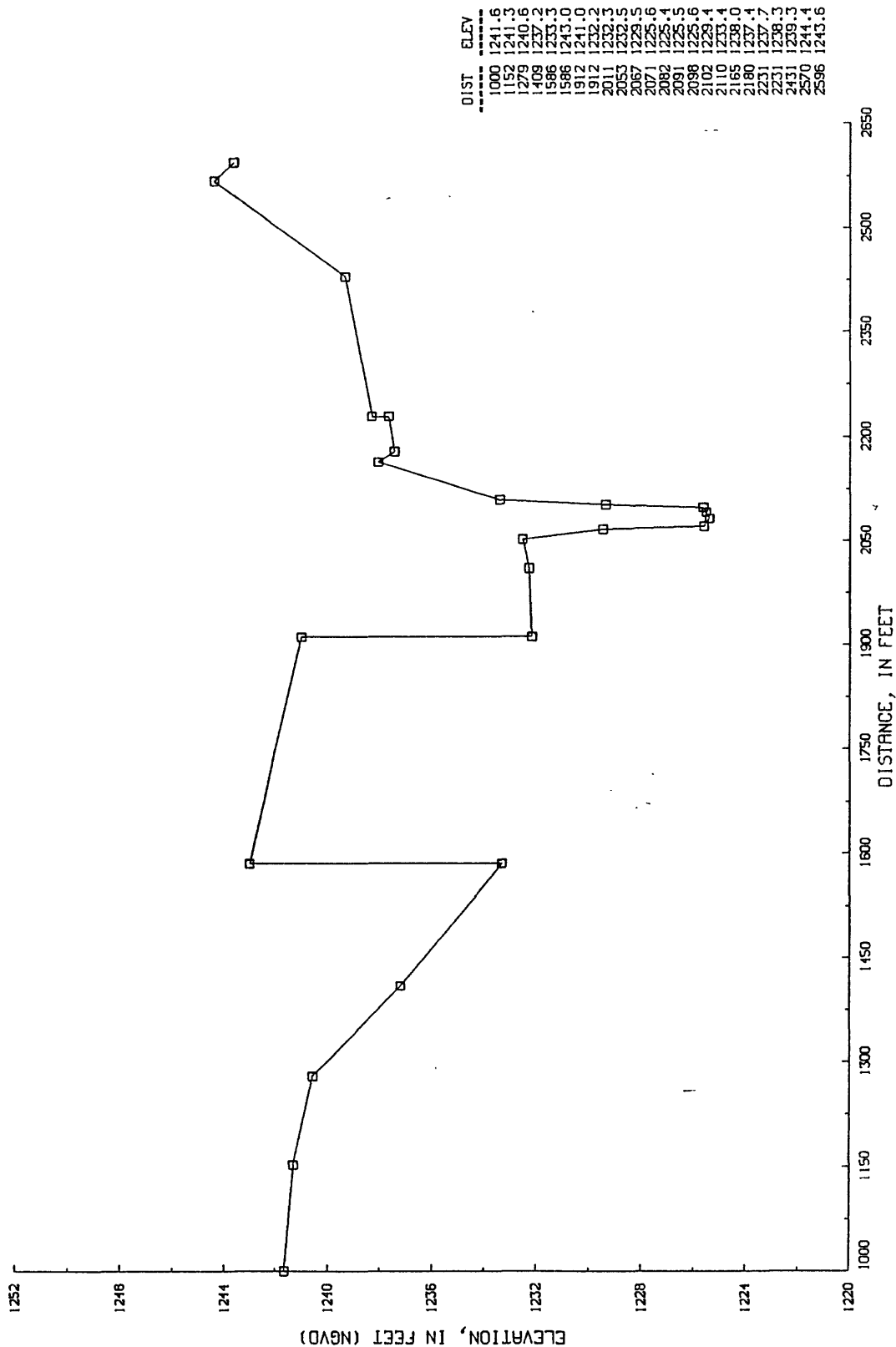
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION T1, NORTH SIDE HOMELAND STORE - STATION-21805



Appendix 2-3. Plot of cross section 1, Twin Creek at SW 44th Street (site 2).

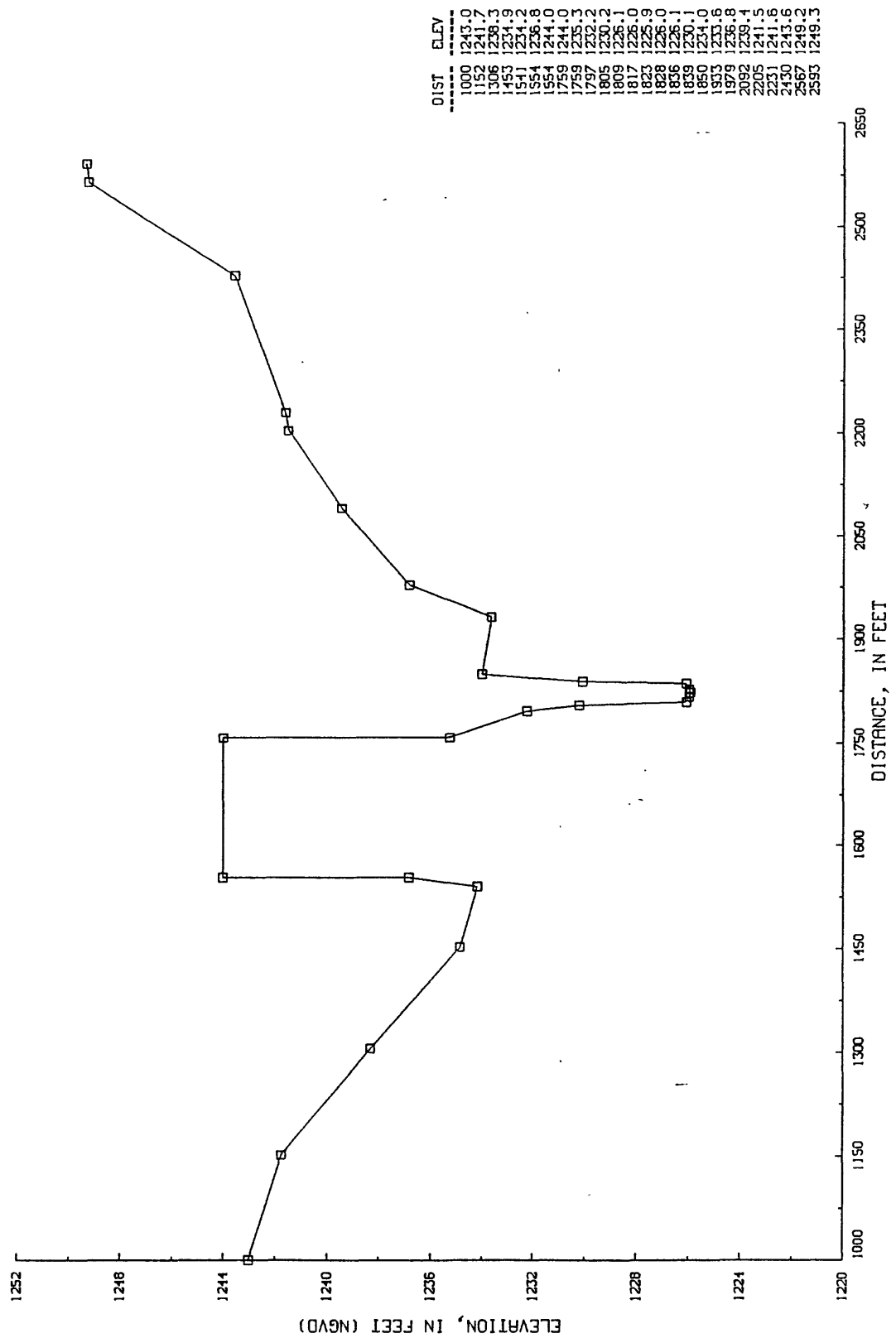
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION T1A, NORTH SIDE OIL TANKS - STATION-22000



Appendix 2-4. Plot of cross section 1A, Twin Creek at SW 44th Street (site 2).

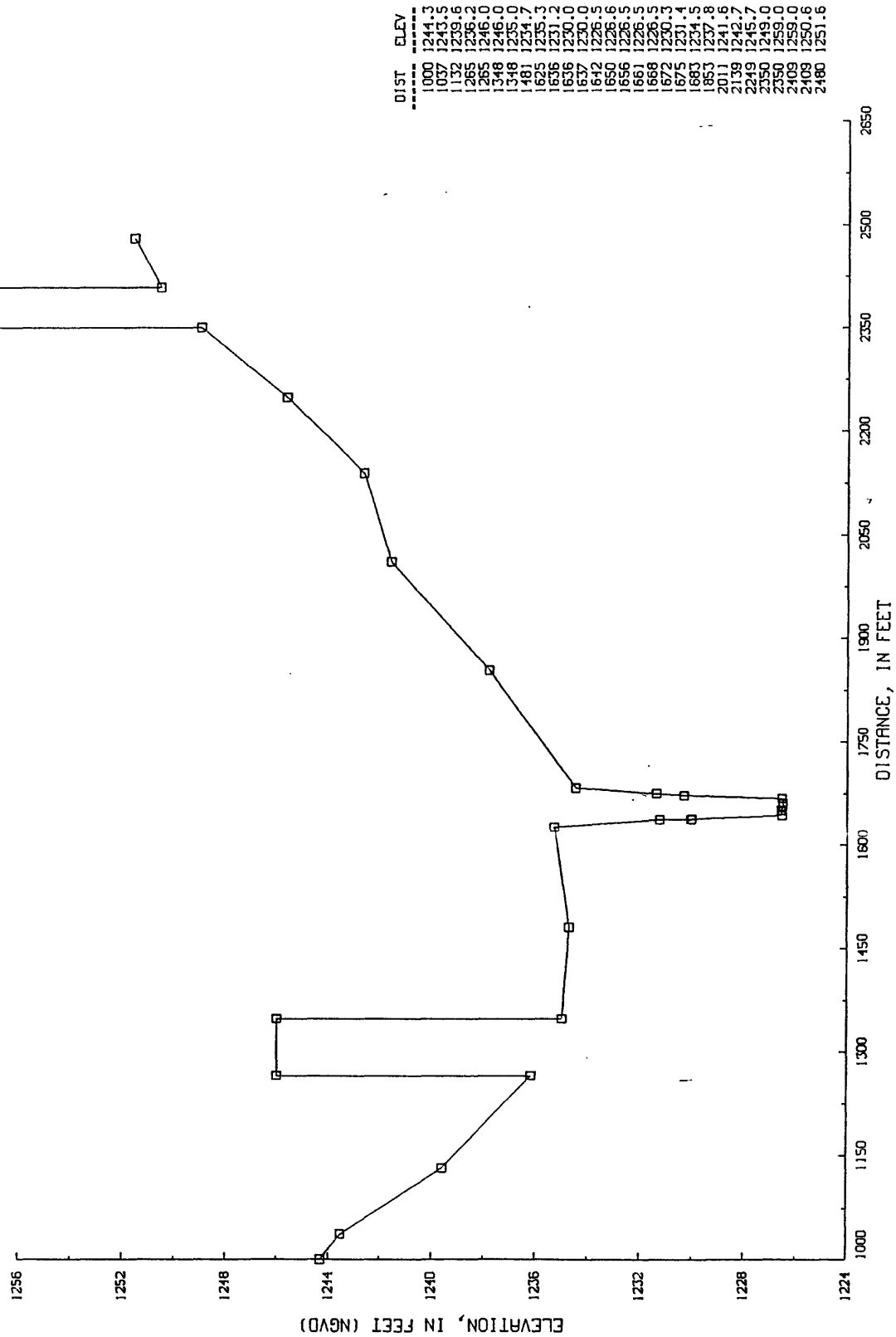
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD
CROSS SECTION T2, 260 FEET DOWNSTREAM SW 44TH-STATION-22240



Appendix 2-5. Plot of cross section 2, Twin Creek at SW 44th Street (site 2).

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

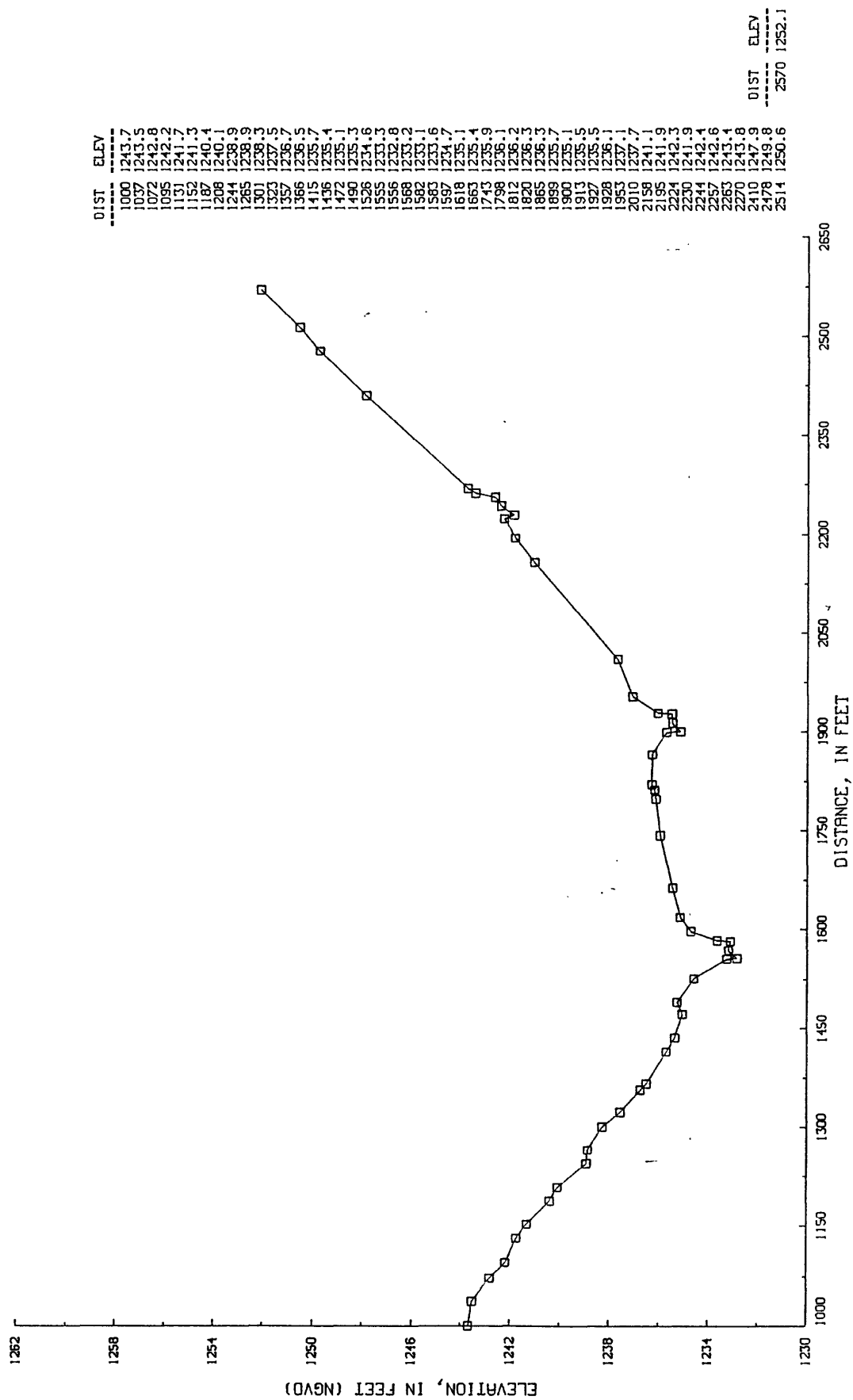
CROSS SECTION 13EH, DOWNSTREAM SW 44TH CULVERT - STA-22490



Appendix 2-6. Plot of cross section 3EH, Twin Creek at SW 44th Street (site 2).

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

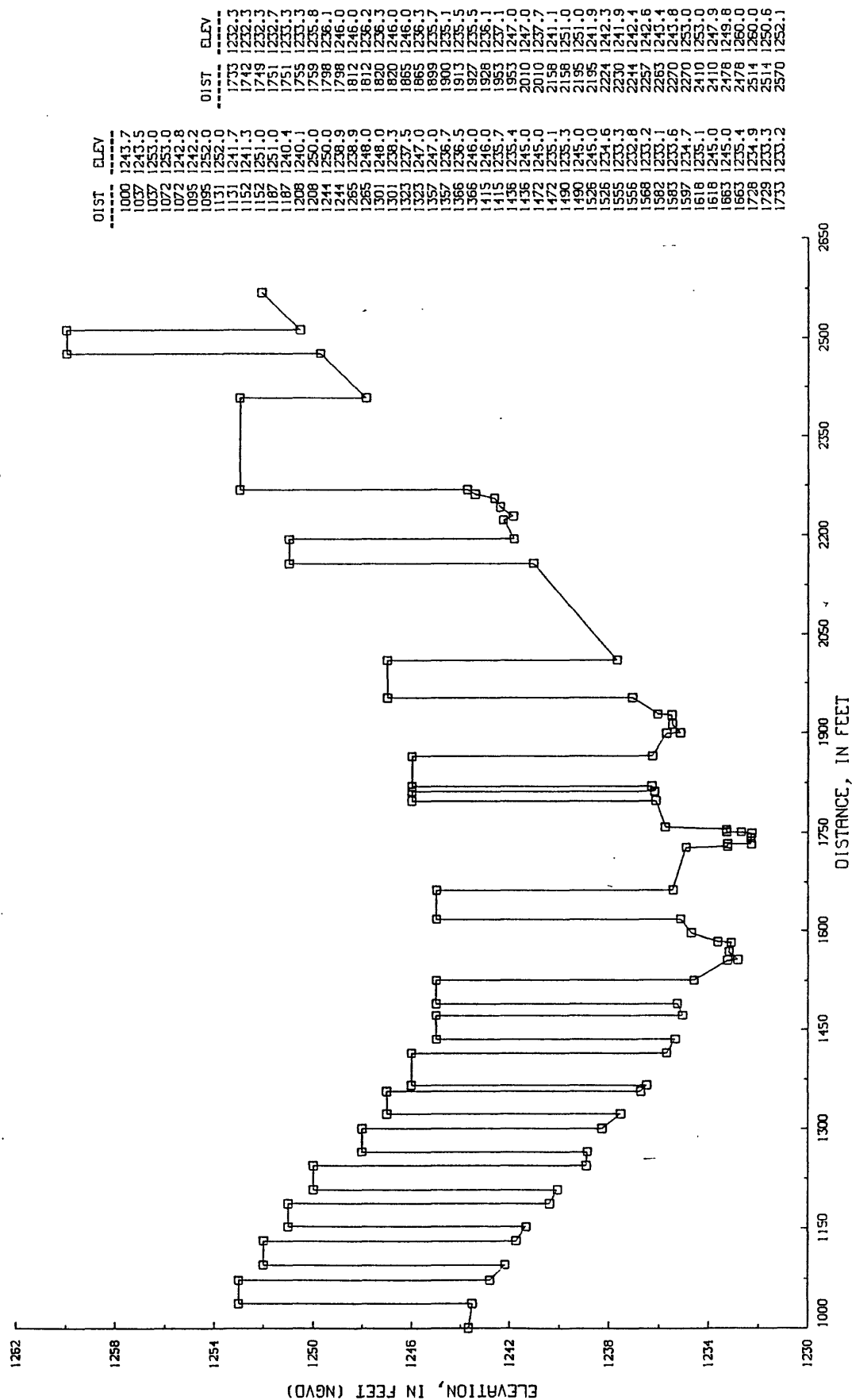
CROSS SECTION T3A, SOUTH SIDE SW 44TH - STATION - 22590



Appendix 2-7. Plot of cross section 3A, Twin Creek at SW 44th Street (site 2).

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

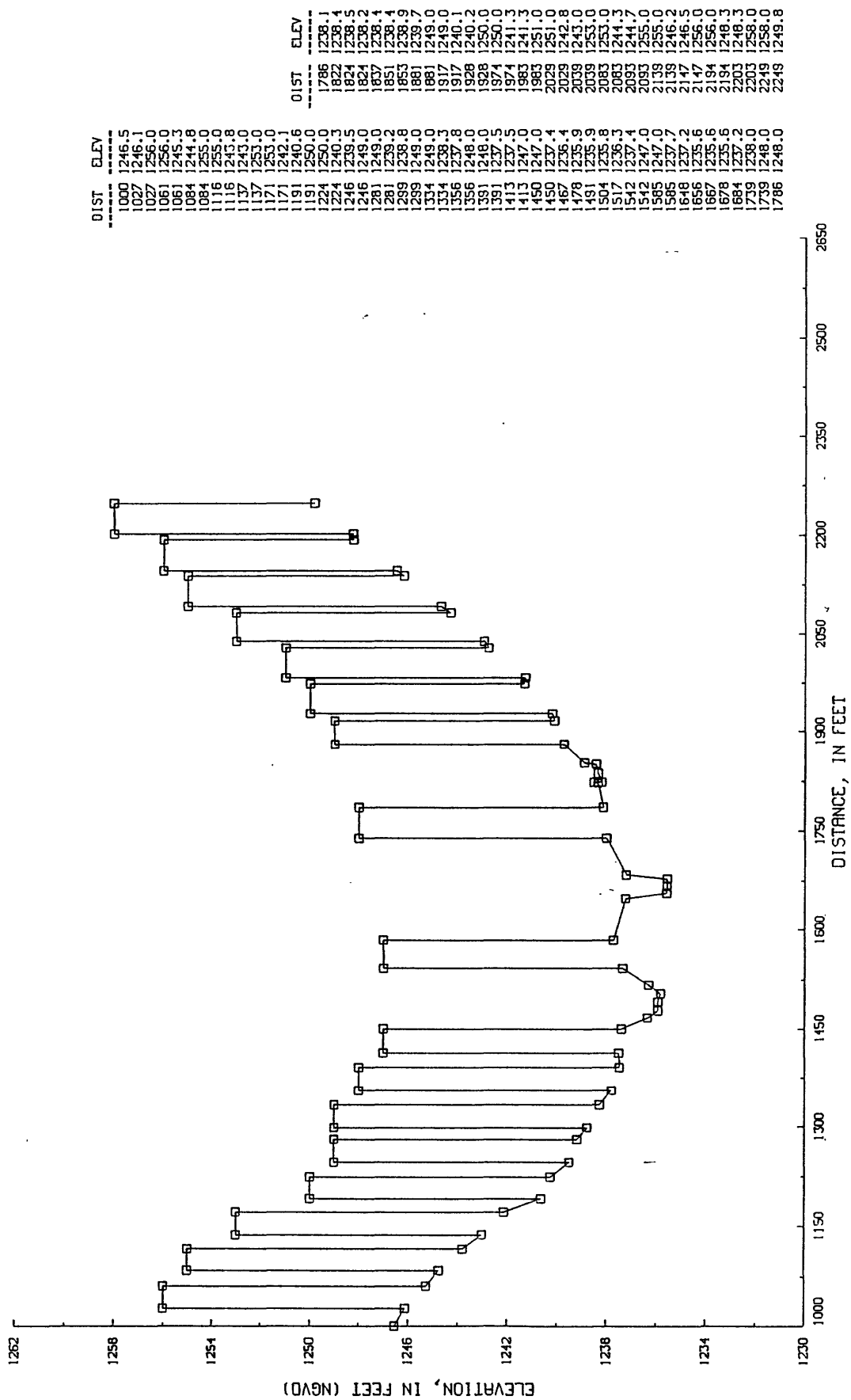
CROSS SECTION T3AH, UPSTREAM SW 44TH - STATION - 22610



Appendix 2-8. Plot of cross section 3AH, Twin Creek at SW 44th Street (site 2).

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

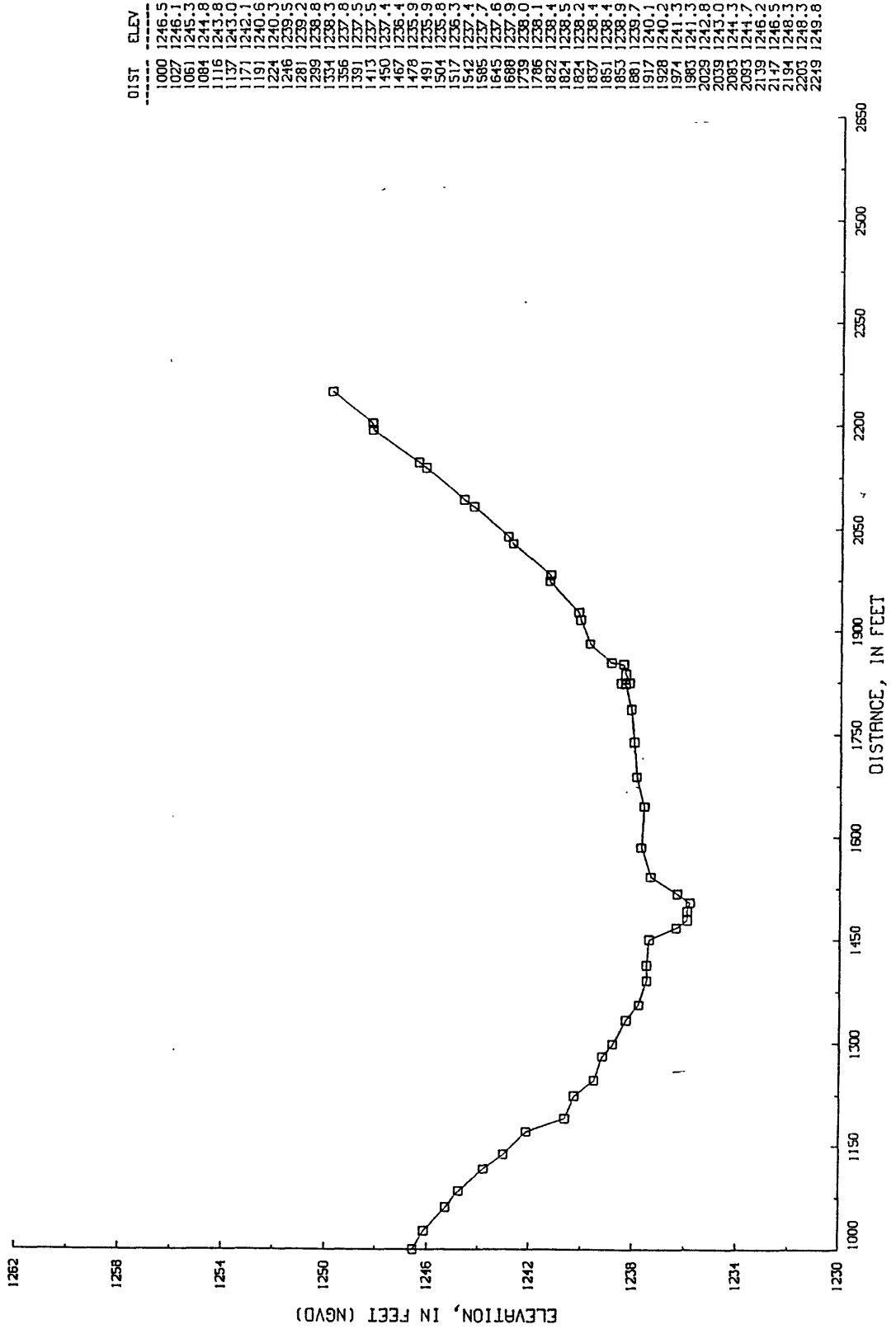
CROSS SECTION T4EH, DOWNSTREAM SW 48TH - STATION - 23790



Appendix 2-9. Plot of cross section 4EH, Twin Creek at SW 44th Street (site 2)

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

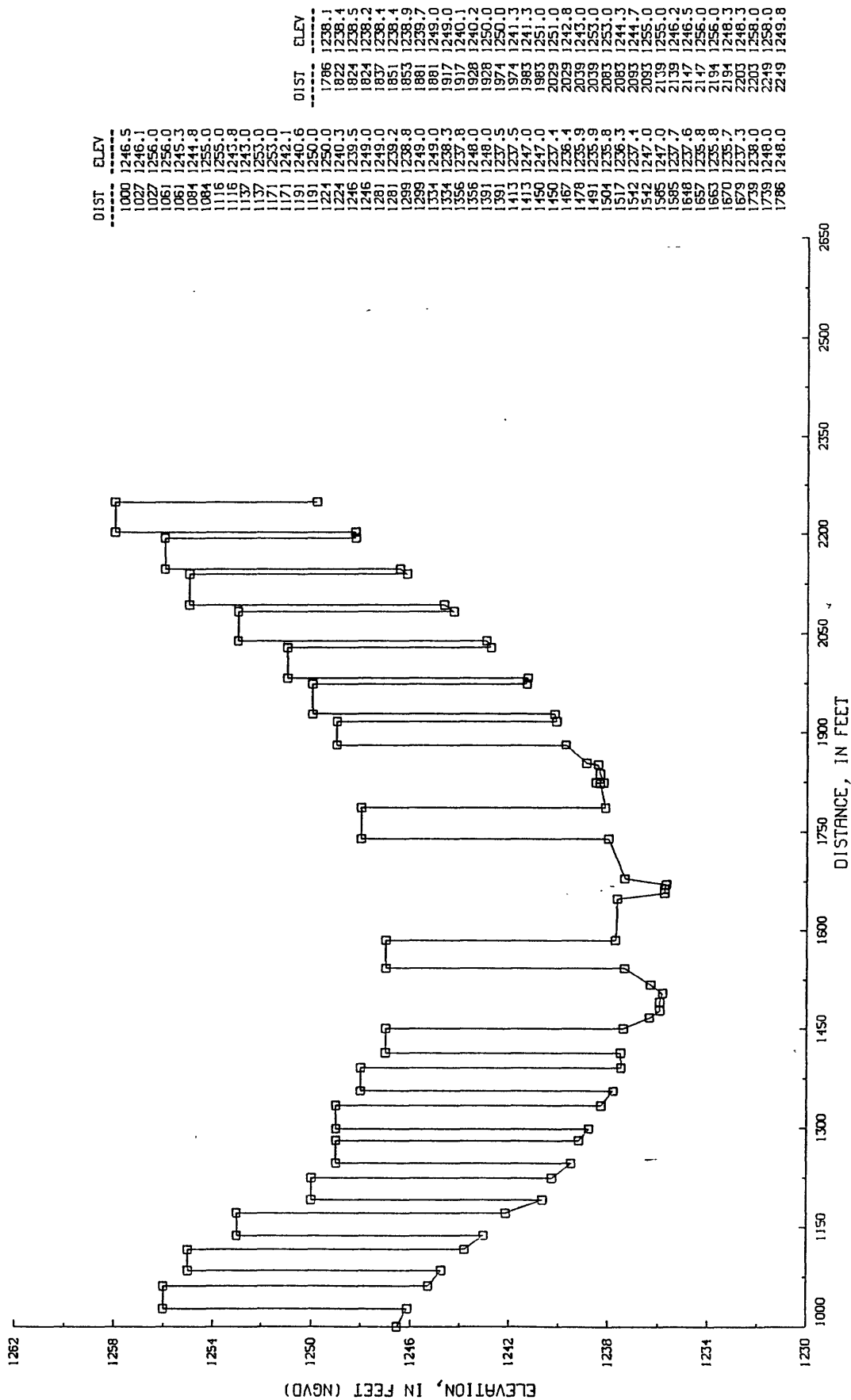
CROSS SECTION T4E, NORTH SIDE SW 48TH - STATION - 23865



Appendix 2-10. Plot of cross section 4E, Twin Creek at SW 44th Street (site 2).

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

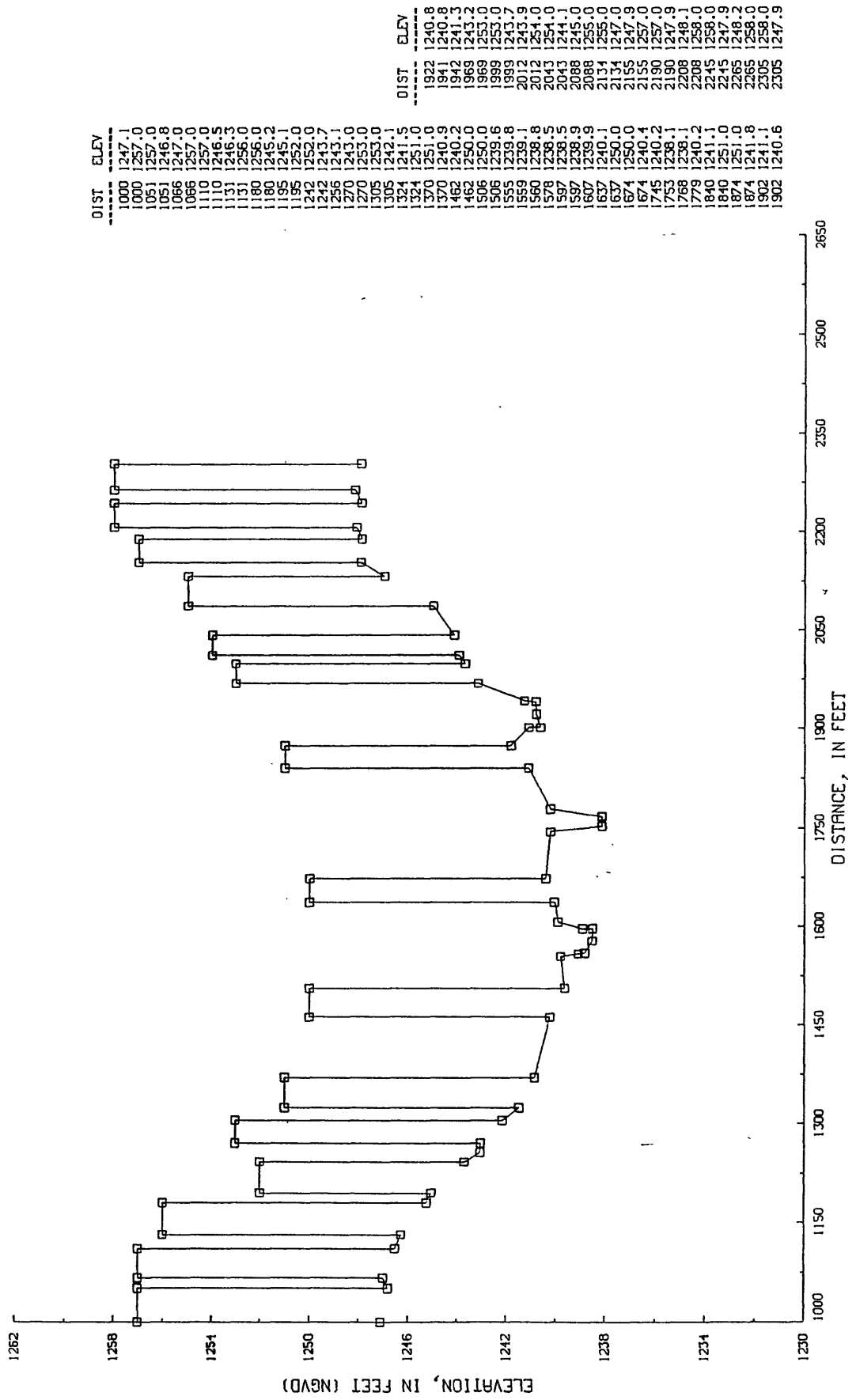
CROSS SECTION T4AH, UPSTREAM SW 48TH - STATION - 23945



Appendix 2-11. Plot of cross section 4AH, Twin Creek at SW 44th Street (site 2).

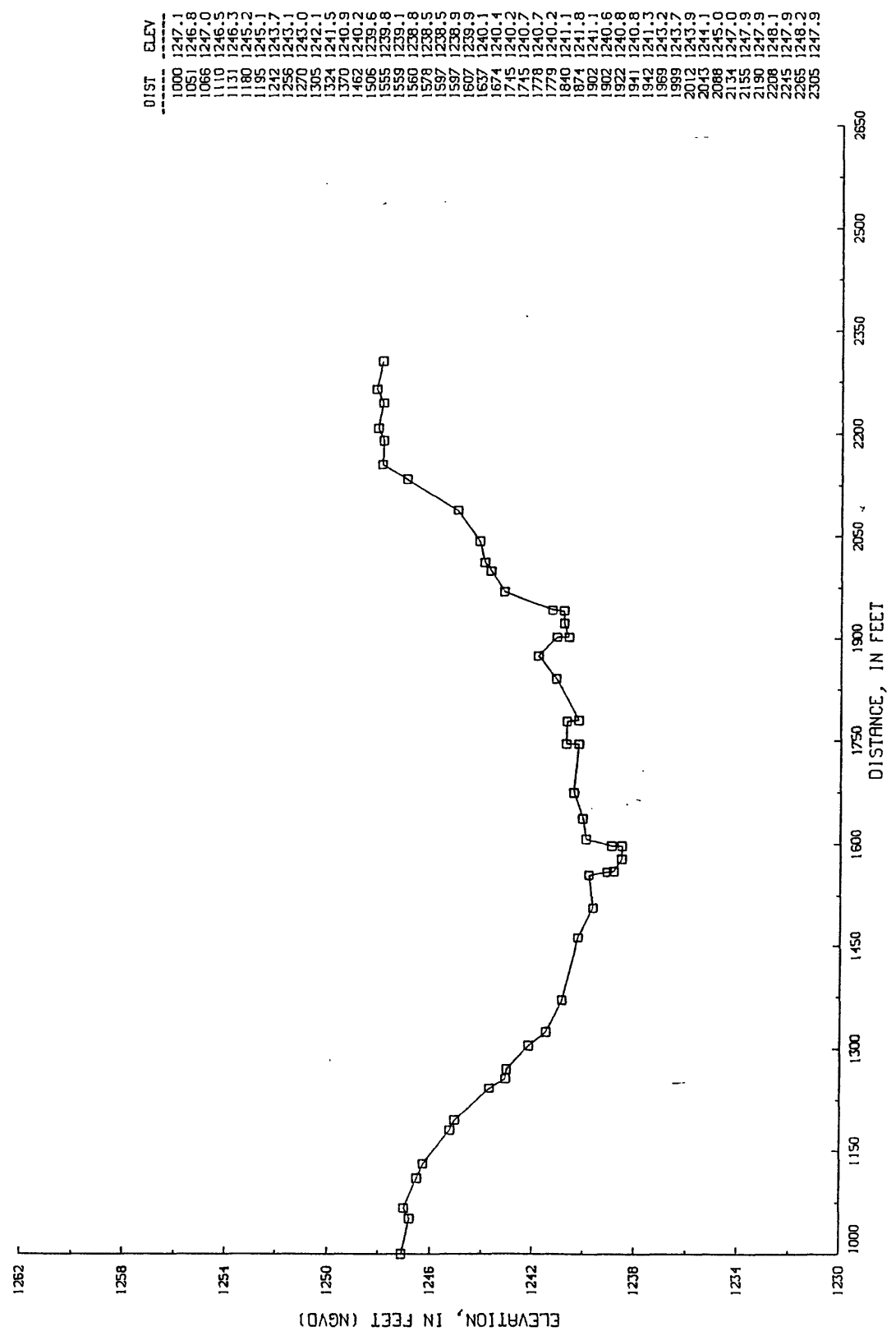
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION T5EH, DOWNSTREAM SOUTH LAND - STATION - 25085



Appendix 2-12. Plot of cross section 5EH, Twin Creek at SW 44th Street (site 2)

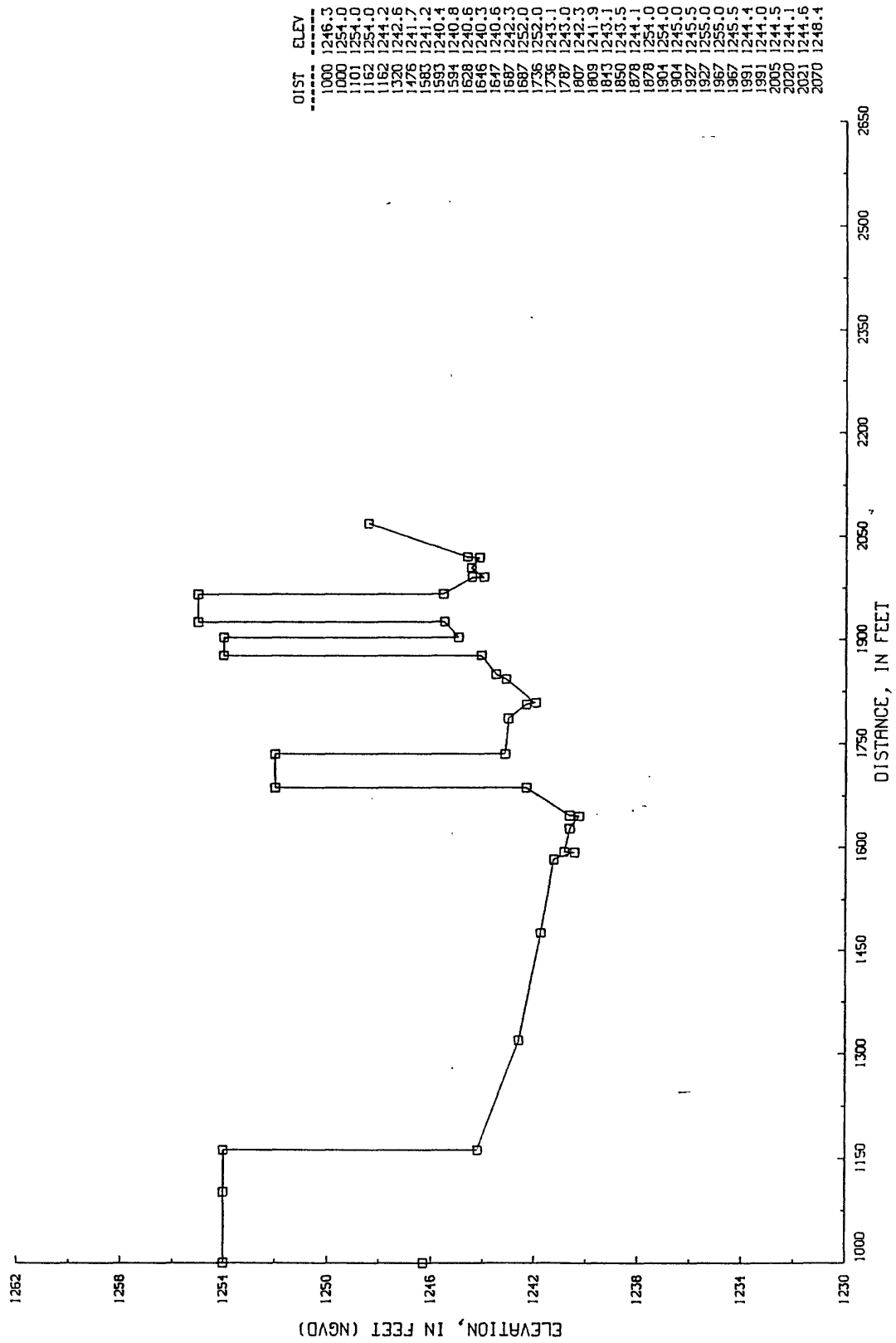
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION T5E, EAST SIDE LAND - STATION - 25125



Appendix 2-13. Plot of cross section 5E, Twin Creek at SW 44th Street (site 2).

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

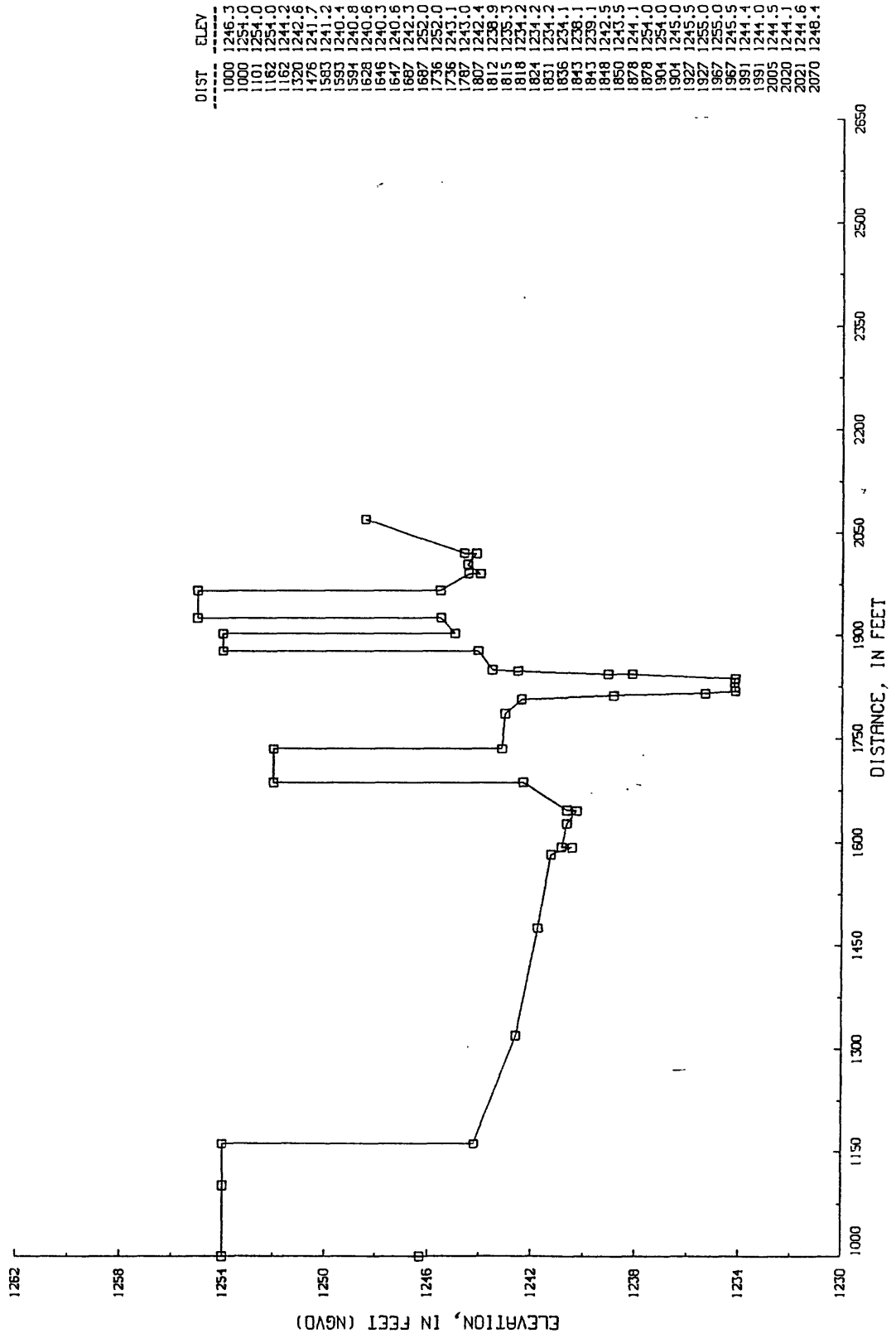
CROSS SECTION T5AH, UPSTREAM OF SW 51ST - STATION-25535



Appendix 2-14. Plot of cross section 5AH, Twin Creek at SW 44th Street (site 2).

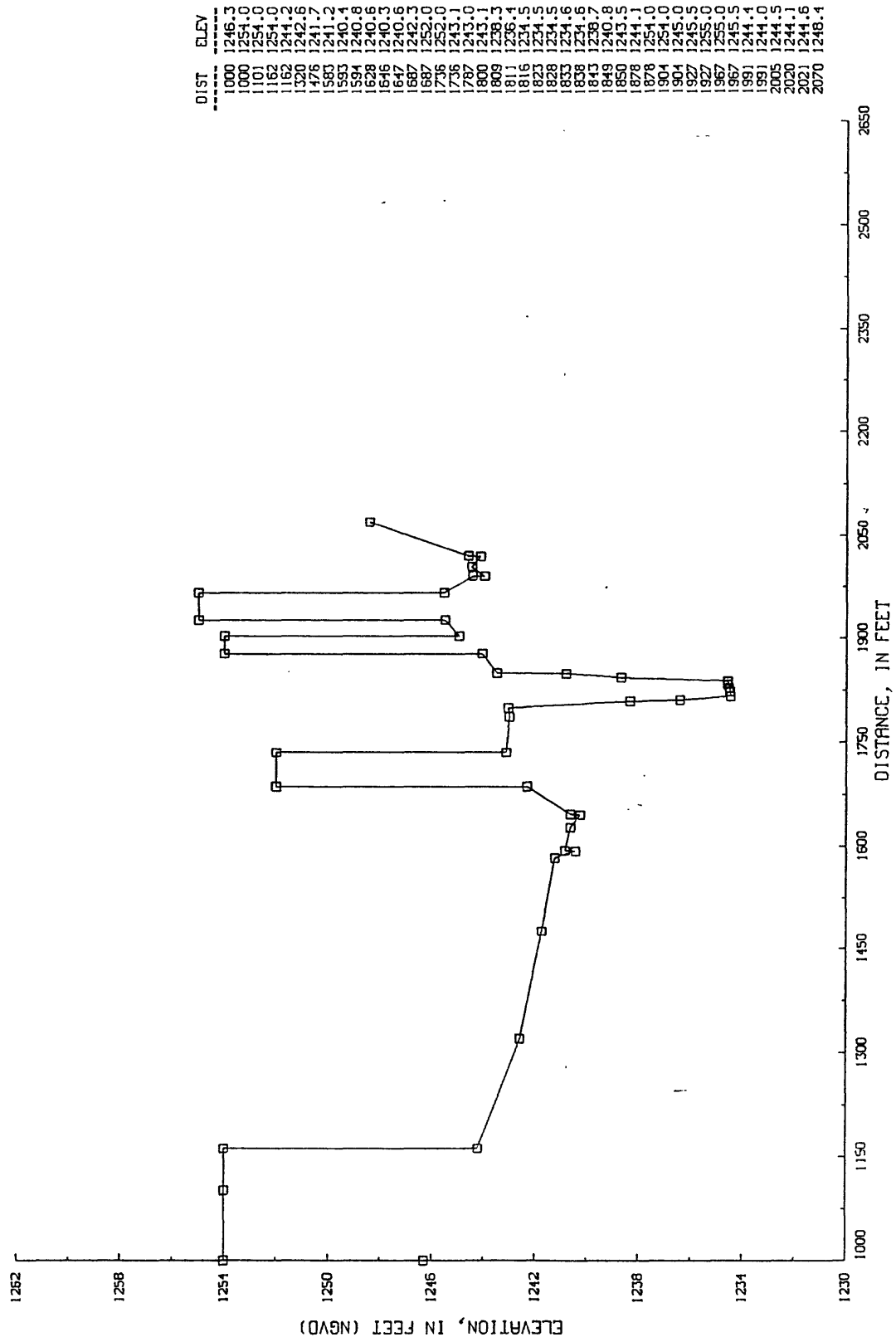
TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION T6C, CULVERT ENTRANCE - STATION - 25545

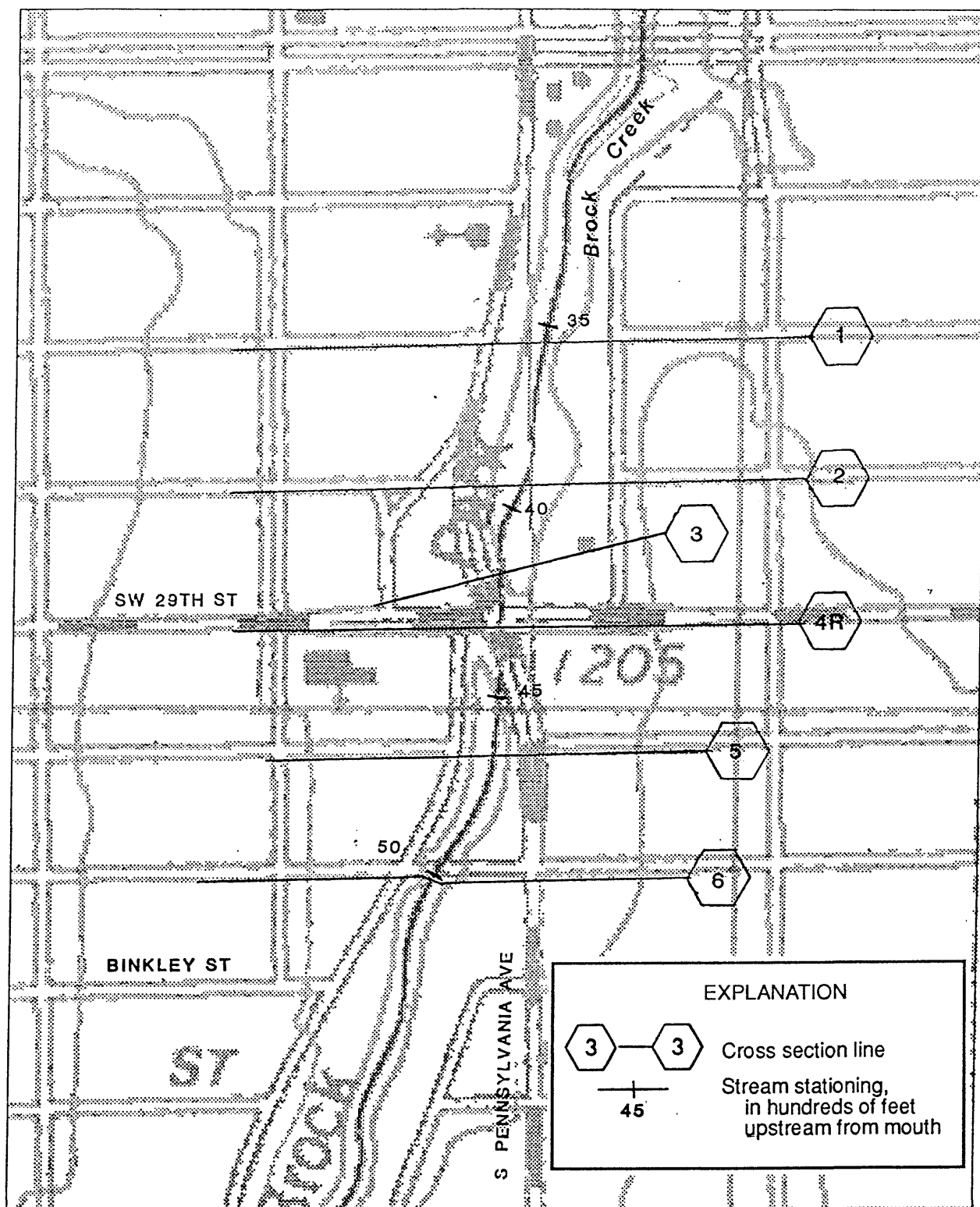


Appendix 2-15. Plot of cross section 6C, Twin Creek at SW 44th Street (site 2)

TWIN CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION T6A,UPSTREAM OF CULVERT ENTRANCE-STATION-25615



Appendix 2-16. Plot of cross section 6A, Twin Creek at SW 44th Street (site 2).

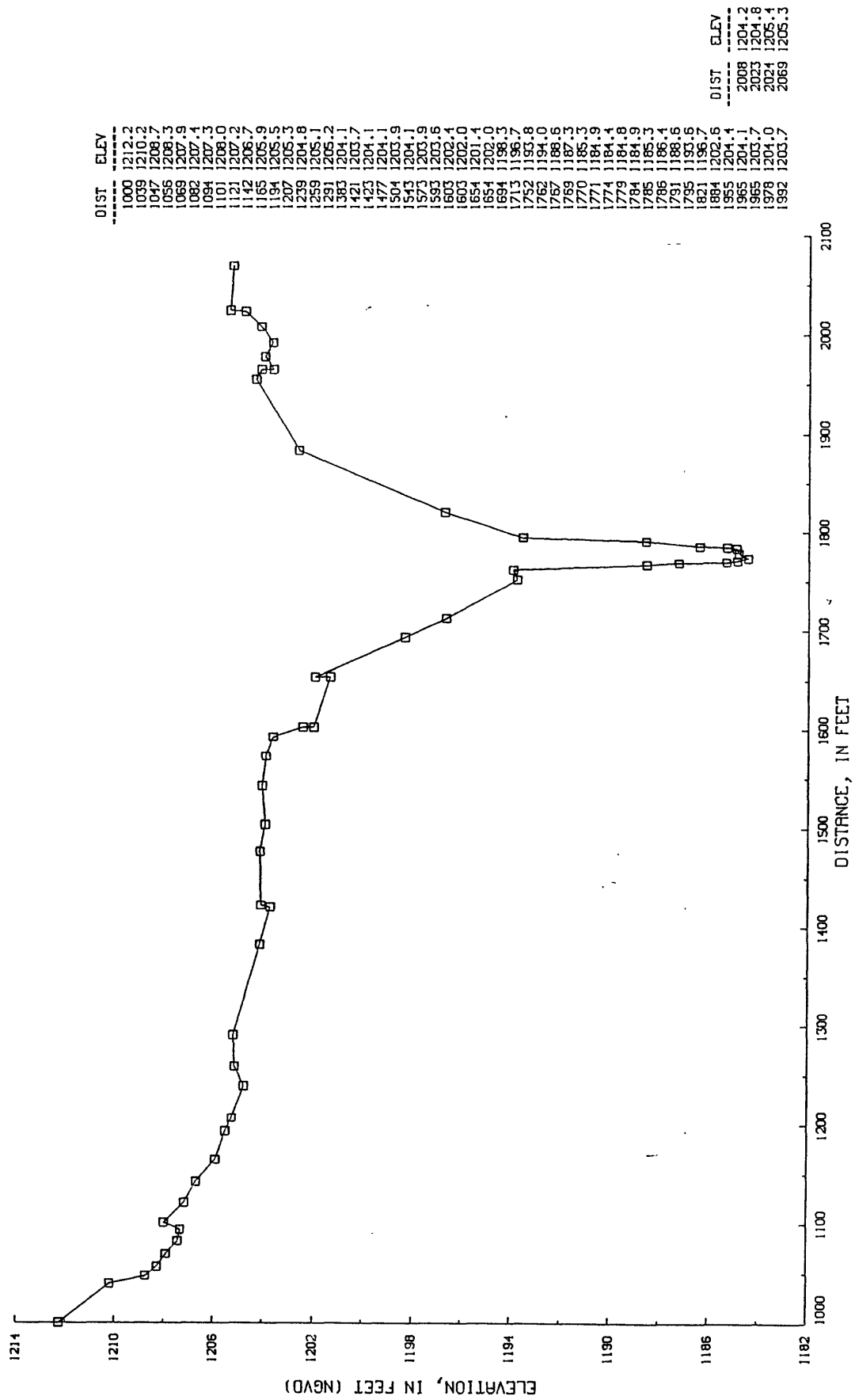


Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

Appendix 3-1. Location of study cross sections on Brock Creek at SW 29th Street (site 3).

BROCK CREEK AT SW 29TH STREET - MAY 8, 1993, FLOOD

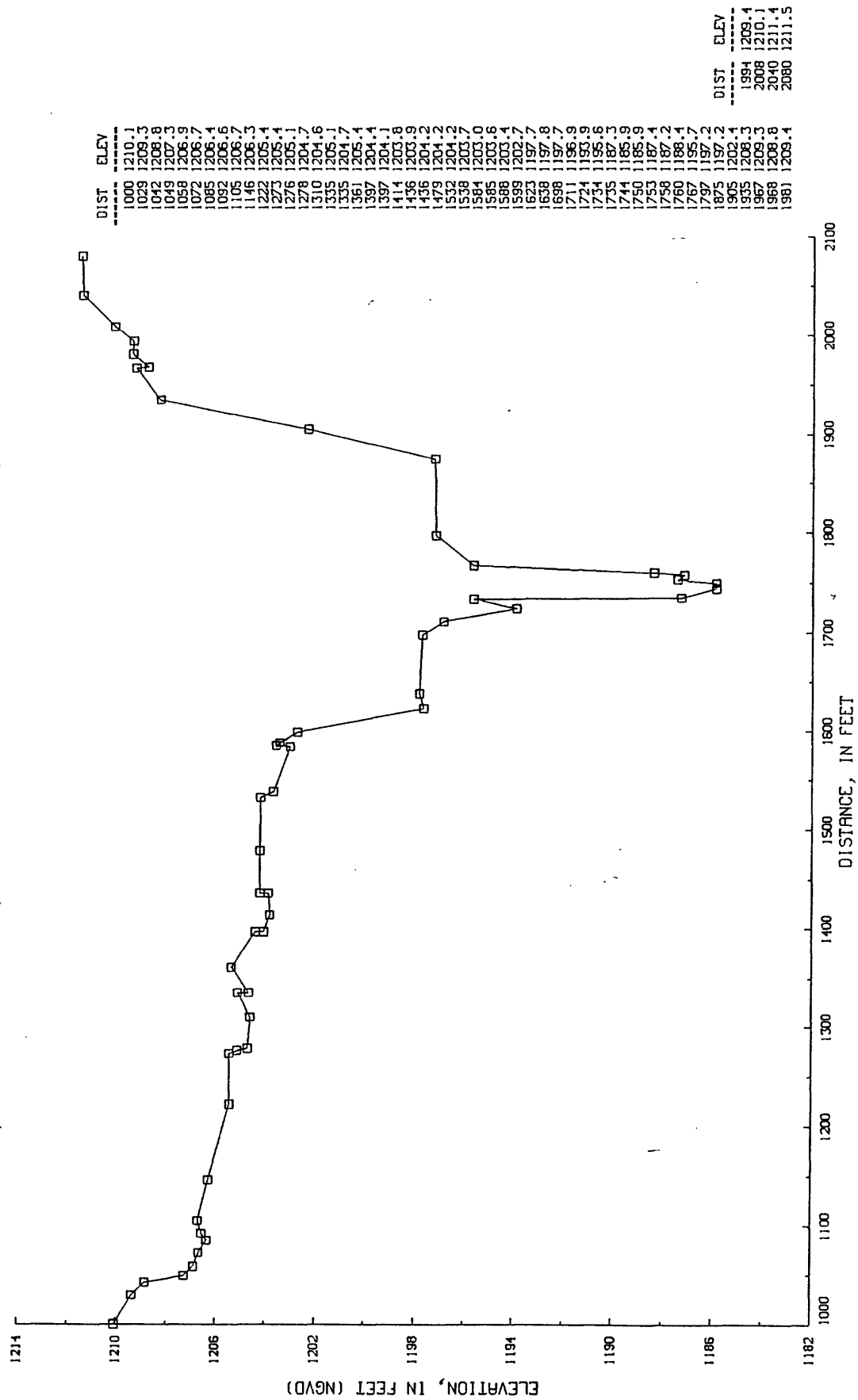
CROSS SECTION BK1, SOUTH SIDE SW 27TH, STATION - 3565



Appendix 3-2. Plot of cross section 1, Brock Creek at SW 29th Street (site 3).

BROCK CREEK AT SW 29TH STREET - MAY 8, 1993, FLOOD

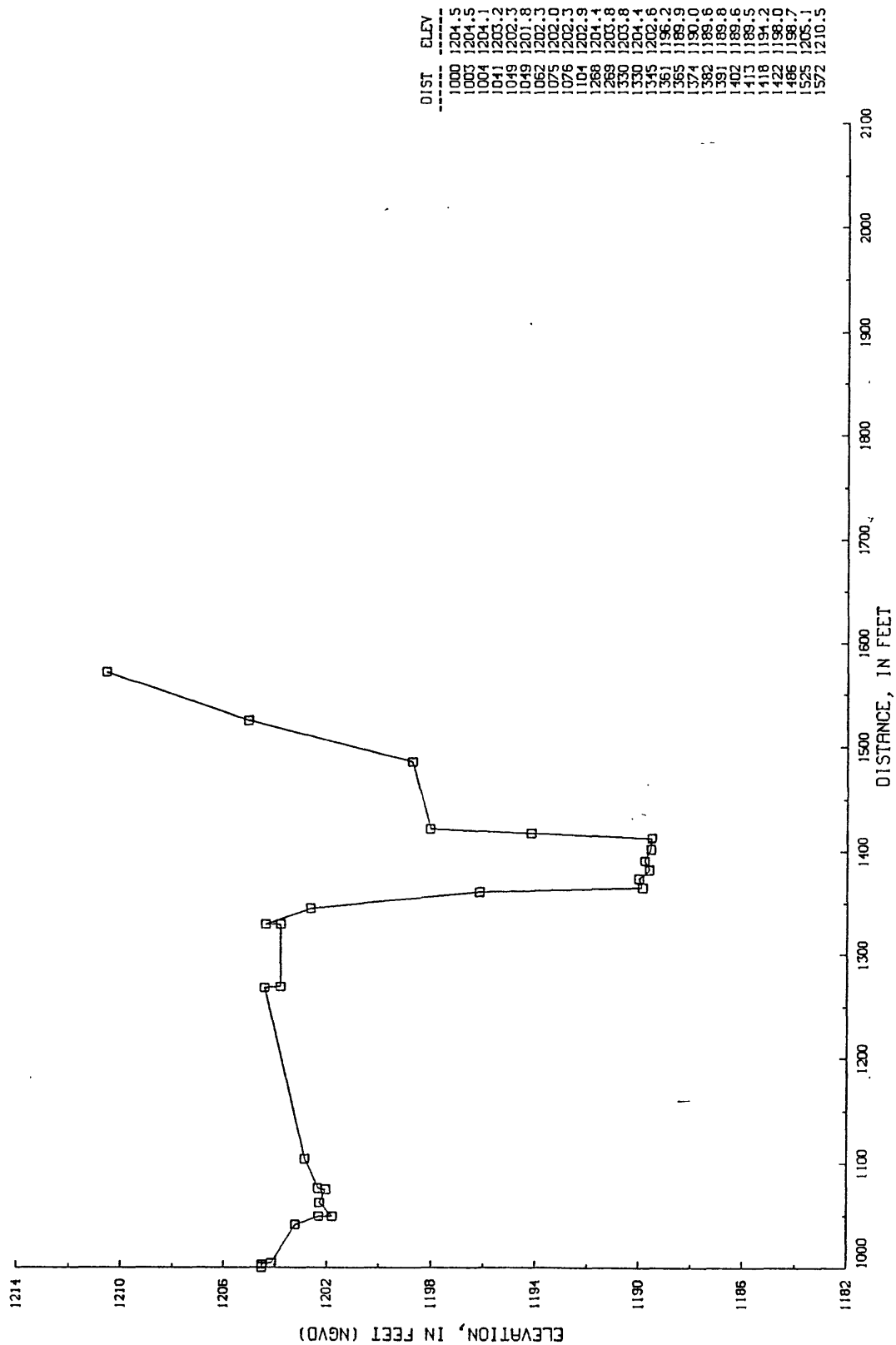
CROSS SECTION BK2, SOUTH SIDE SW 28TH, STATION - 3915



Appendix 3-3. Plot of cross section 2, Brock Creek at SW 29th Street (site 3).

BROCK CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

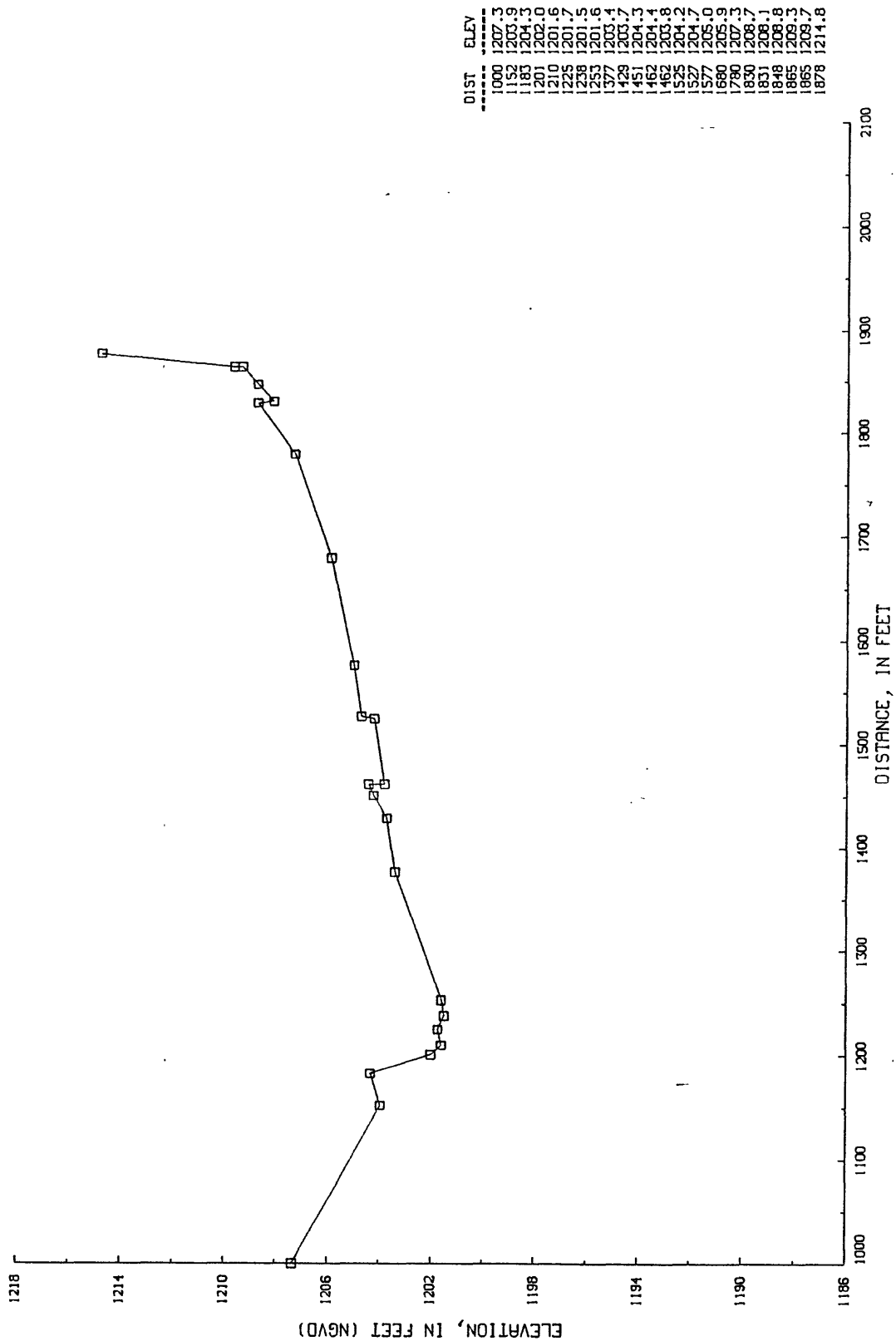
CROSS SECTION BK3, 50 FEET DOWNSTREAM CULVERT, STATION-4175



Appendix 3-4. Plot of cross section 3, Brock Creek at SW 29th Street (site 3).

BROCK CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

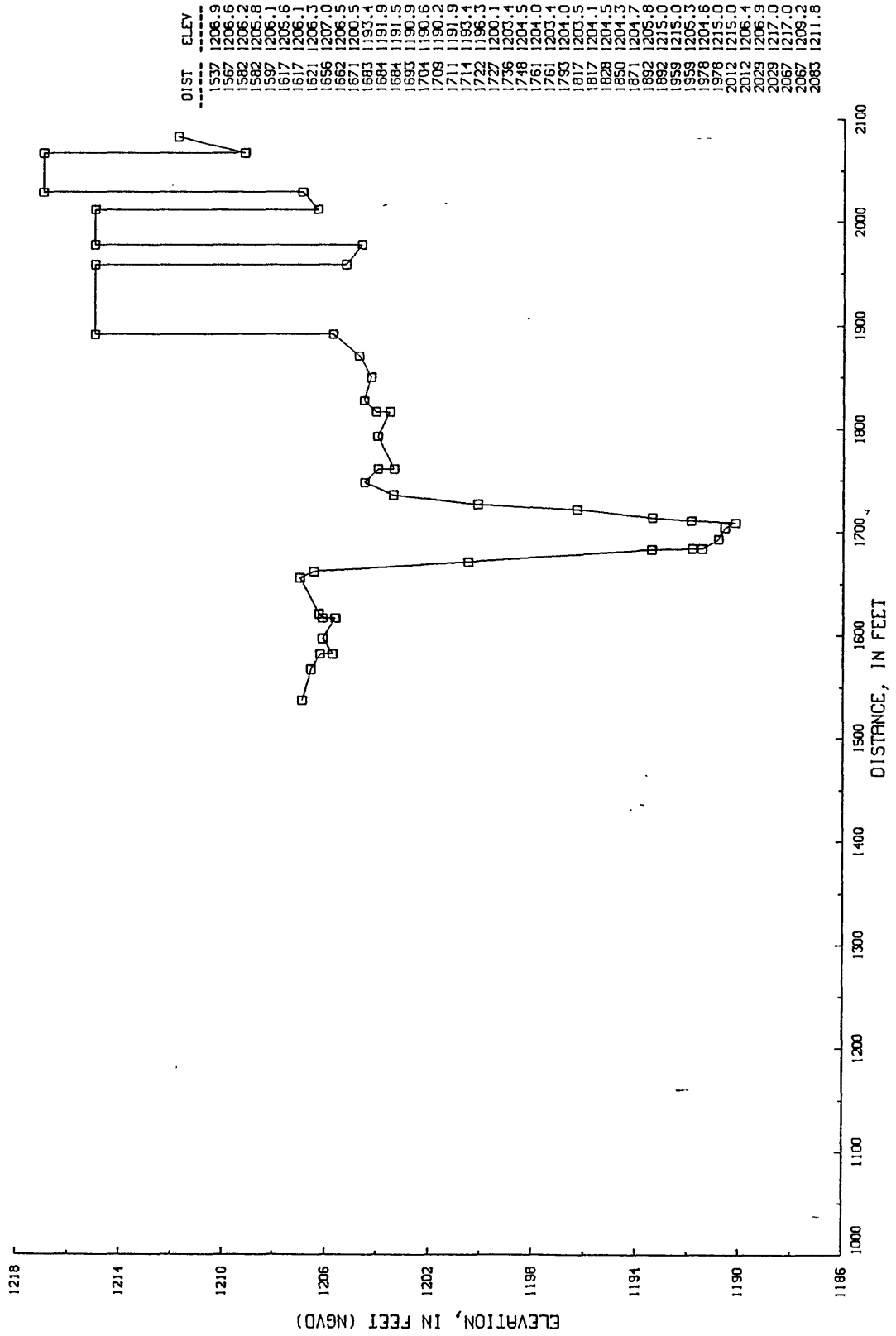
CROSS SECTION BK4R, SOUTH SIDE SW 29TH, STATION-4365



Appendix 3-5. Plot of cross section 4R, Brock Creek at SW 29th Street (site 3).

BROCK CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

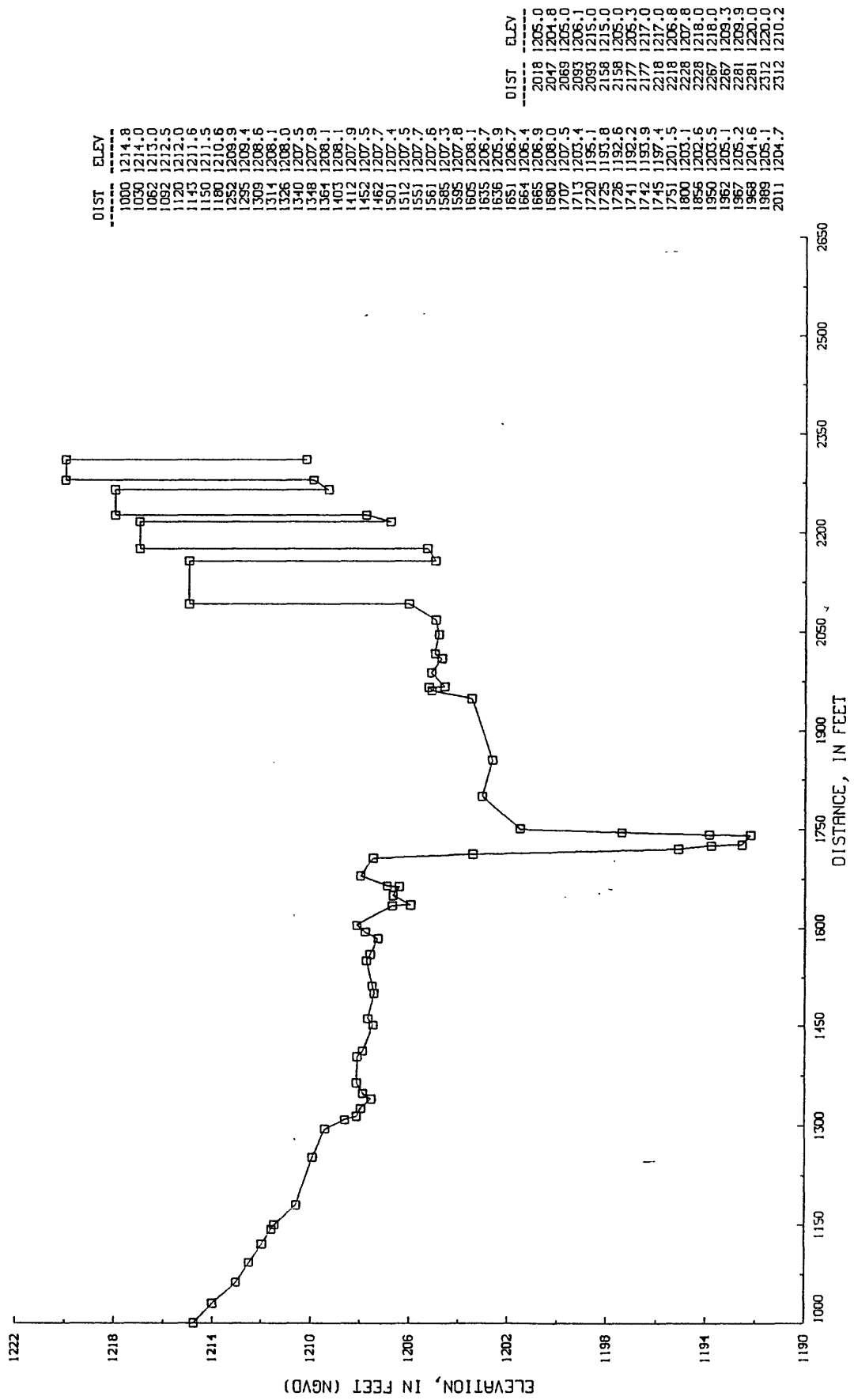
CROSS SECTION BKS, SOUTH SIDE SW 30TH, STATION - 4670



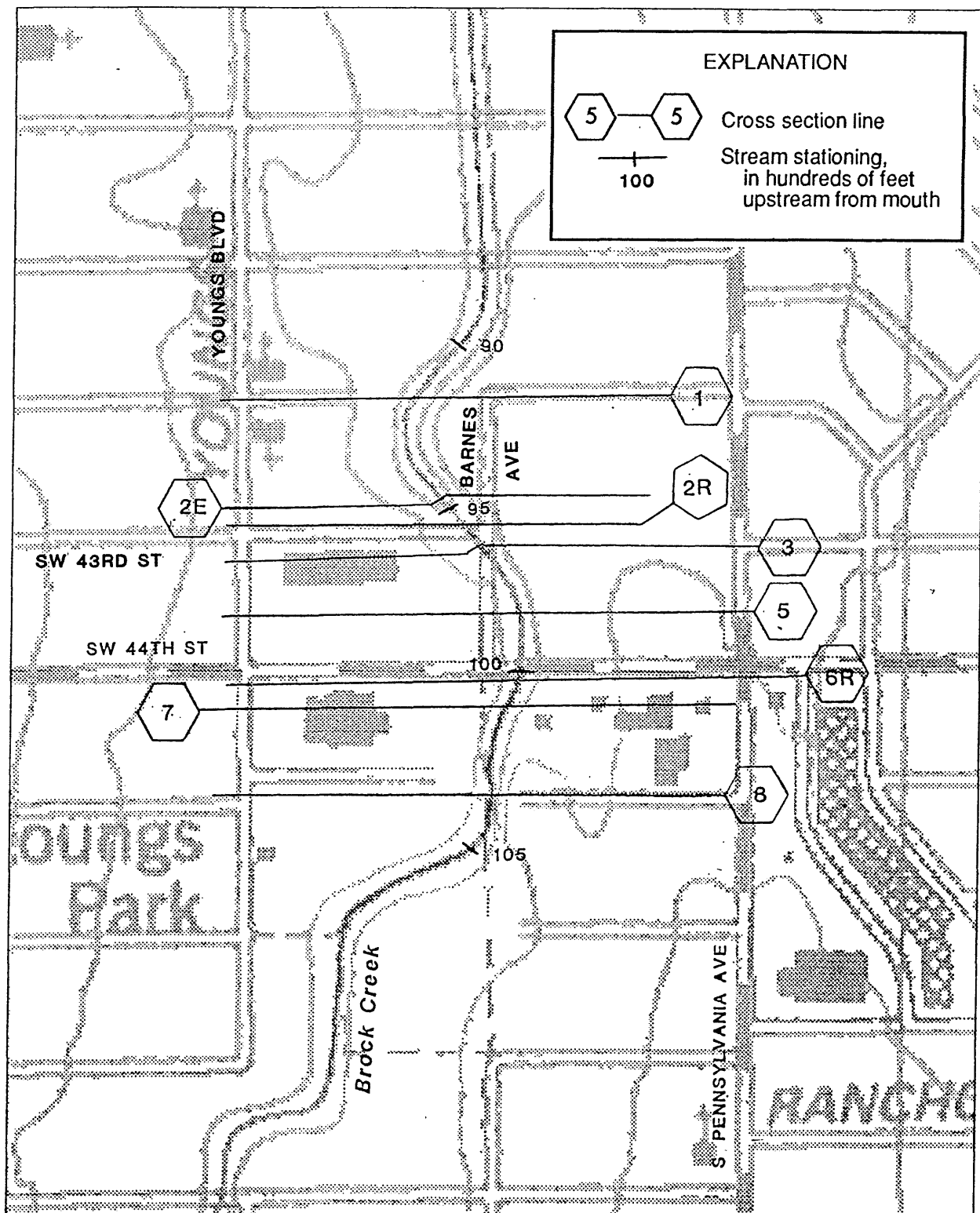
Appendix 3-6. Plot of cross section 5, Brock Creek at SW 29th Street (site 3).

BROCK CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK6, NORTH SIDE SW 31ST, STATION - 5020



Appendix 3-7. Plot of cross section 6, Brock Creek at SW 29th Street (site 3).



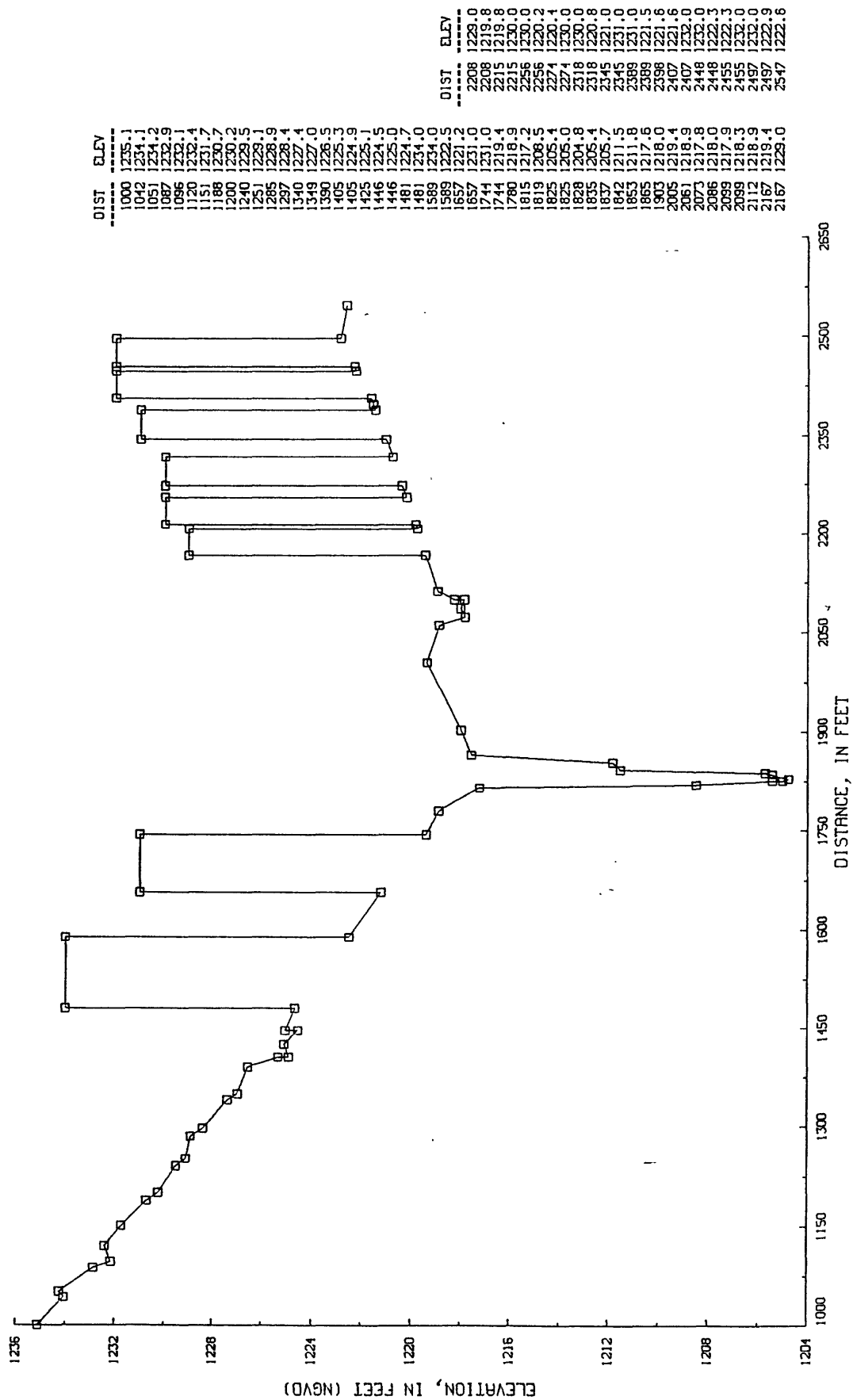
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 4-1. Location of study cross sections on Brock Creek at SW 44th Street (site 4).

BROCK CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

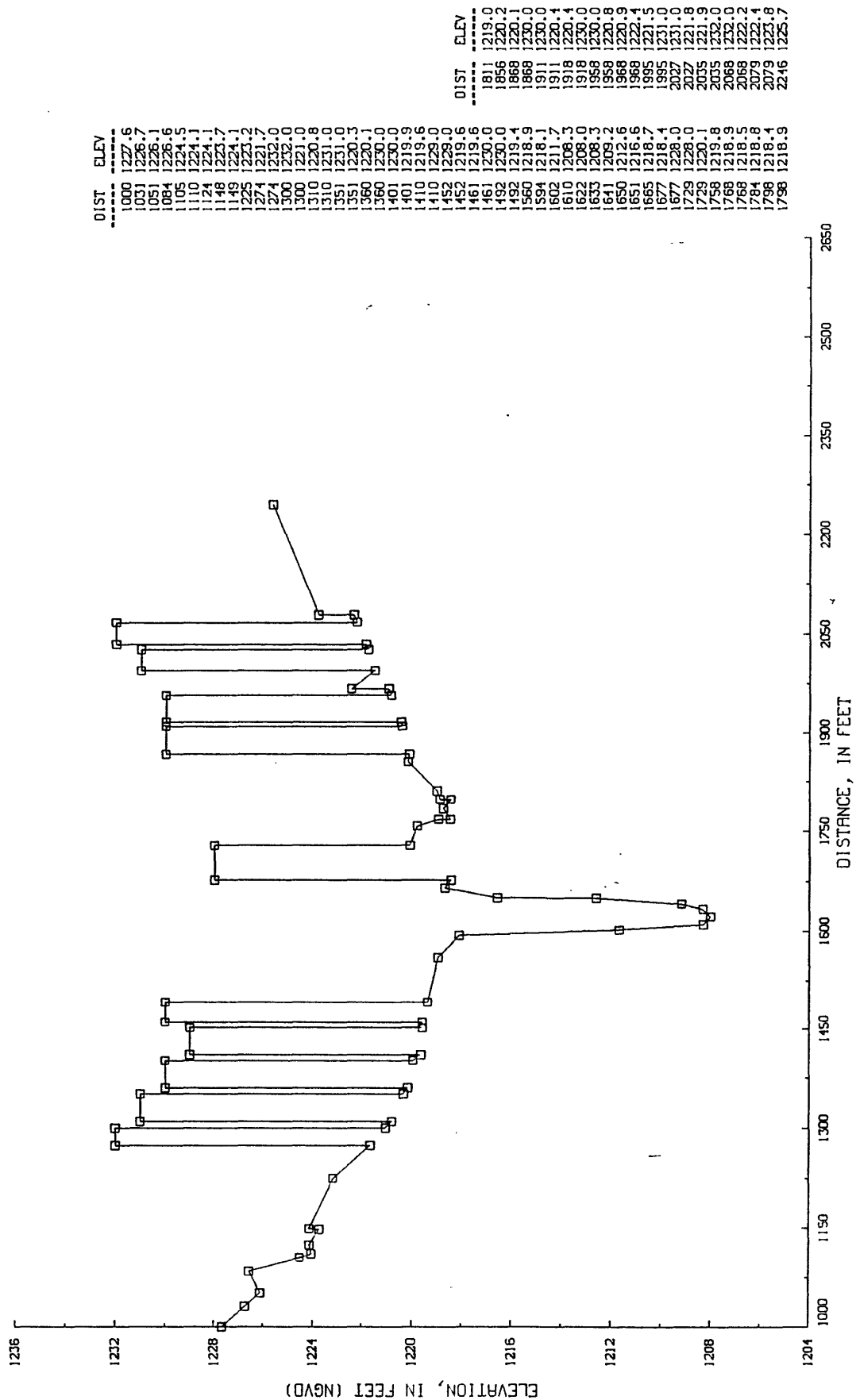
CROSS SECTION BK1, SOUTH SIDE SW 42ND, STATION - 9105



Appendix 4-2. Plot of cross section 1, Brock Creek at SW 44th Street (site 4).

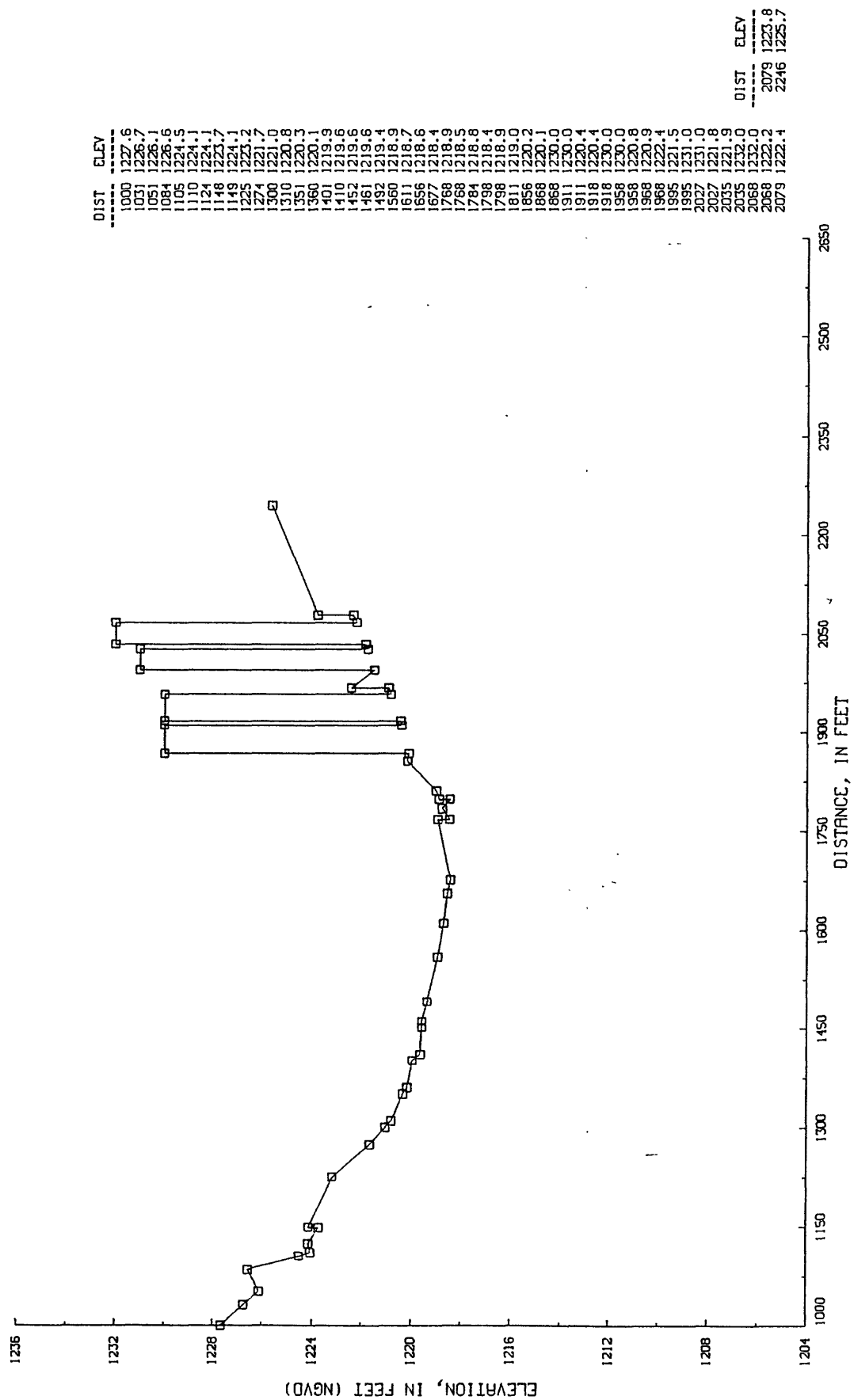
BROCK CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK2E, EXIT SW 43RD CULVERT, STATION - 9470



Appendix 4-3. Plot of cross section 2E, Brock Creek at SW 44th Street (site 4).

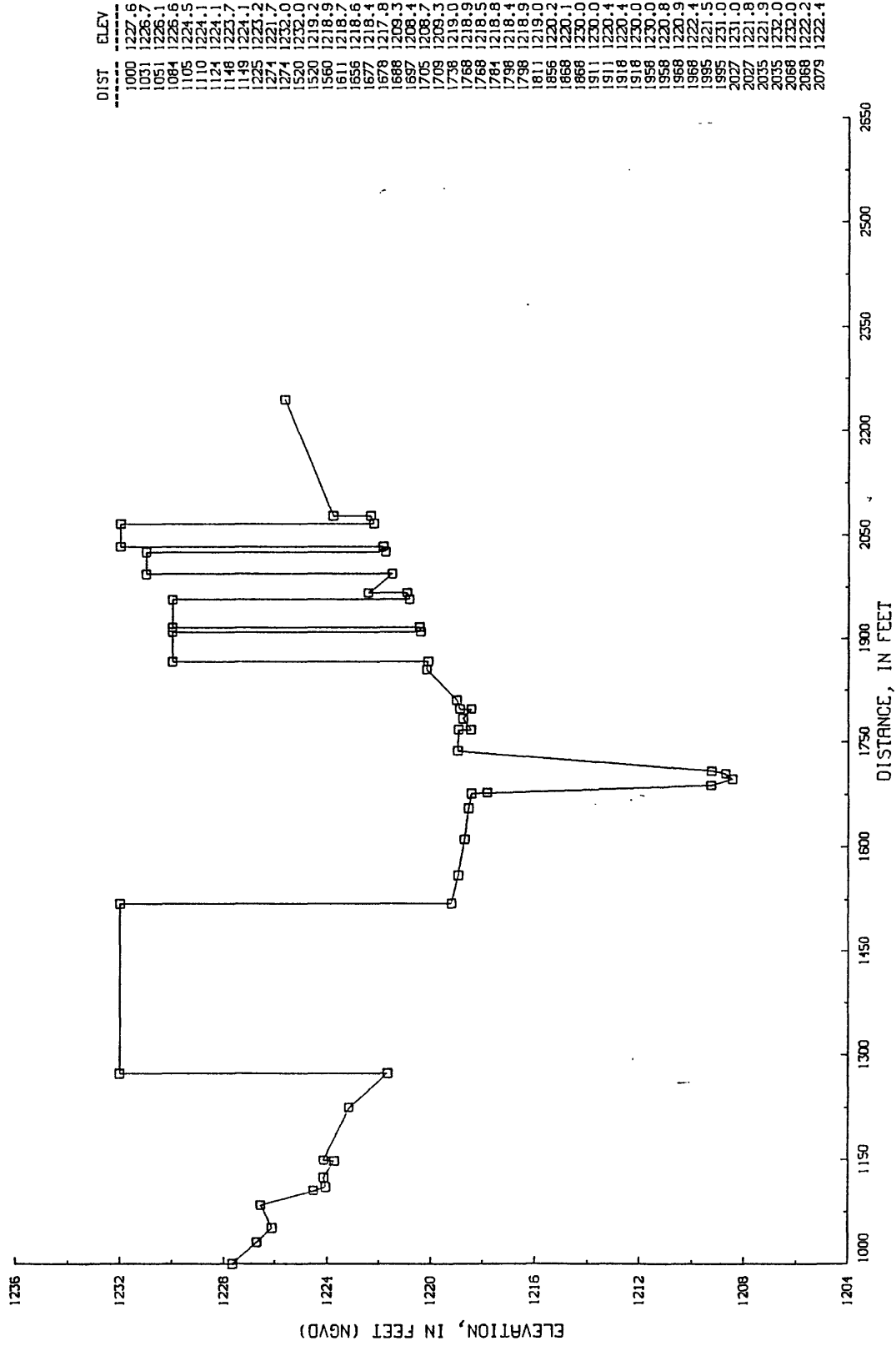
BROCK CREEK AT SW44TH STREET, MAY 8, 1993 FLOOD
CROSS SECTION BK2R, NORTH SIDE SW 43RD, STATION - 9505



Appendix 4-4. Plot of cross section 2R, Brock Creek at SW 44th Street (site 4).

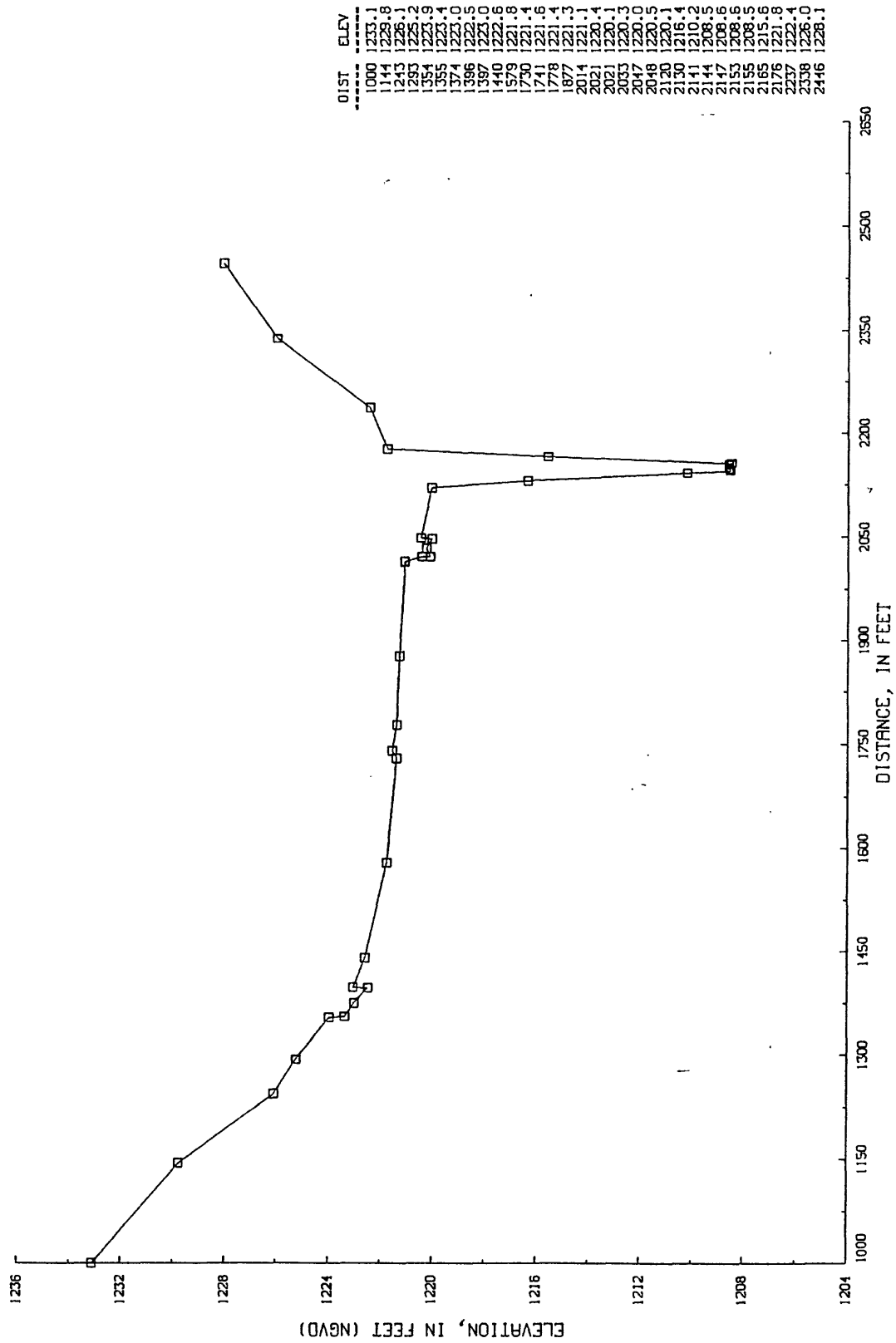
BROCK CREEK AT SW44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK3, BETWEEN SW 43RD/BARNES, STATION - 9635



Appendix 4-5. Plot of cross section 3, Brock Creek at SW 44th Street (site 4).

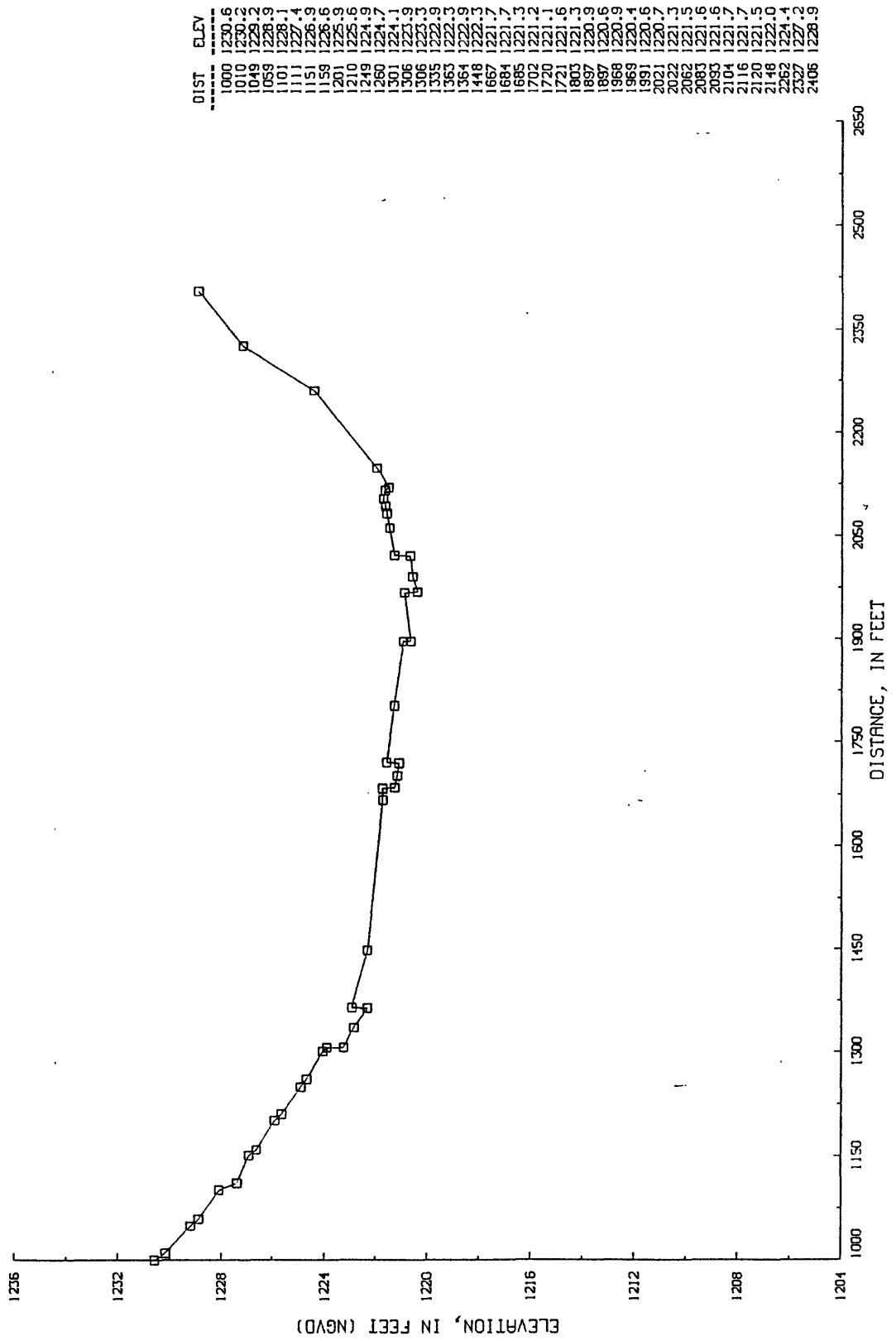
BROCK CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD
CROSS SECTION BKS, BETWEEN BARNES/SW 44TH, STATION - 9855



Appendix 4-6. Plot of cross section 5, Brock Creek at SW 44th Street (site 4).

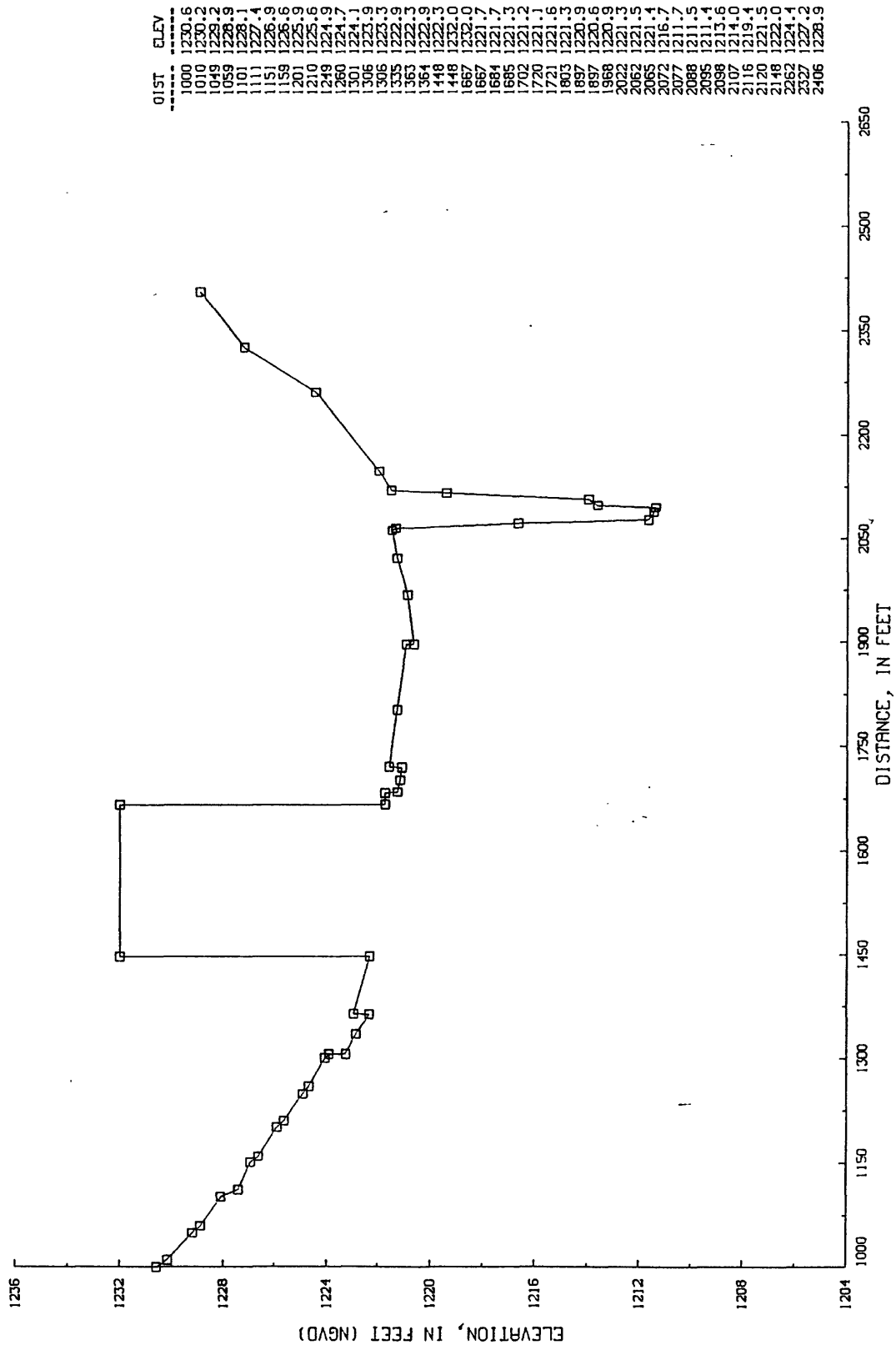
BROCK CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK6R, SOUTH SIDE SW 44TH, STATION - 10010



Appendix 4-7. Plot of cross section 6R, Brock Creek at SW 44th Street (site 4).

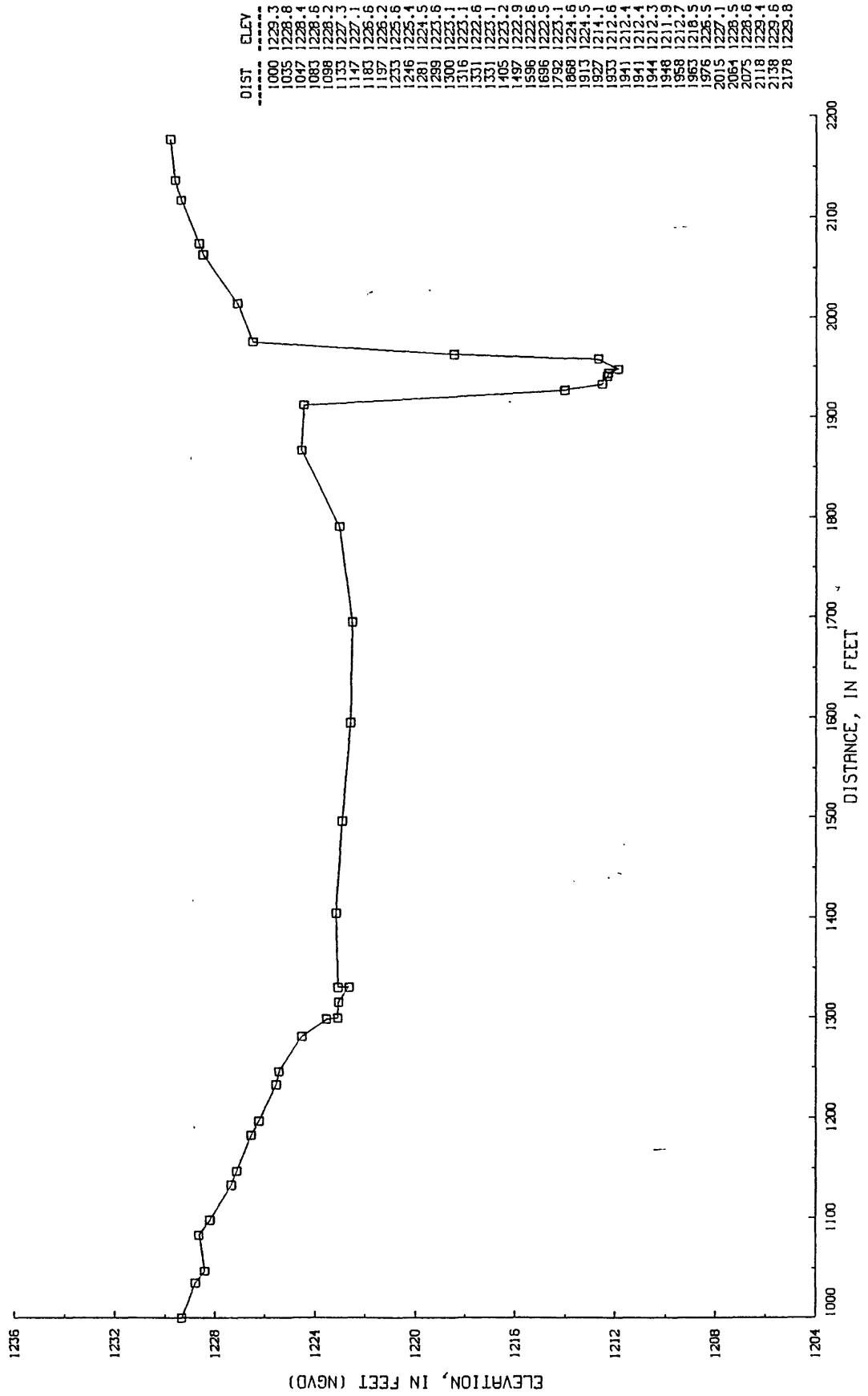
BROCK CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION BK7, ABOVE SW 44TH CULVERT, STATION - 10085



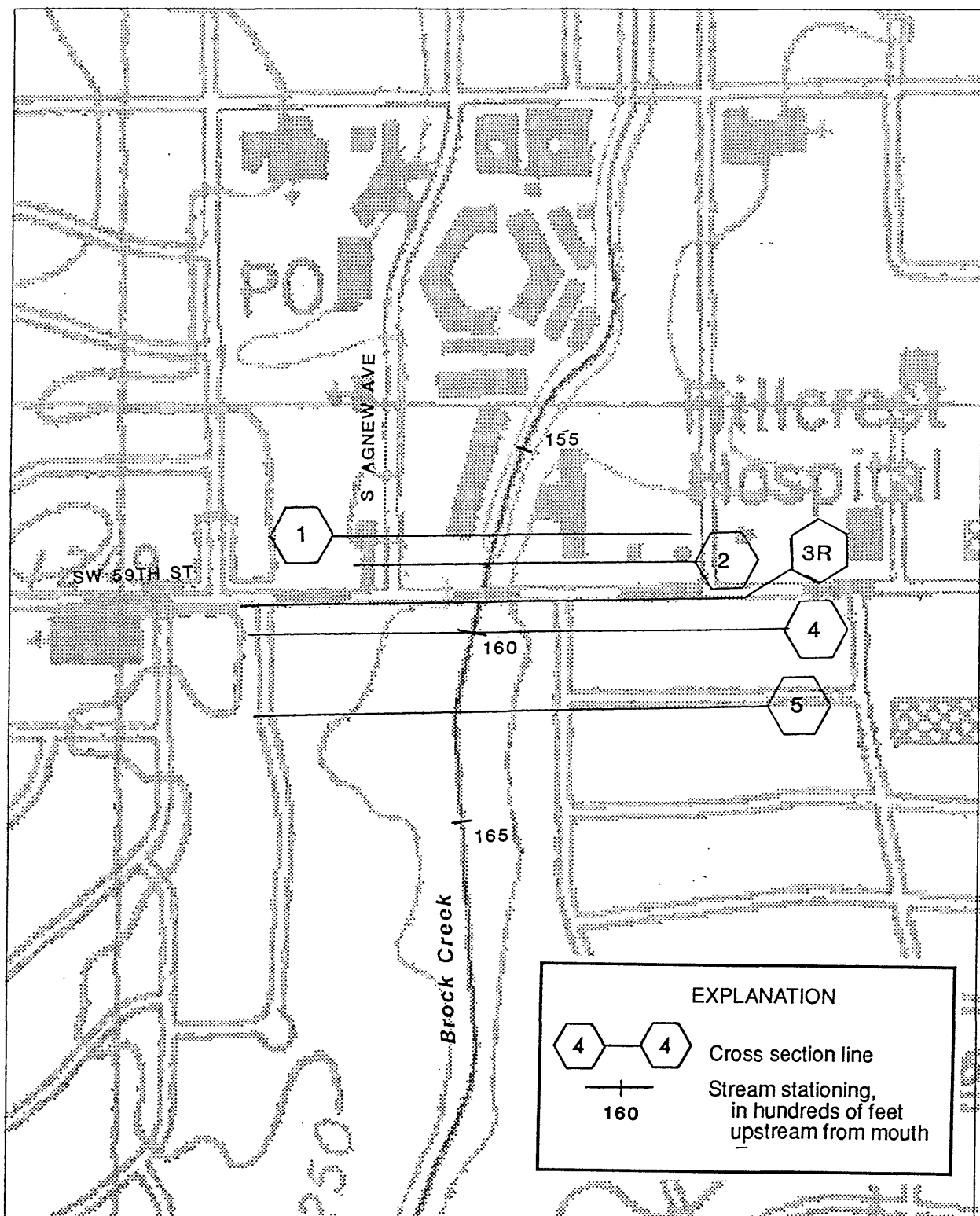
Appendix 4-8. Plot of cross section 7, Brock Creek at SW 44th Street (site 4).

BROCK CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK8, SOUTH SIDE SW 45TH, STATION - 10380



Appendix 4-9. Plot of cross section 8, Brock Creek at SW 44th Street (site 4).



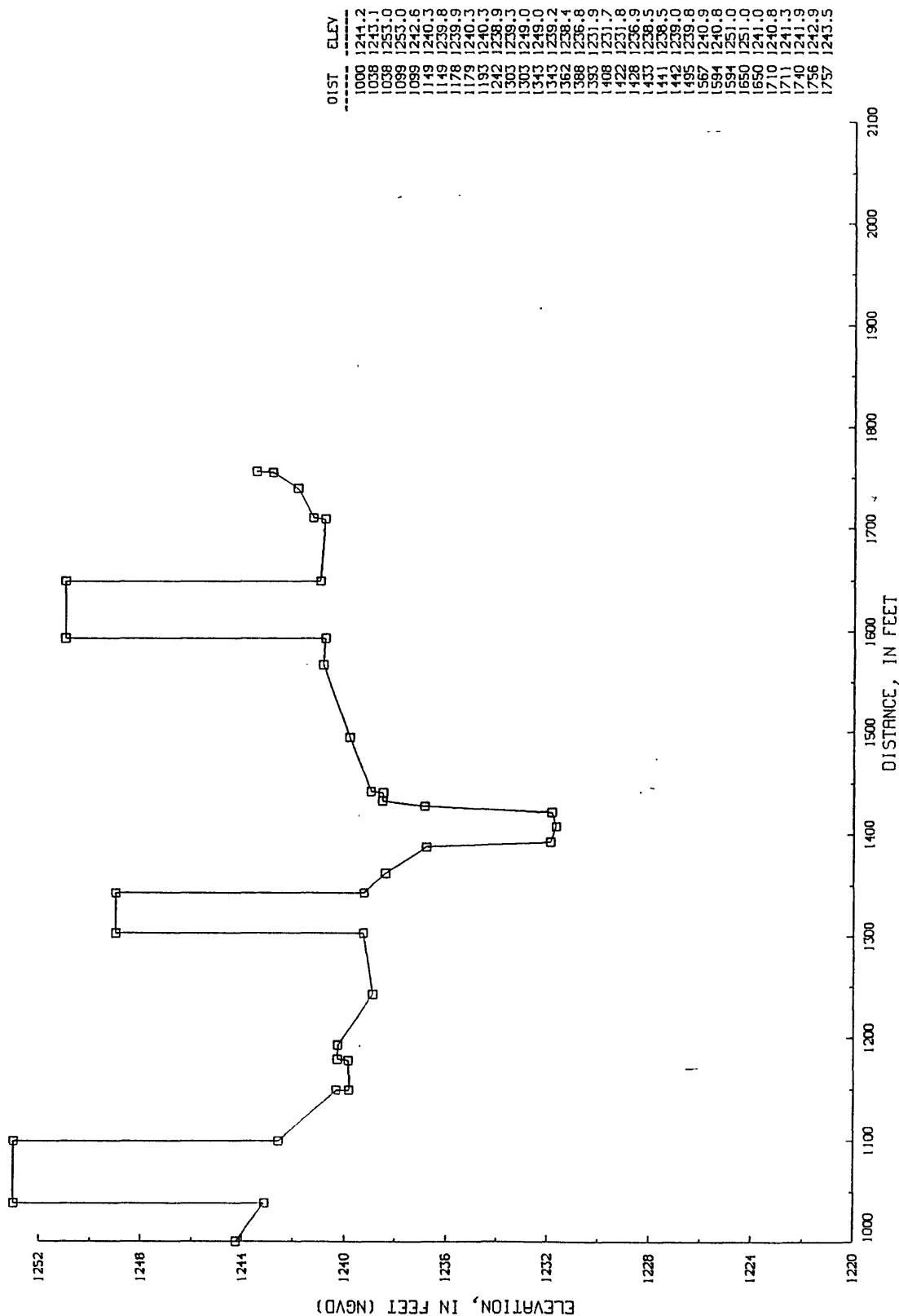
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 5-1. Location of study cross sections on Brock Creek at SW 59th Street (site 5).

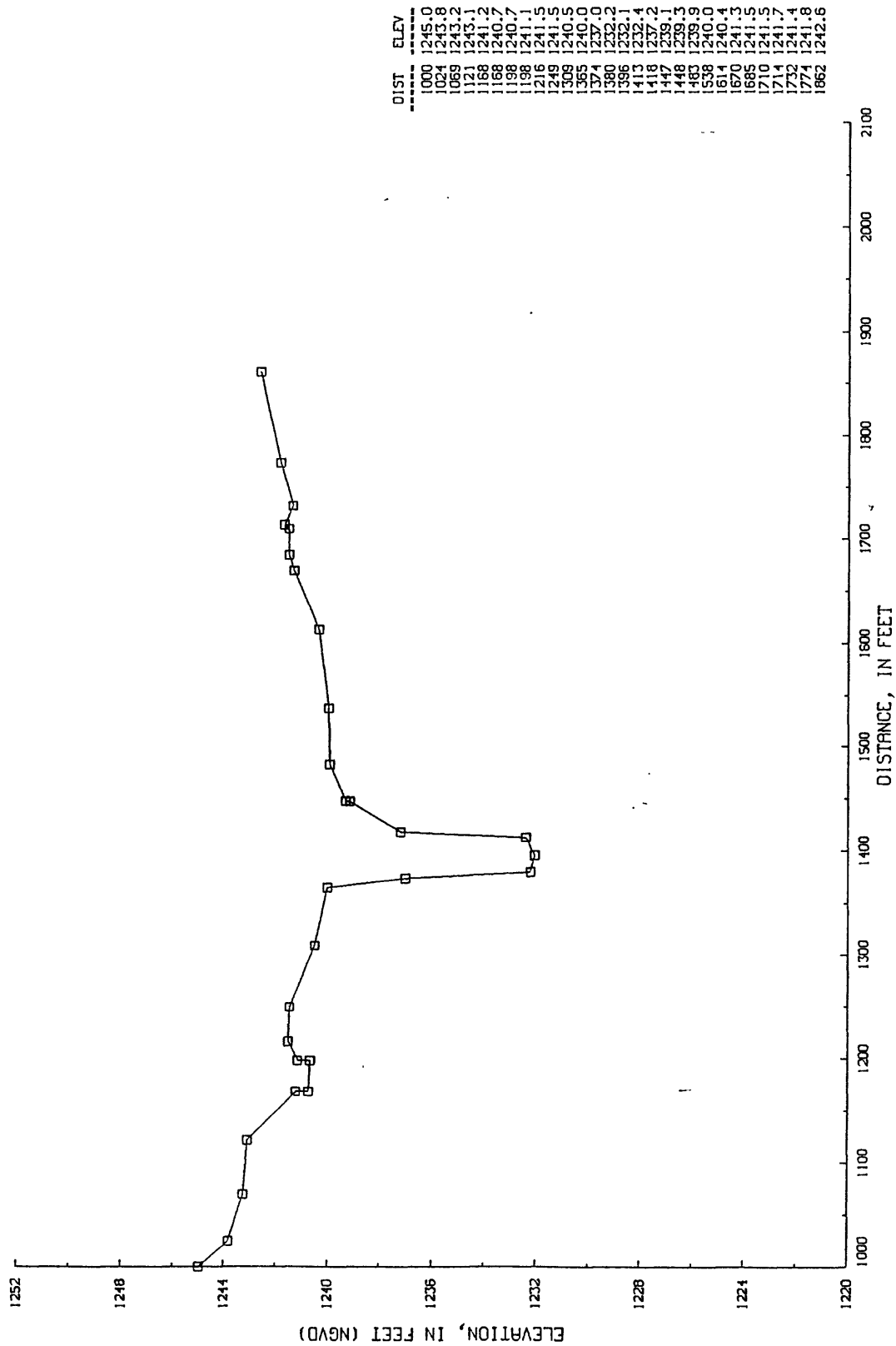
BROCK CREEK AT SW 59TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK1, SOUTH SIDE STRIP MALL, STATION-15765



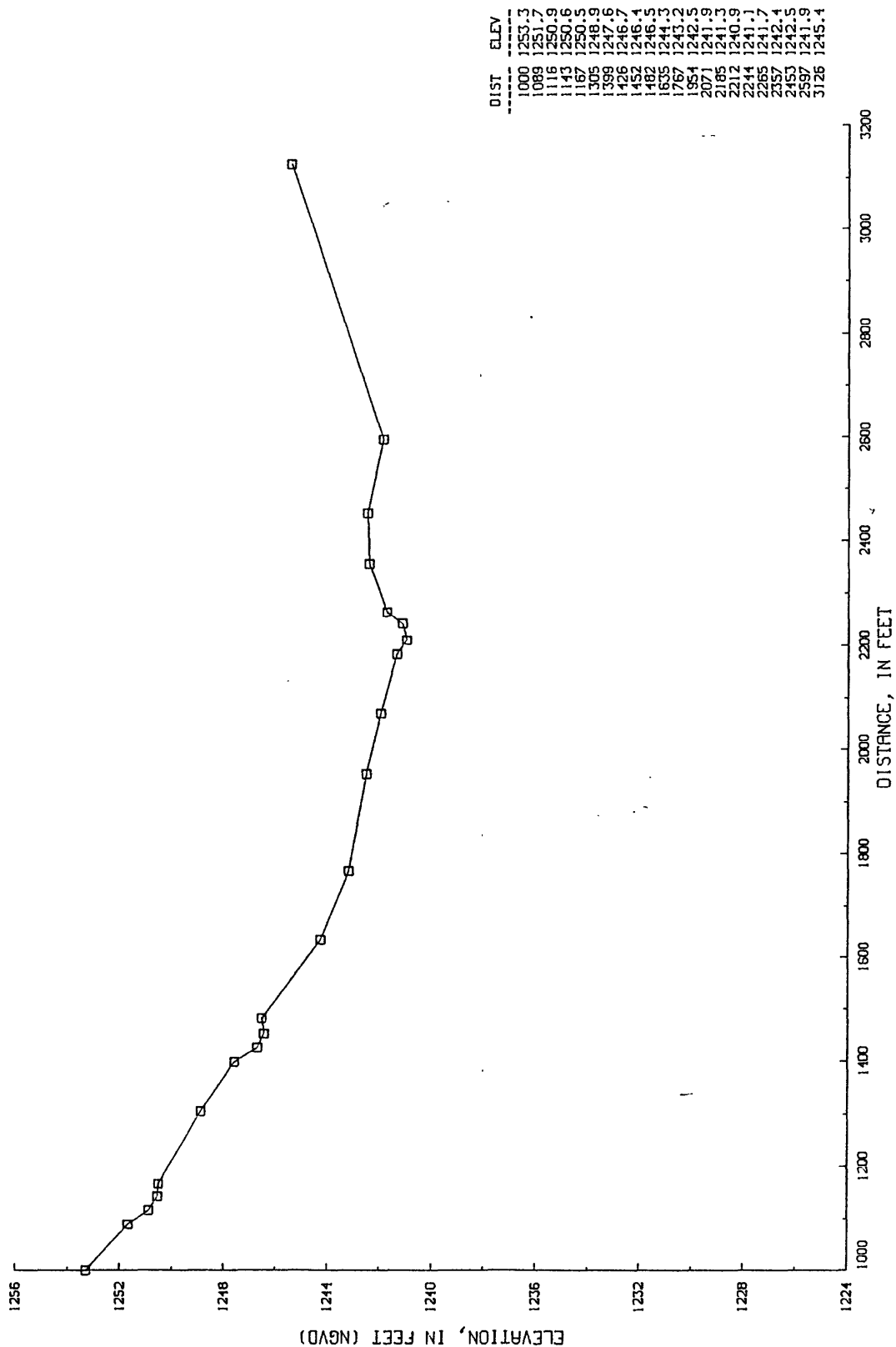
Appendix 5-2. Plot of cross section 1, Brock Creek at SW 59th Street (site 5).

BROCK CREEK AT SW 59TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION BK2, EXIT SW 59TH CULVERT - STATION - 15840



Appendix 5-3. Plot of cross section 2, Brock Creek at SW 59th Street (site 5).

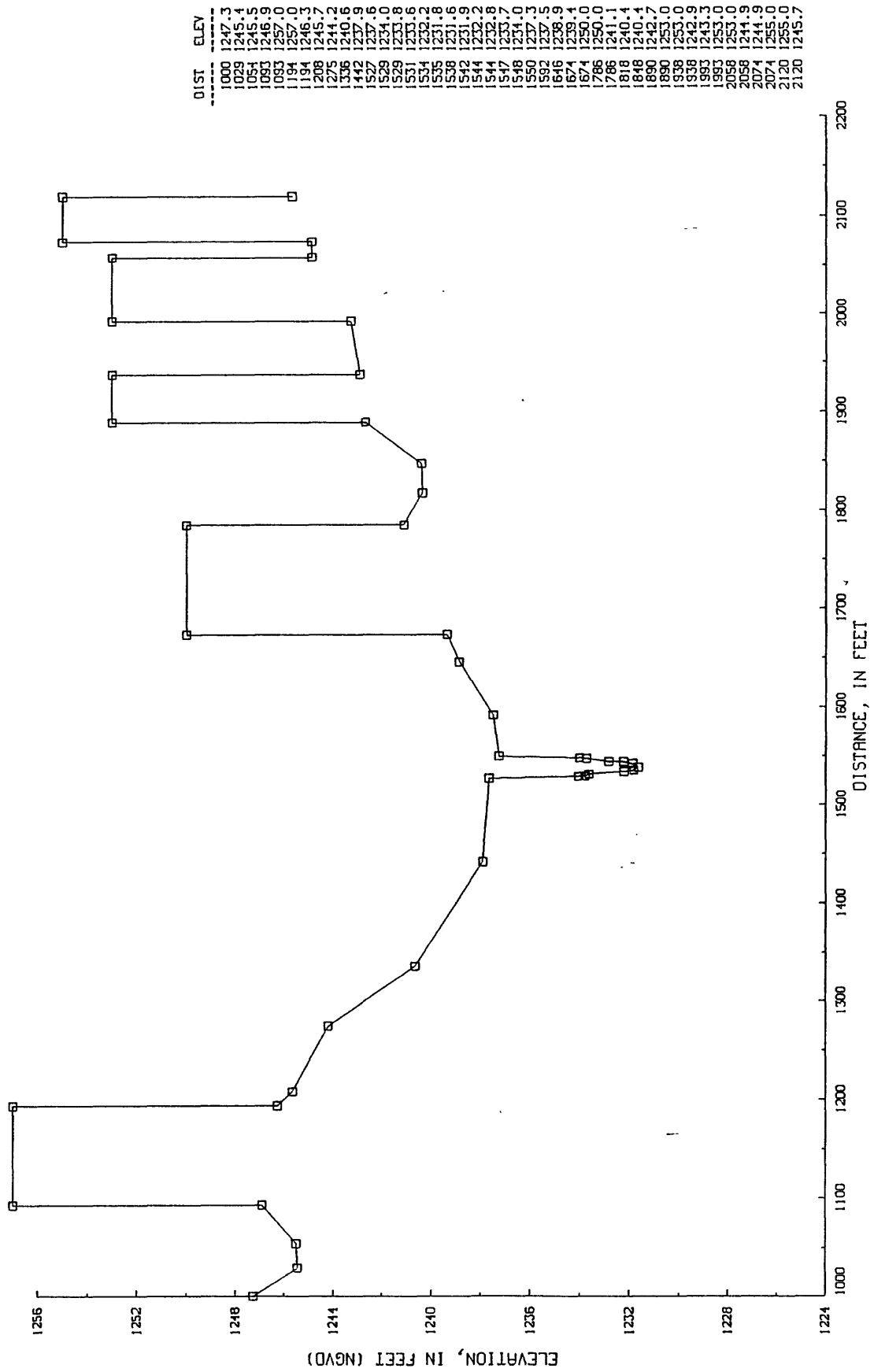
BROCK CREEK AT SW 59TH STREET, MAY 8, 1993, FLOOD
 CROSS SECTION BK3R, SOUTH SIDE SW 59TH - STATION - 15940



Appendix 5-4. Plot of cross section 3R, Brock Creek at SW 59th Street (site 5).

BROCK CREEK AT SW59TH STREET, MAY 8, 1993 ,FLOOD

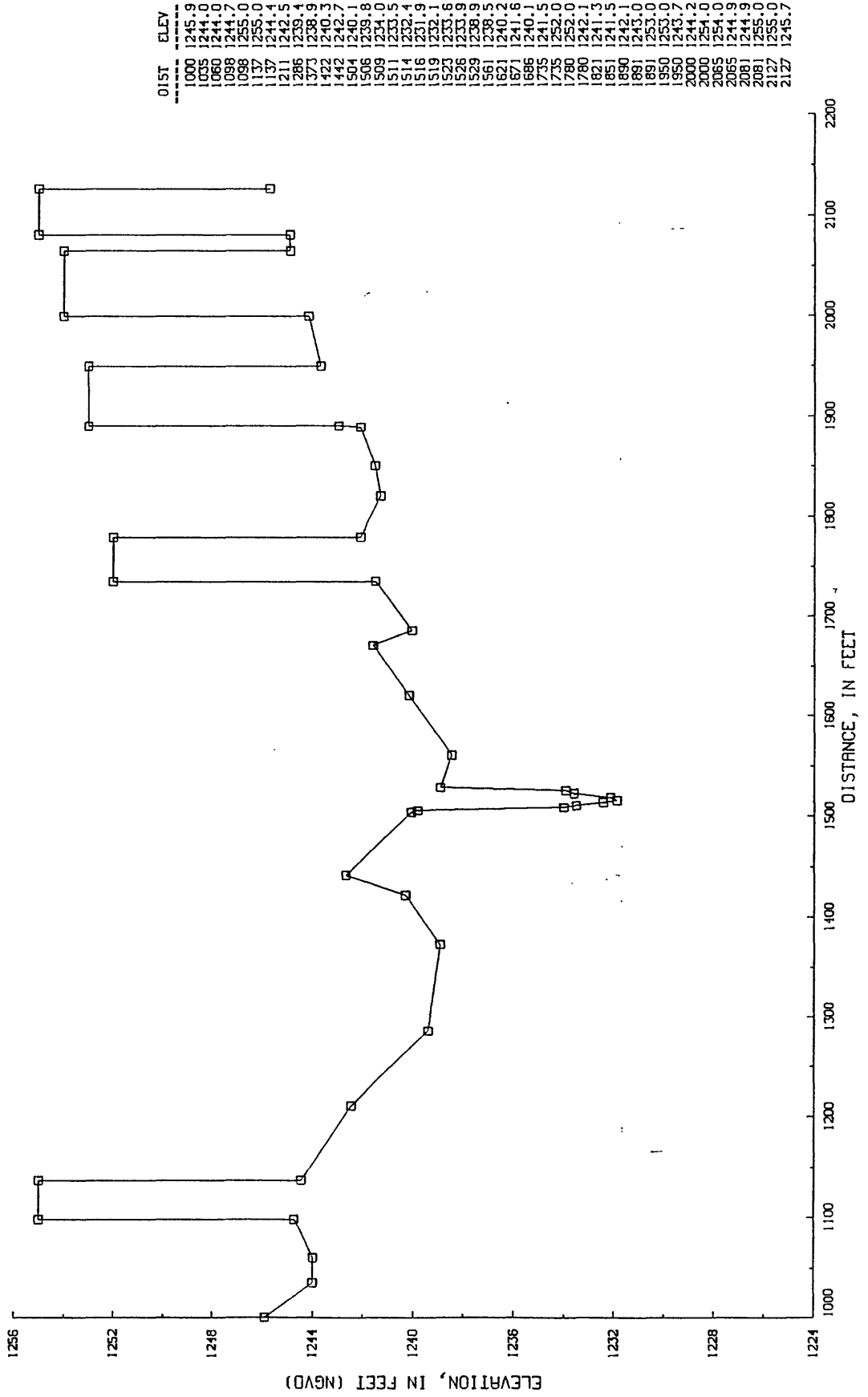
CROSS SECTION BK4, WILLOW CREEK GOLF COURSE - STATION-16000



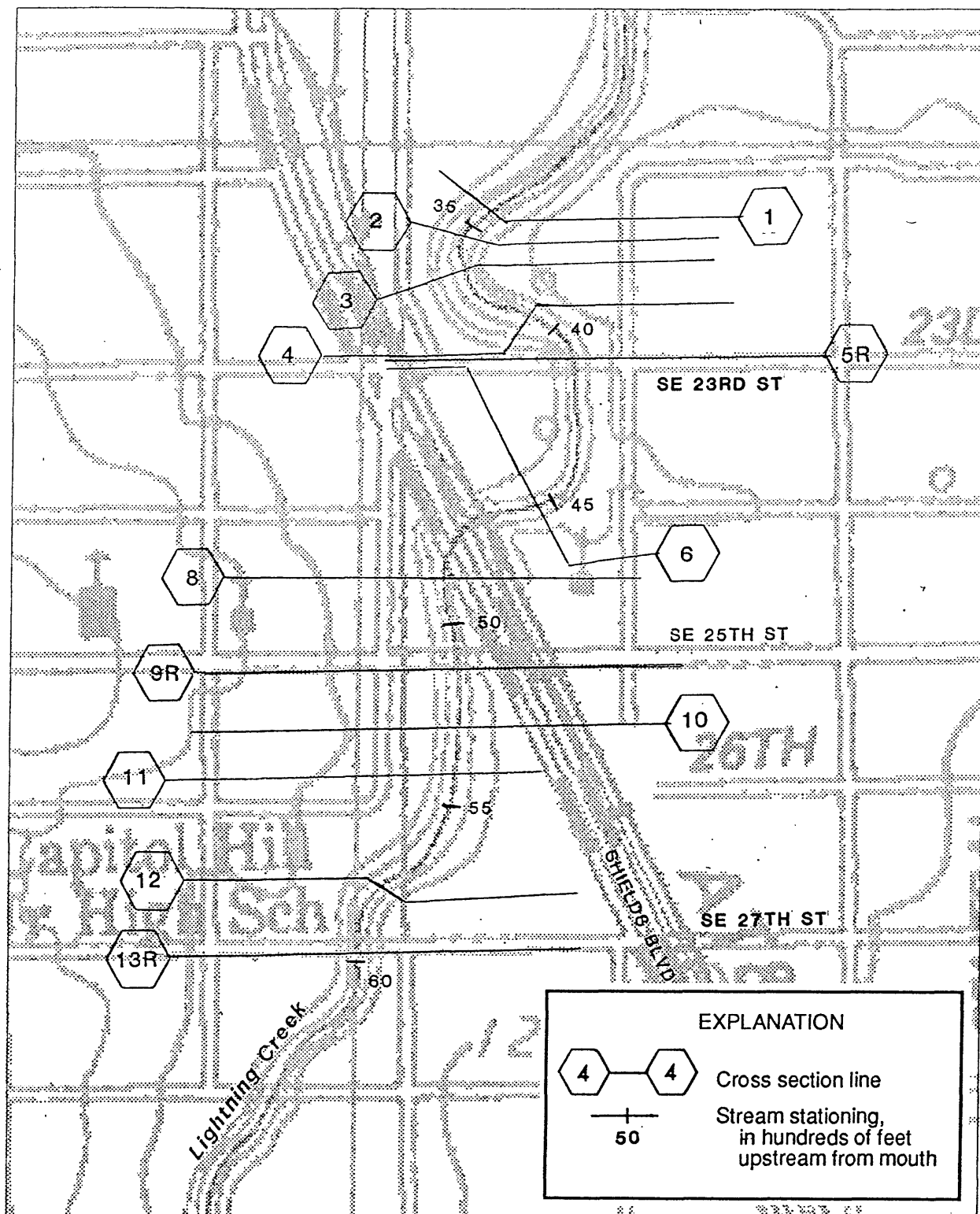
Appendix 5-5. Plot of cross section 4, Brock Creek at SW 59th Street (site 5).

BROCK CREEK AT SWS9TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION BK5, SW 59TH PLACE - STATION - 16205



Appendix 5-6. Plot of cross section 5, Brock Creek at SW 59th Street (site 5).



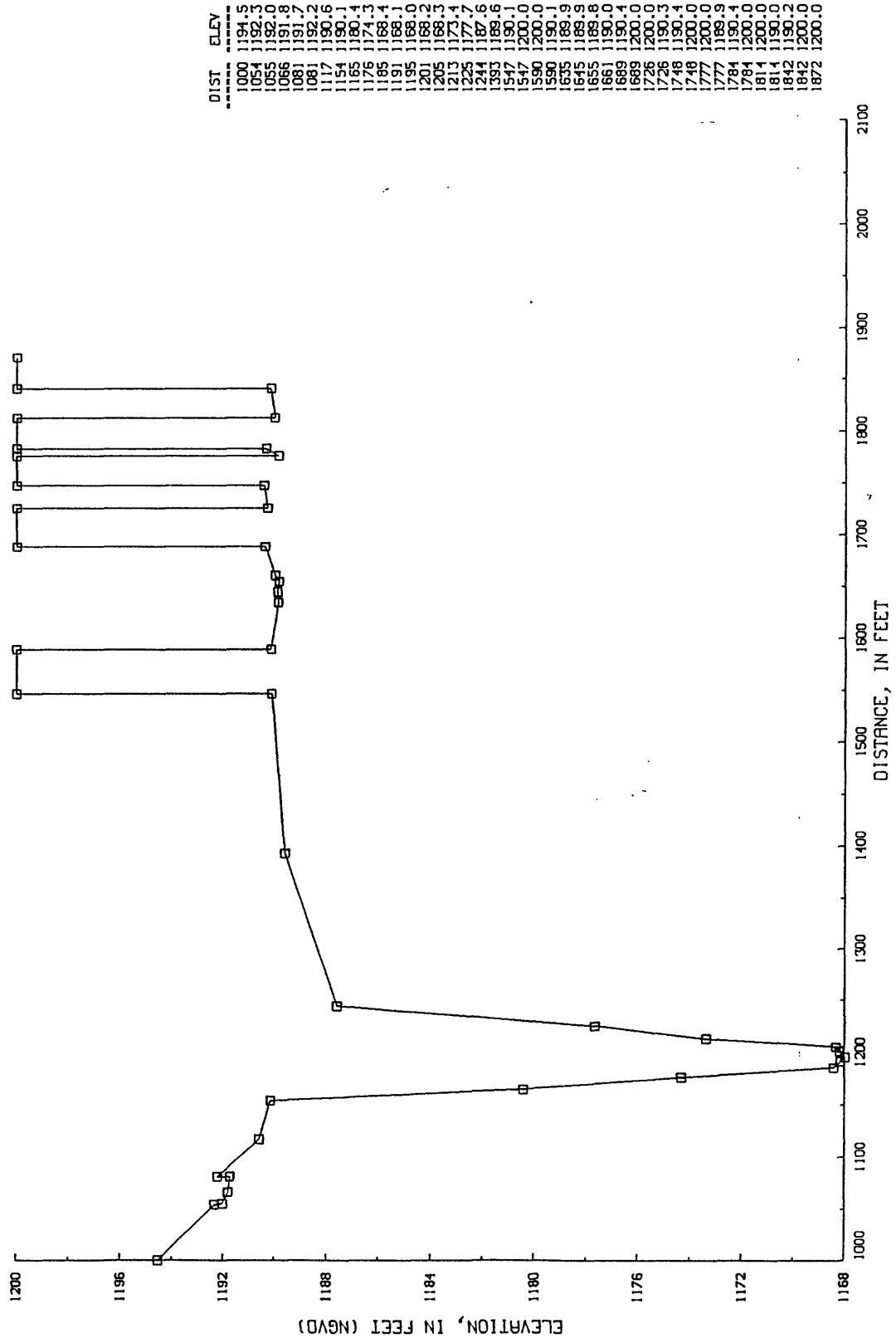
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 6-1. Location of study cross sections on Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

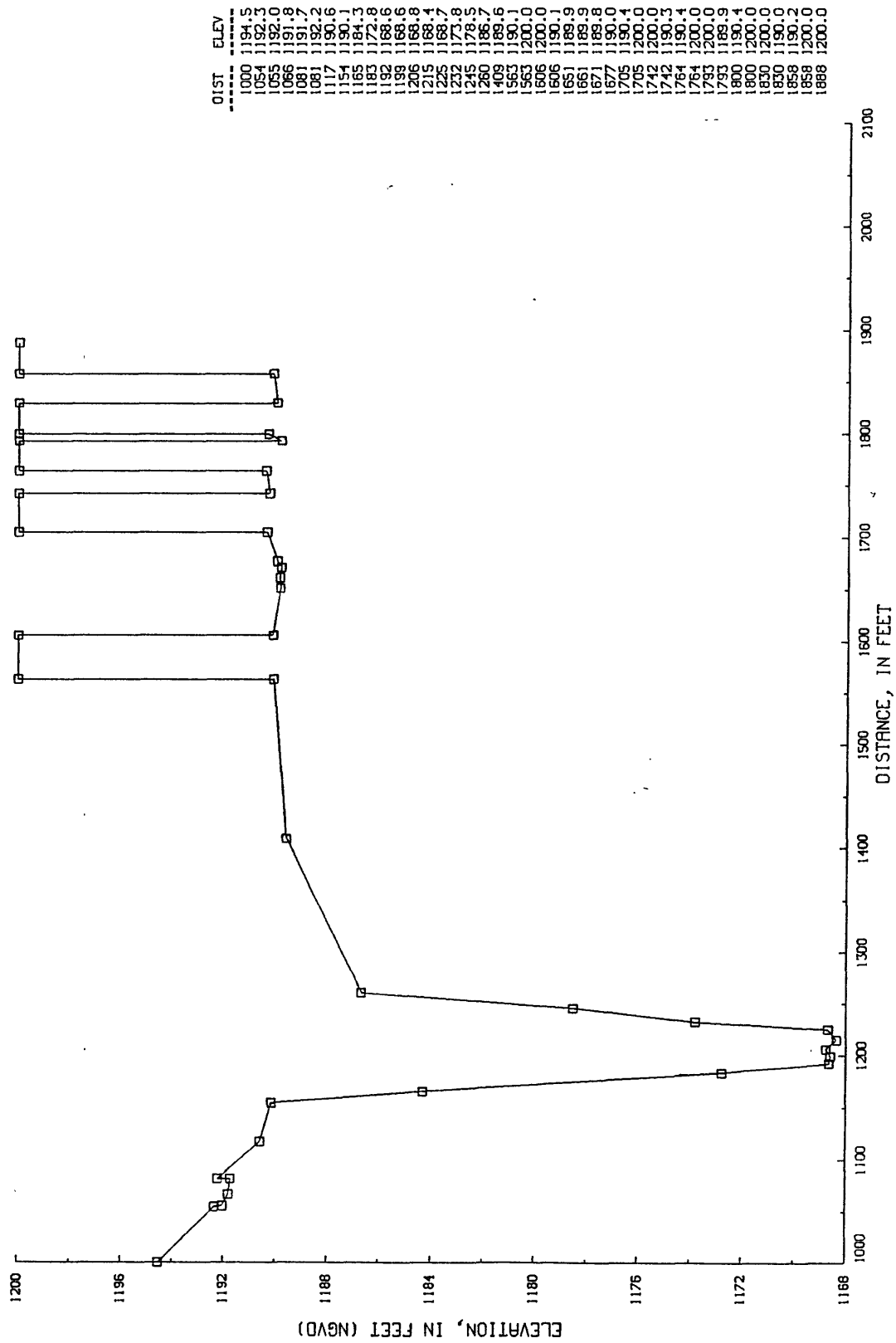
CROSS SECTION LG1, 110 FEET DOWNSTREAM LONG EXIT-STATION-3450



Appendix 6-2. Plot of cross section 1, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

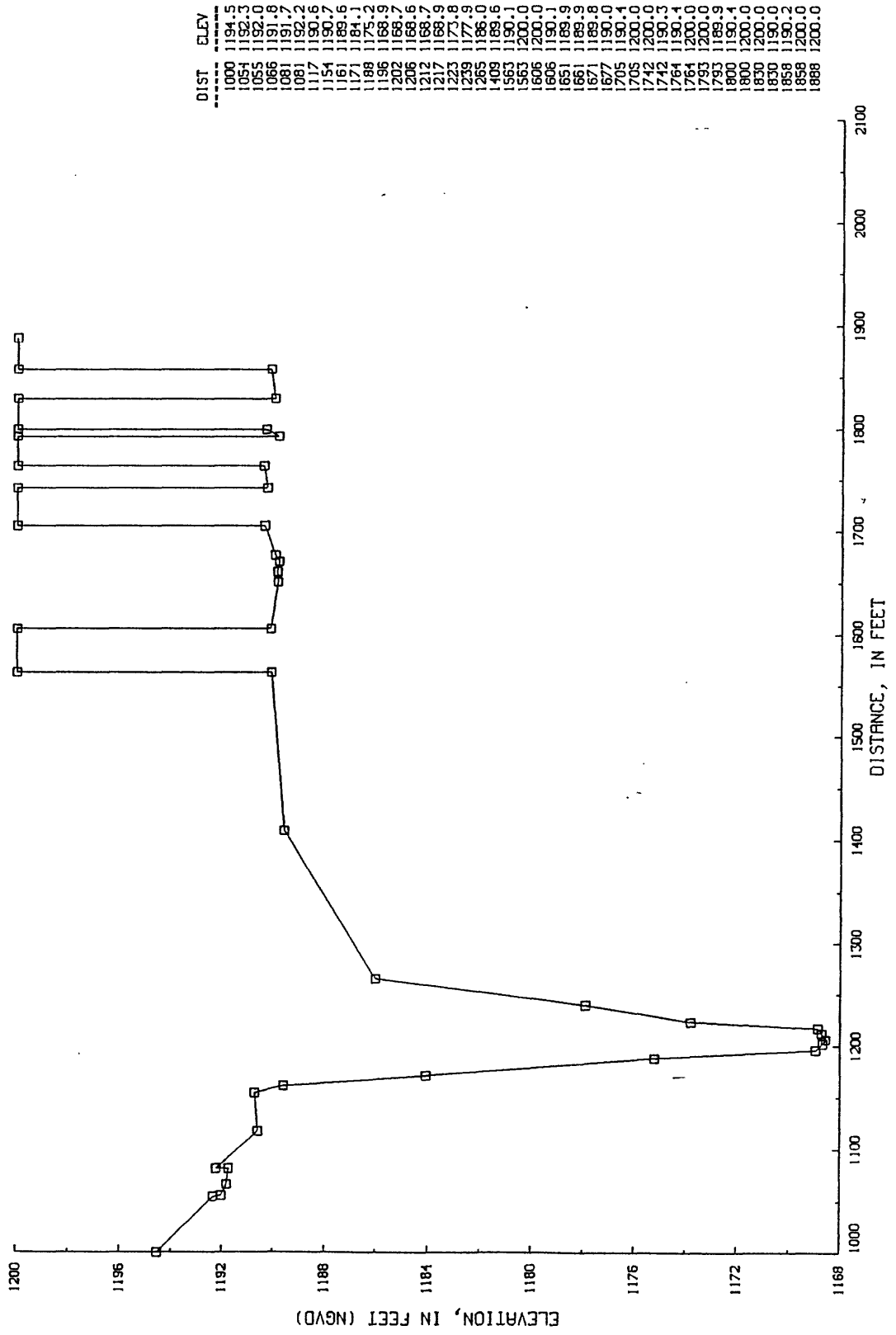
CROSS SECTION 162, 30 FEET DOWNSTREAM LONG EXIT-STATION-3530



Appendix 6-3. Plot of cross section 2, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

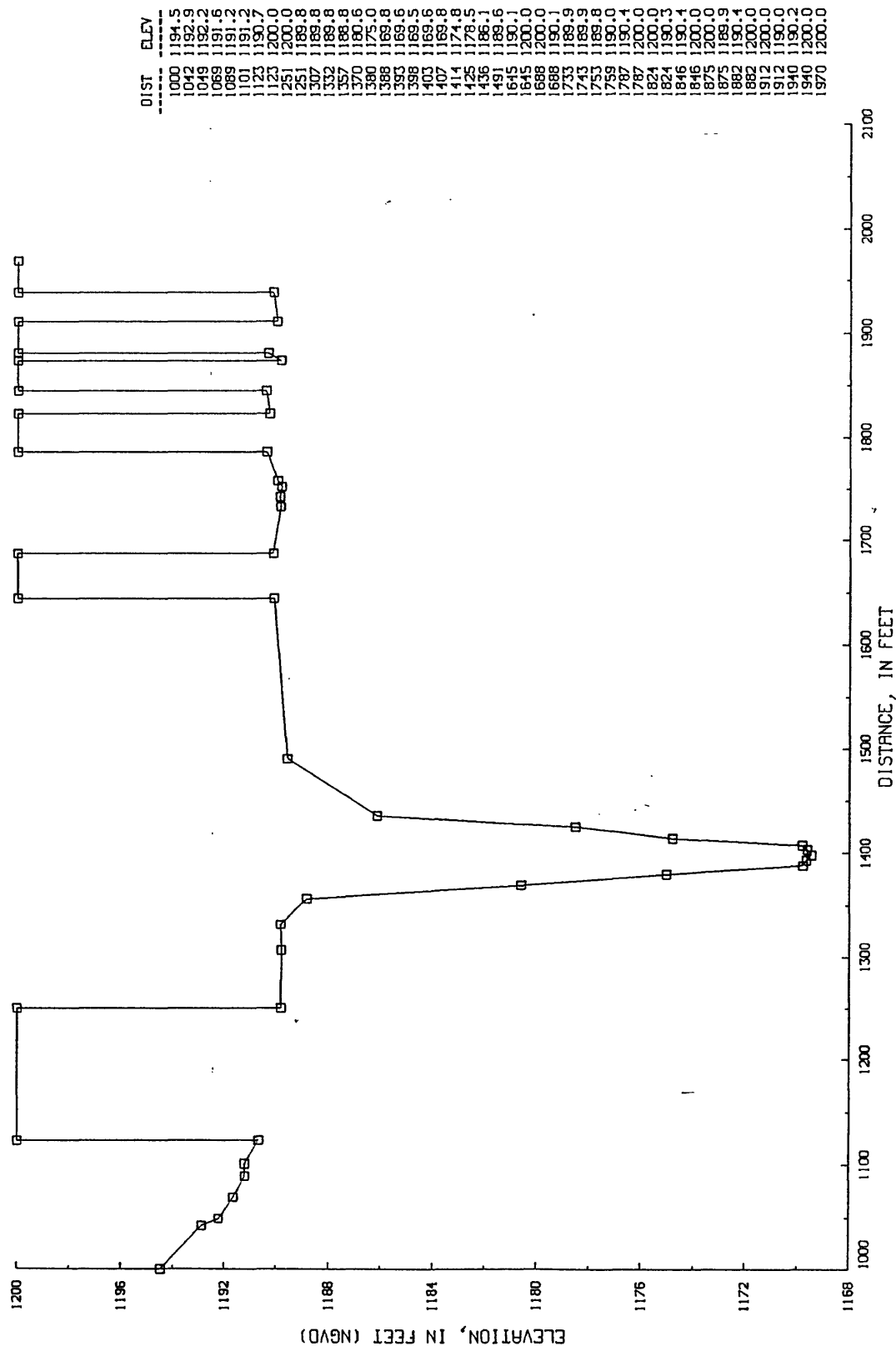
CROSS SECTION LG3, UPSTREAM LONG CULVERT EXIT - STATION-3630



Appendix 6-4. Plot of cross section 3, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

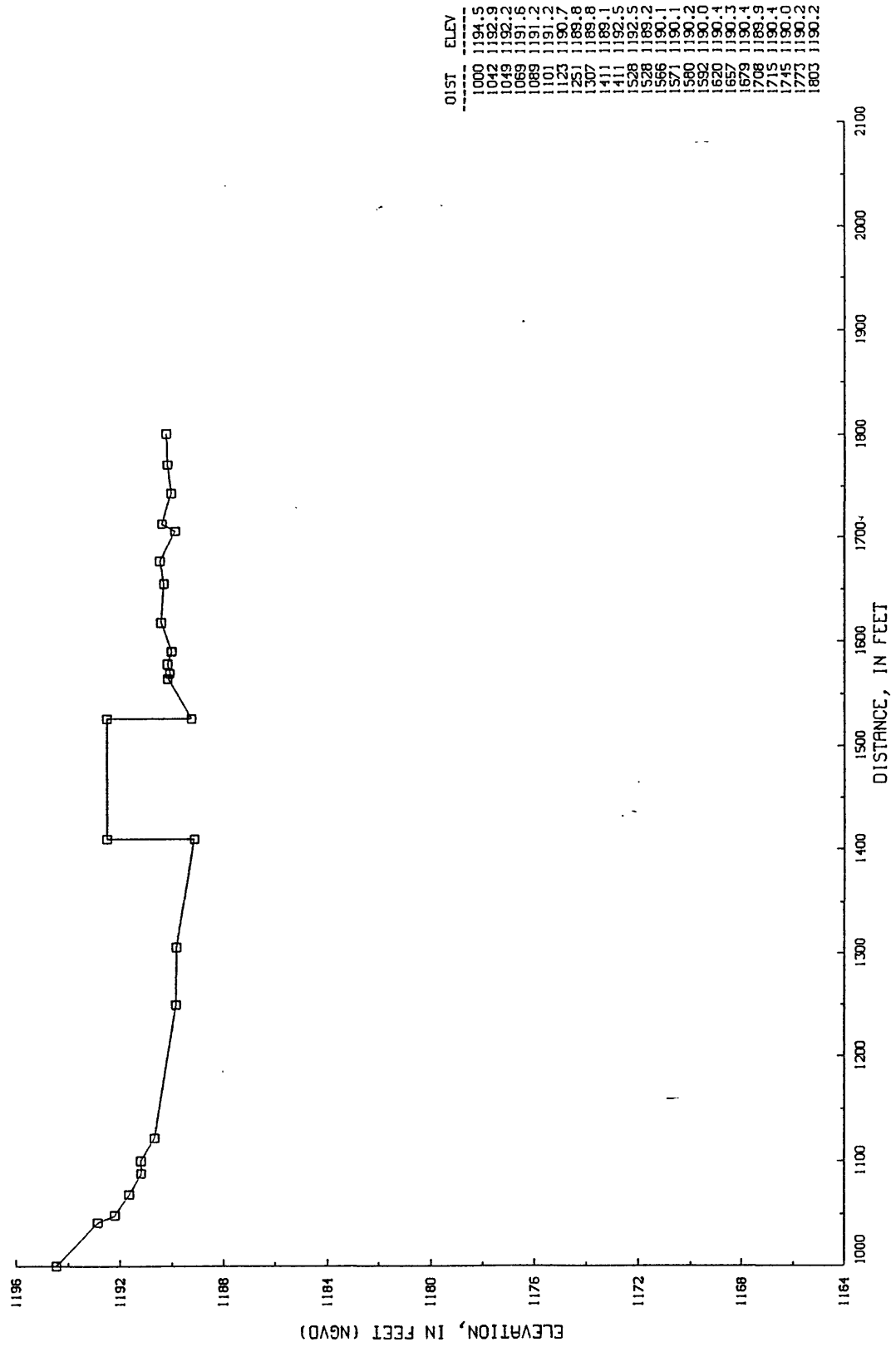
CROSS SECTION LG4, DOWNSTREAM SE 23RD - STATION - 3905



Appendix 6-5. Plot of cross section 4, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

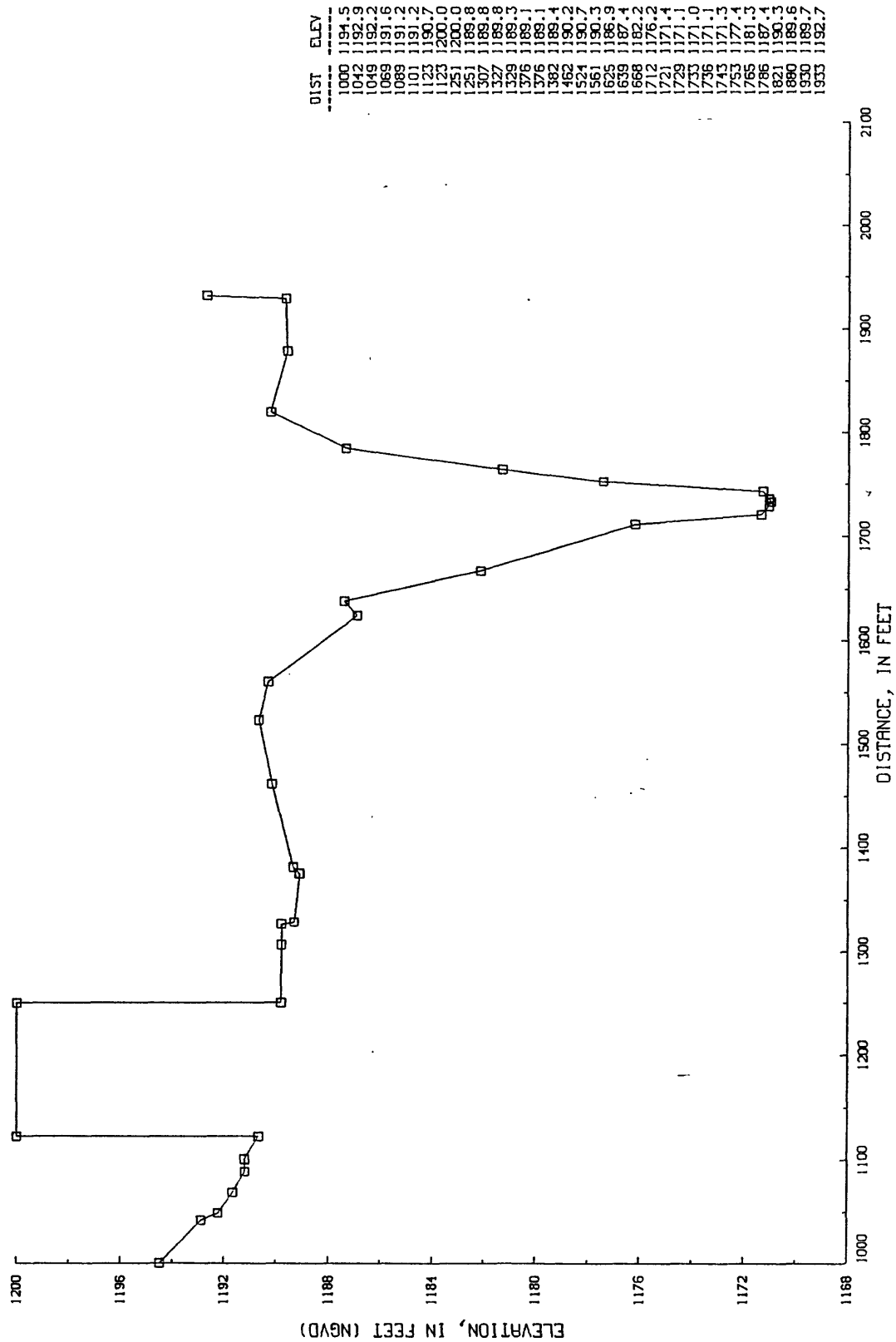
CROS SECTION L65R, NORTH SIDE SE 23RD - STATION - 4065



Appendix 6-6. Plot of cross section 5R, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

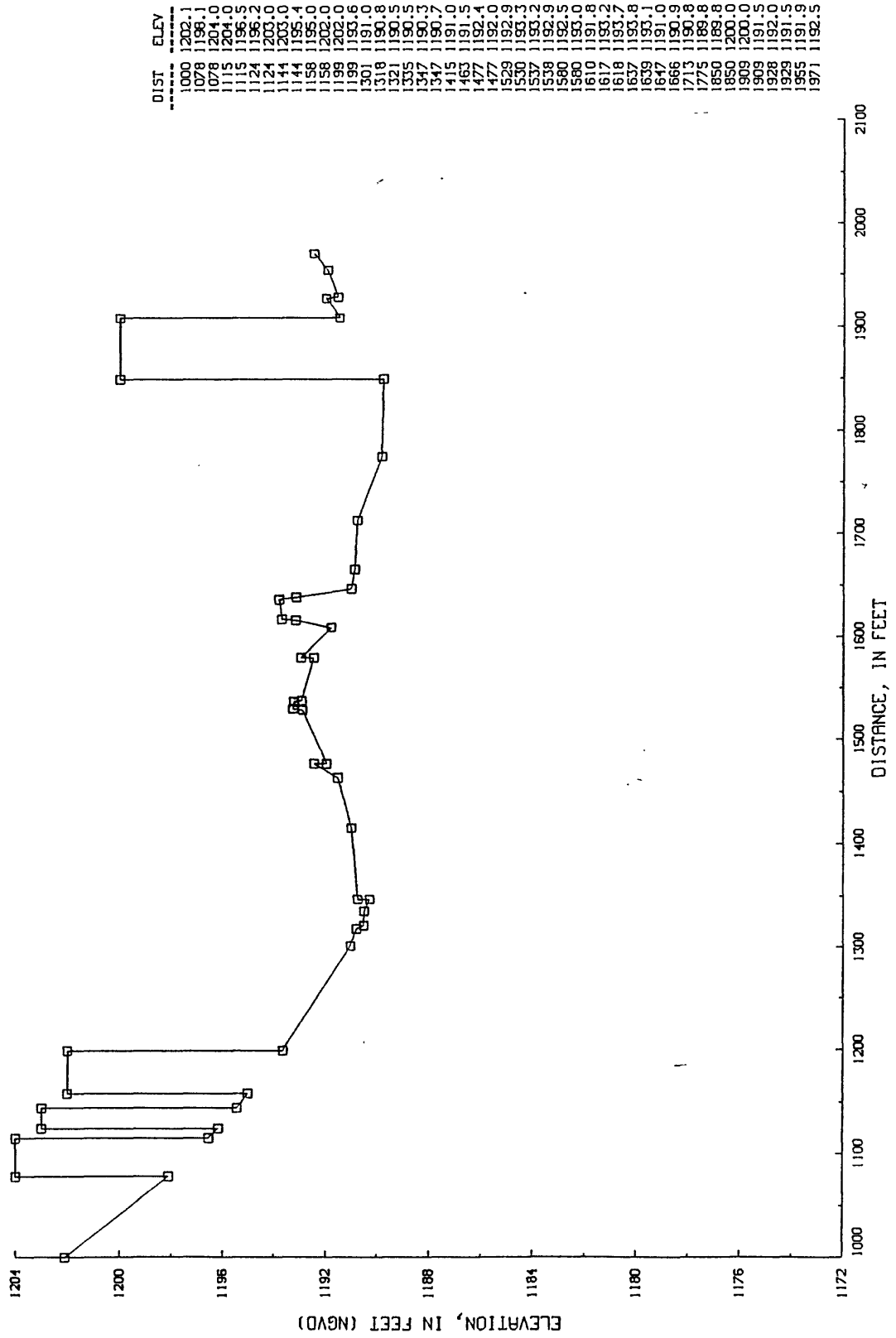
CROSS SECTION L66, DOWNSTREAM SHORT CULVERT- STATION - 4535



Appendix 6-7. Plot of cross section 6, Lightning Creek at SE 25th Street (site 6).

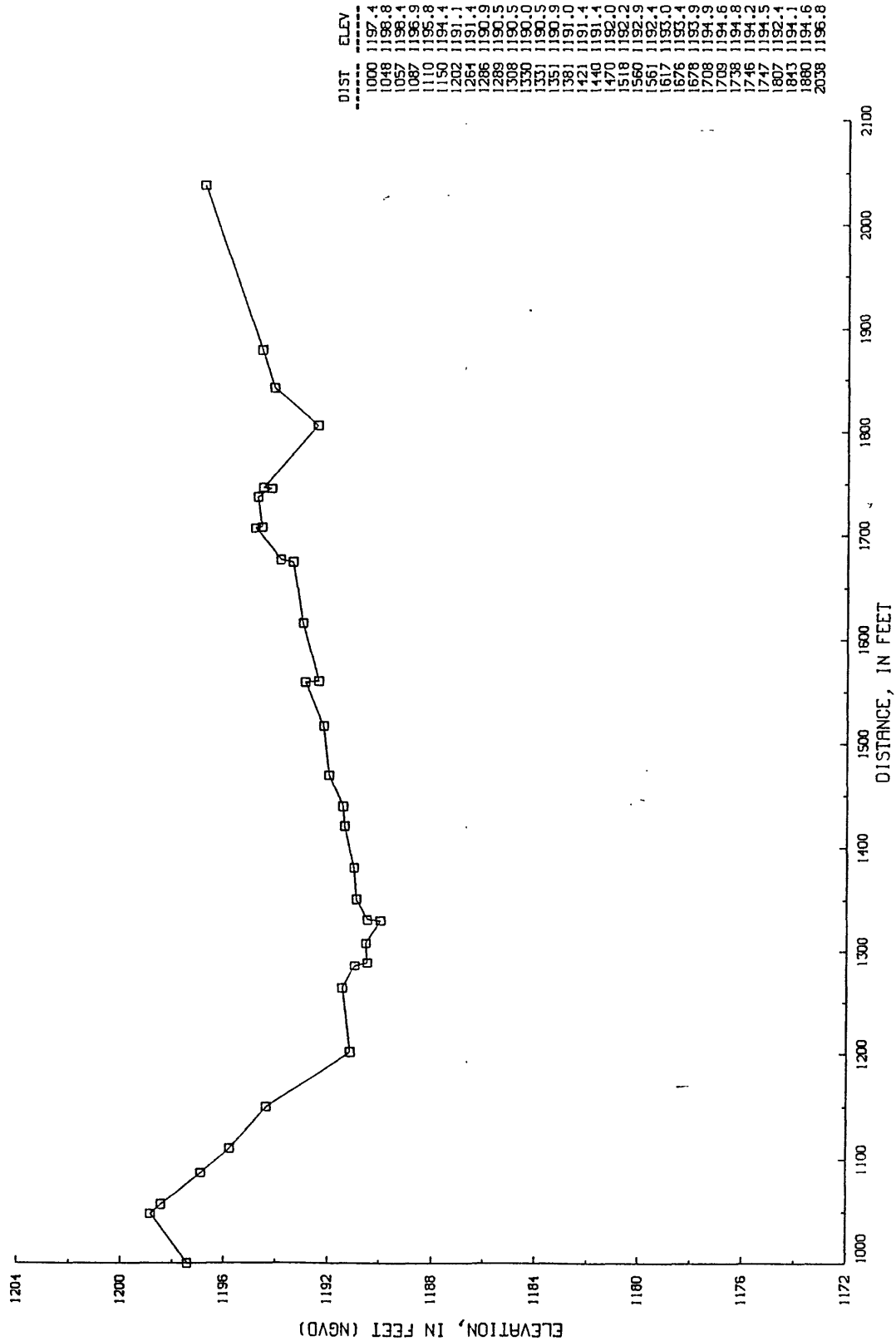
LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION L68, 165 FEET NORTH OF SE 25TH - STATION-4870



Appendix 6-8. Plot of cross section 8, Lightning Creek at SE 25th Street (site 6).

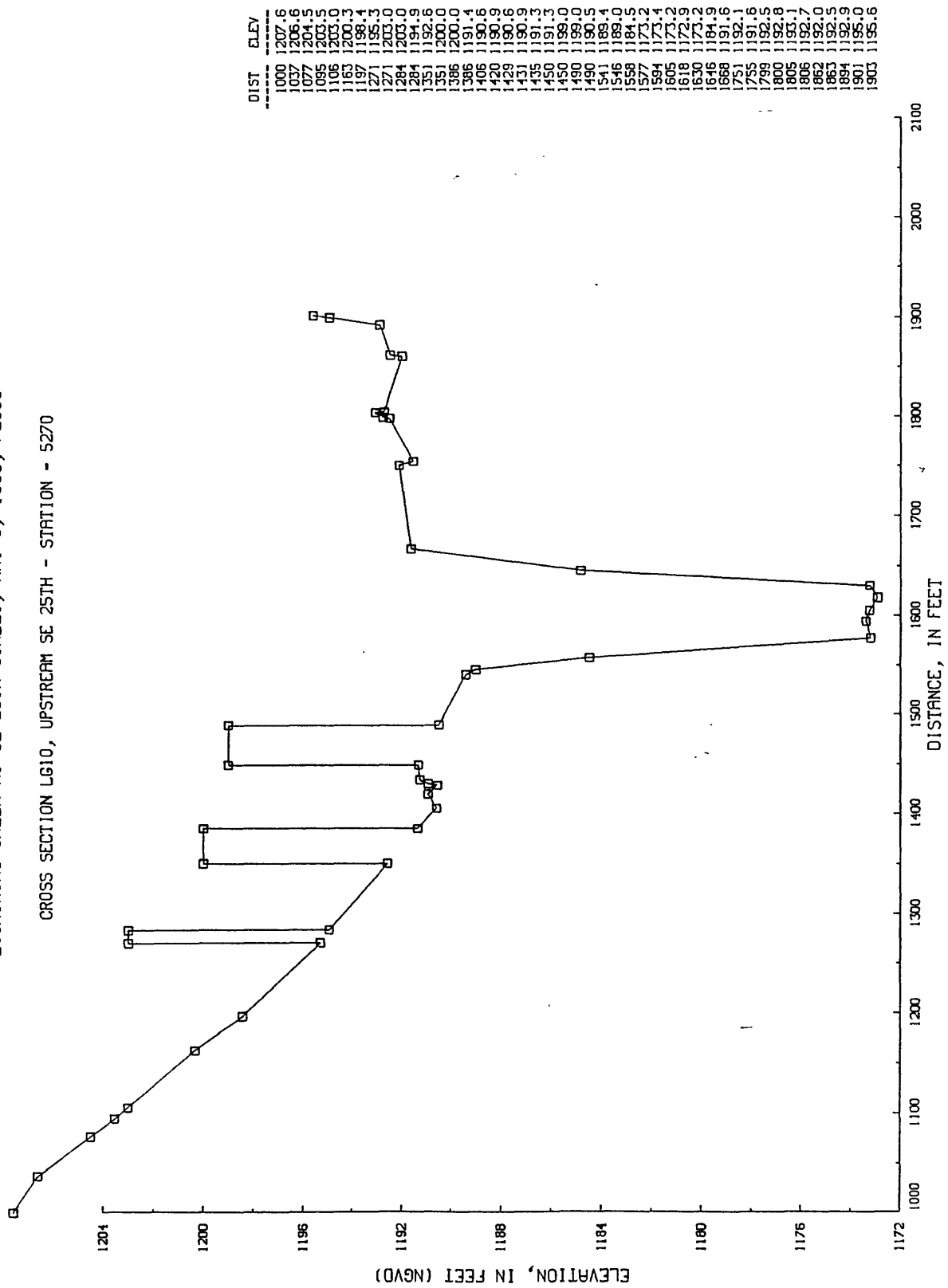
LIGHTNING CREEK AT SE 25TH, MAY 8, 1993, FLOOD
CROSS SECTION LG9R, SOUTH SIDE SE 25TH - STATION - 5105



Appendix 6-9. Plot of cross section 9R, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

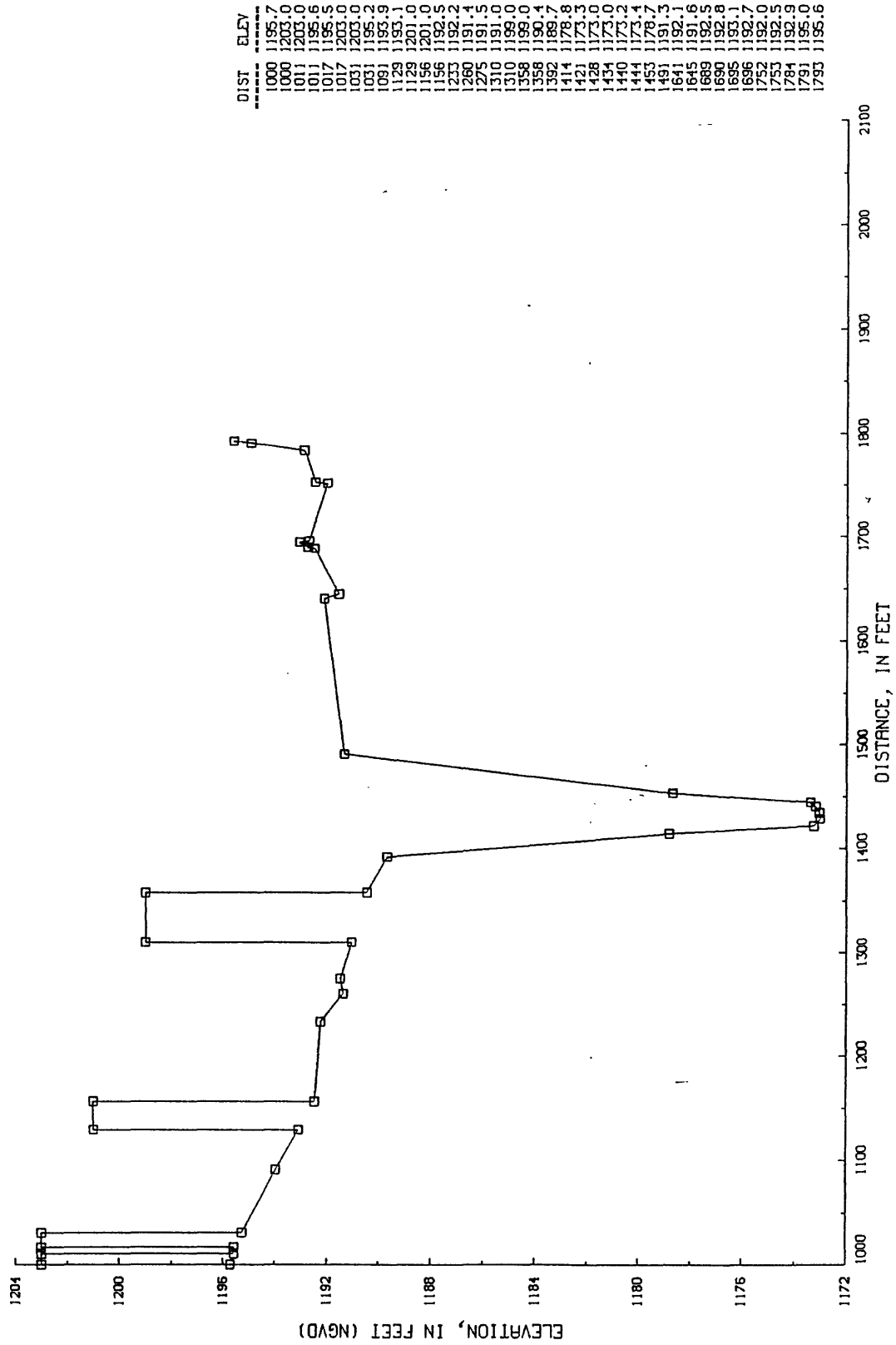
CROSS SECTION LG10, UPSTREAM SE 25TH - STATION - 5270



Appendix 6-10. Plot of cross section 10, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

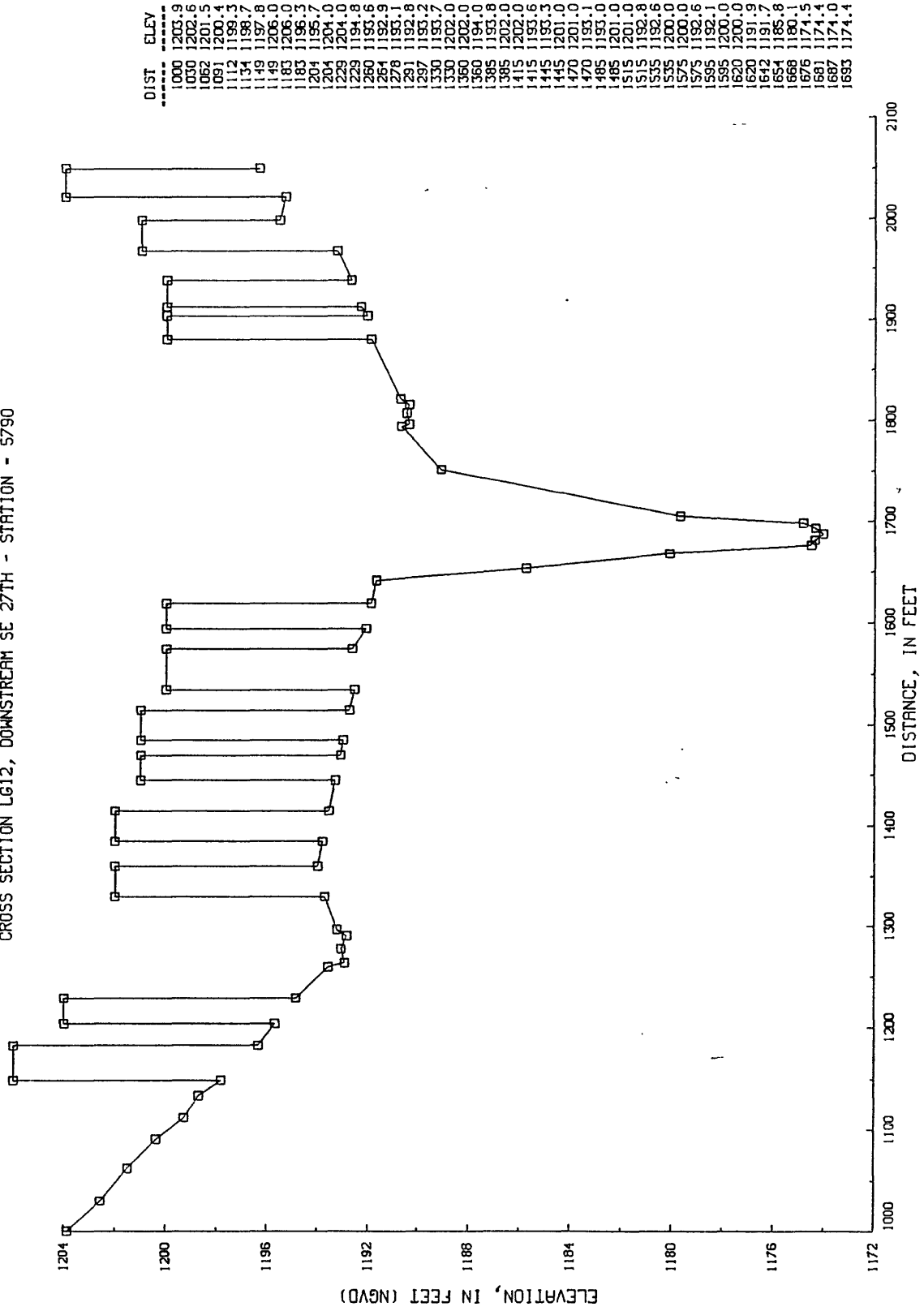
CROSS SECTION LG11, NORTH SIDE SE 26TH - STATION - 5375



Appendix 6-11. Plot of cross section 11, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

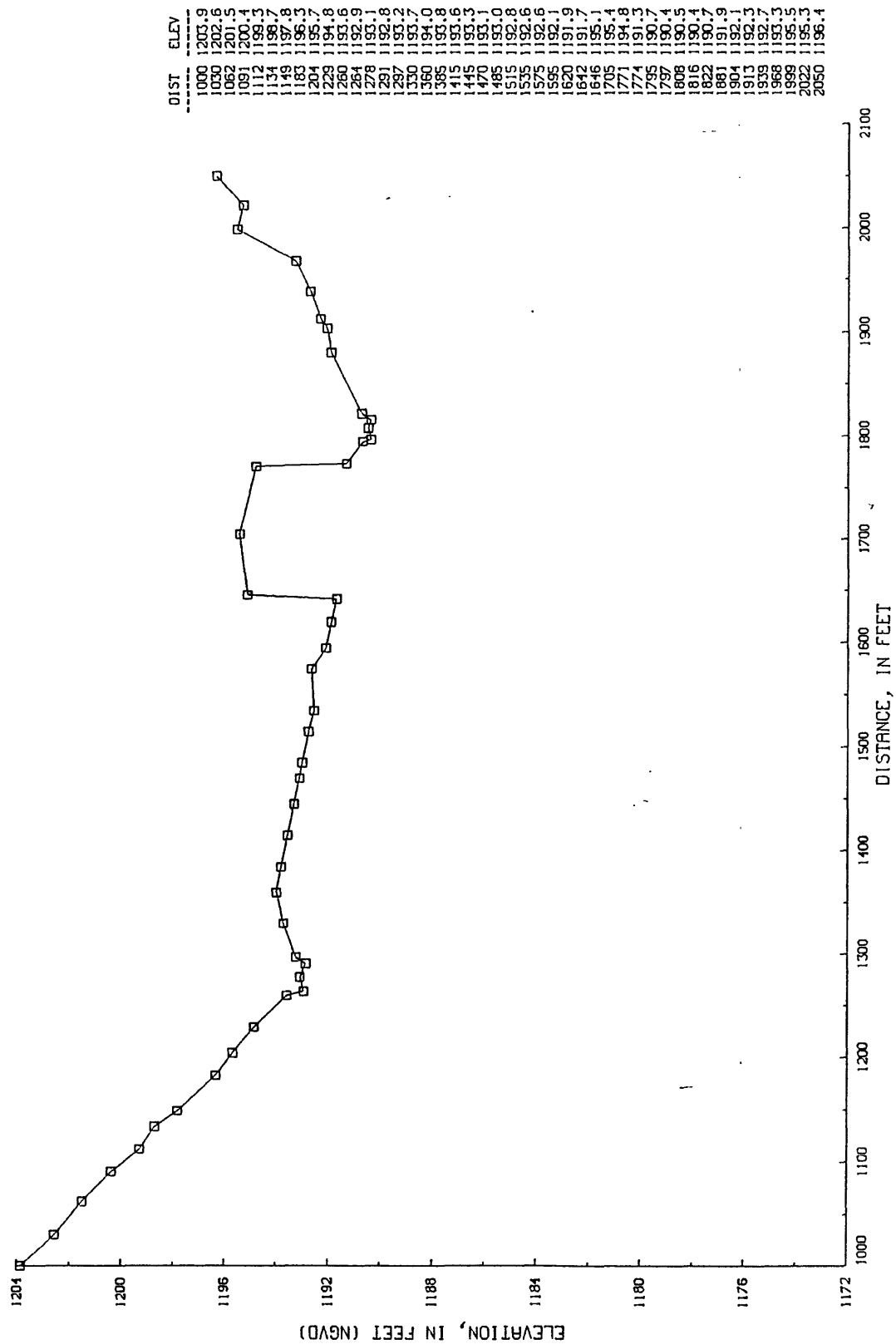
CROSS SECTION LG12, DOWNSTREAM SE 27TH - STATION - 5790



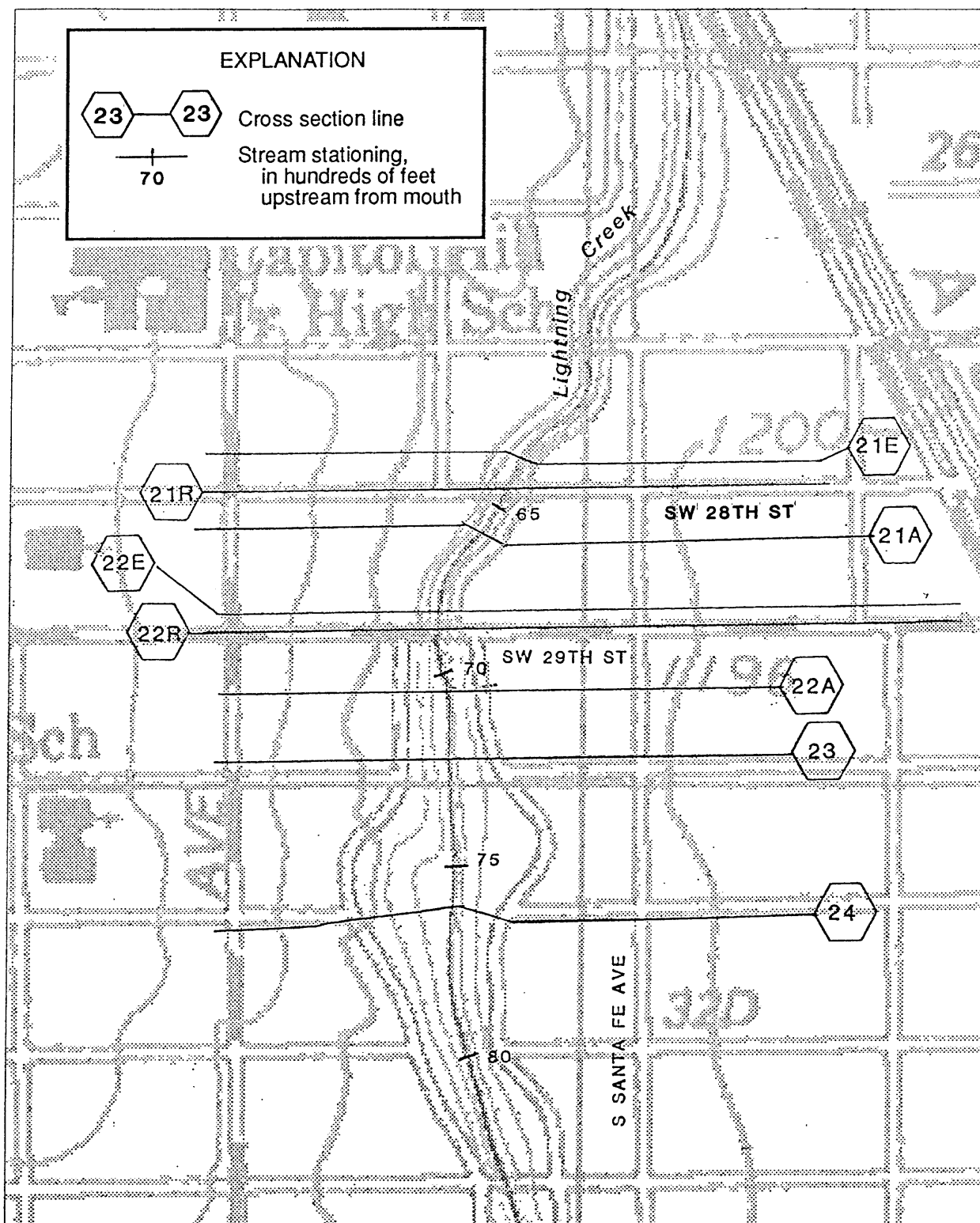
Appendix 6-12. Plot of cross section 12, Lightning Creek at SE 25th Street (site 6).

LIGHTNING CREEK AT SE 25TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION LG13R, SOUTH SIDE SE 27TH - STATION - 5972



Appendix 6-13. Plot of cross section 13R, Lightning Creek at SE 25th Street (site 6).



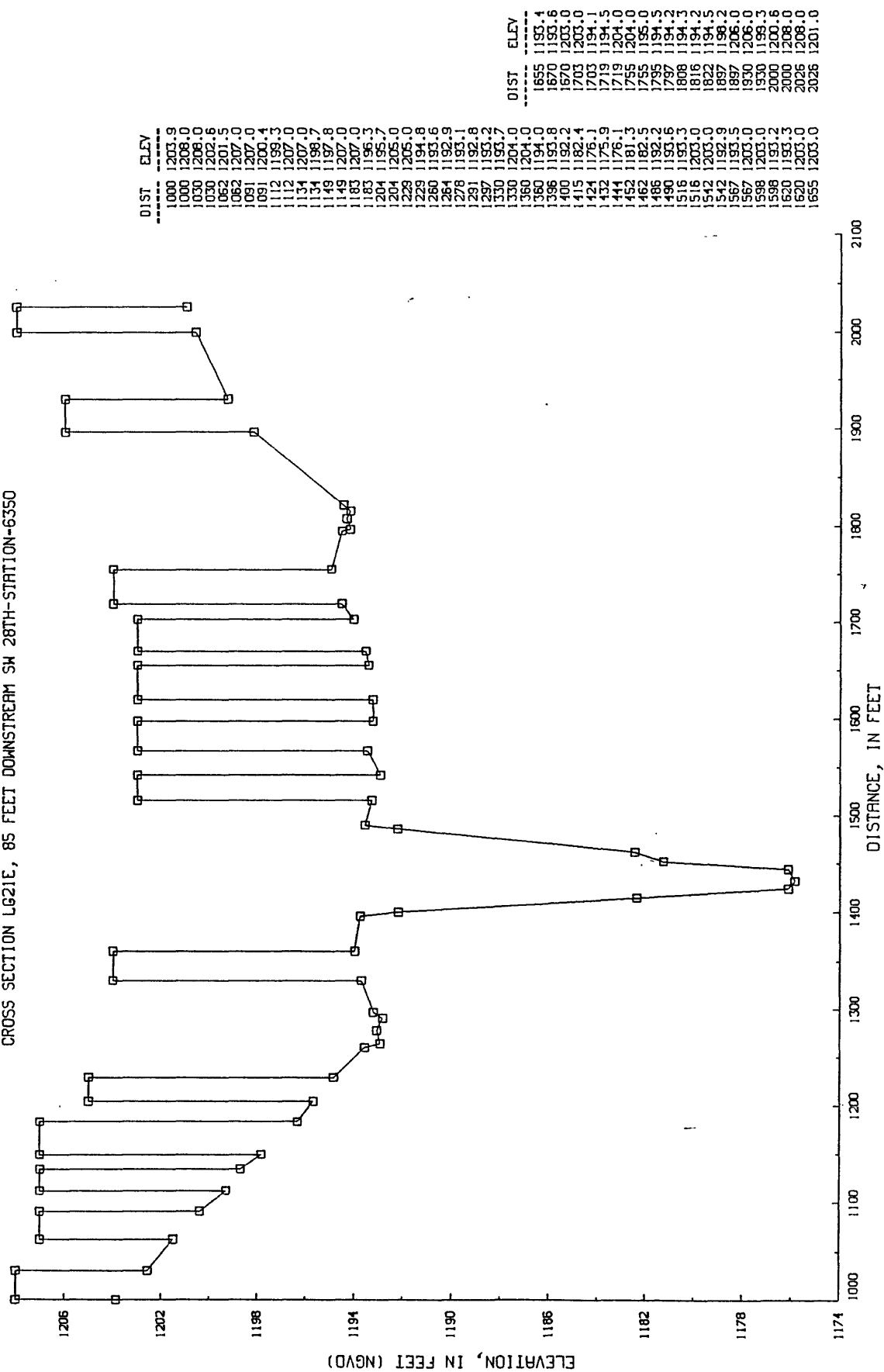
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 7-1. Location of study cross sections on Lightning Creek at SW 29th Street (site 7).

LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

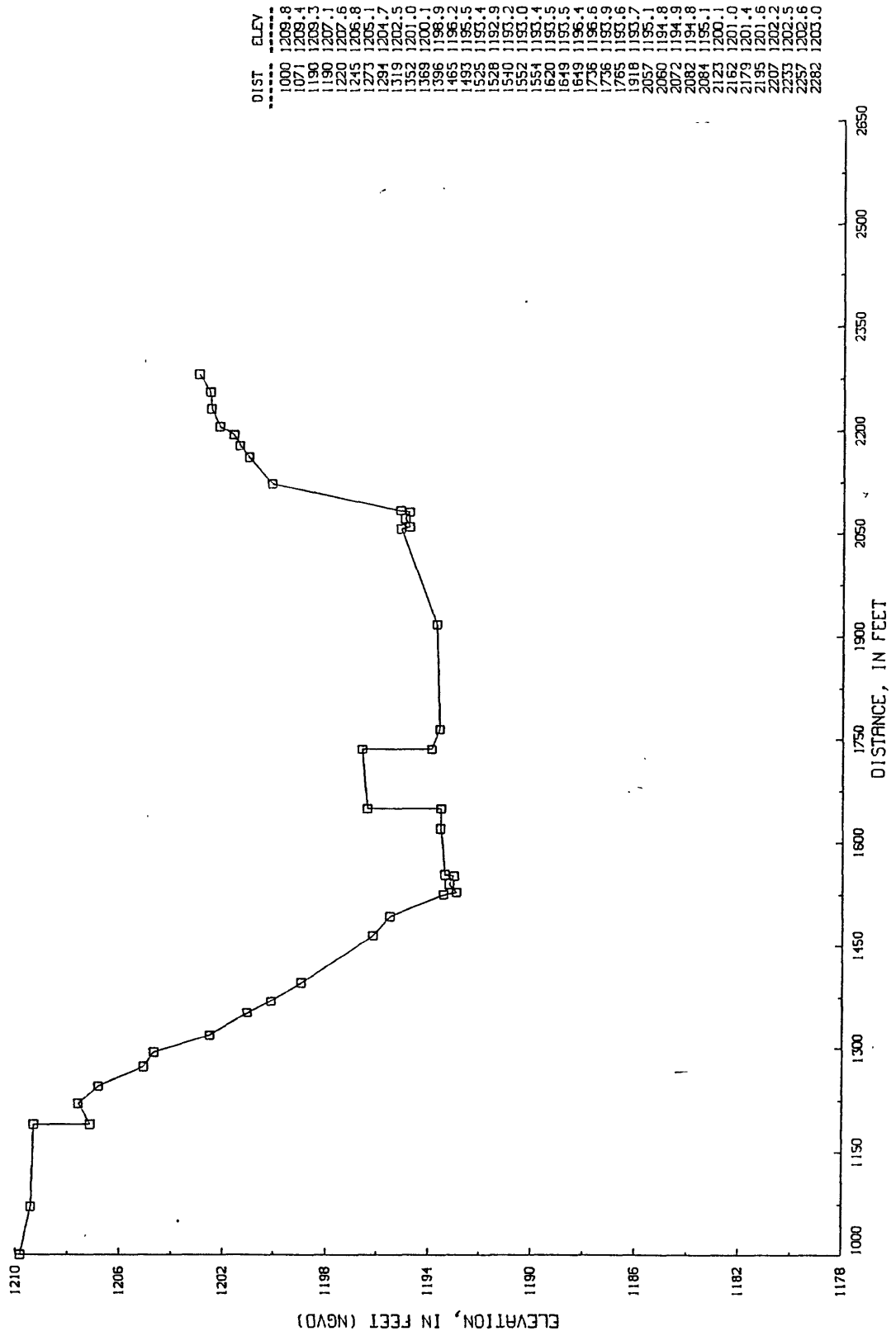
CROSS SECTION LG21E, 85 FEET DOWNSTREAM SW 28TH-STATION-6350



Appendix 7-2. Plot of cross section 21E, Lightning Creek at SW 29th Street (site 7).

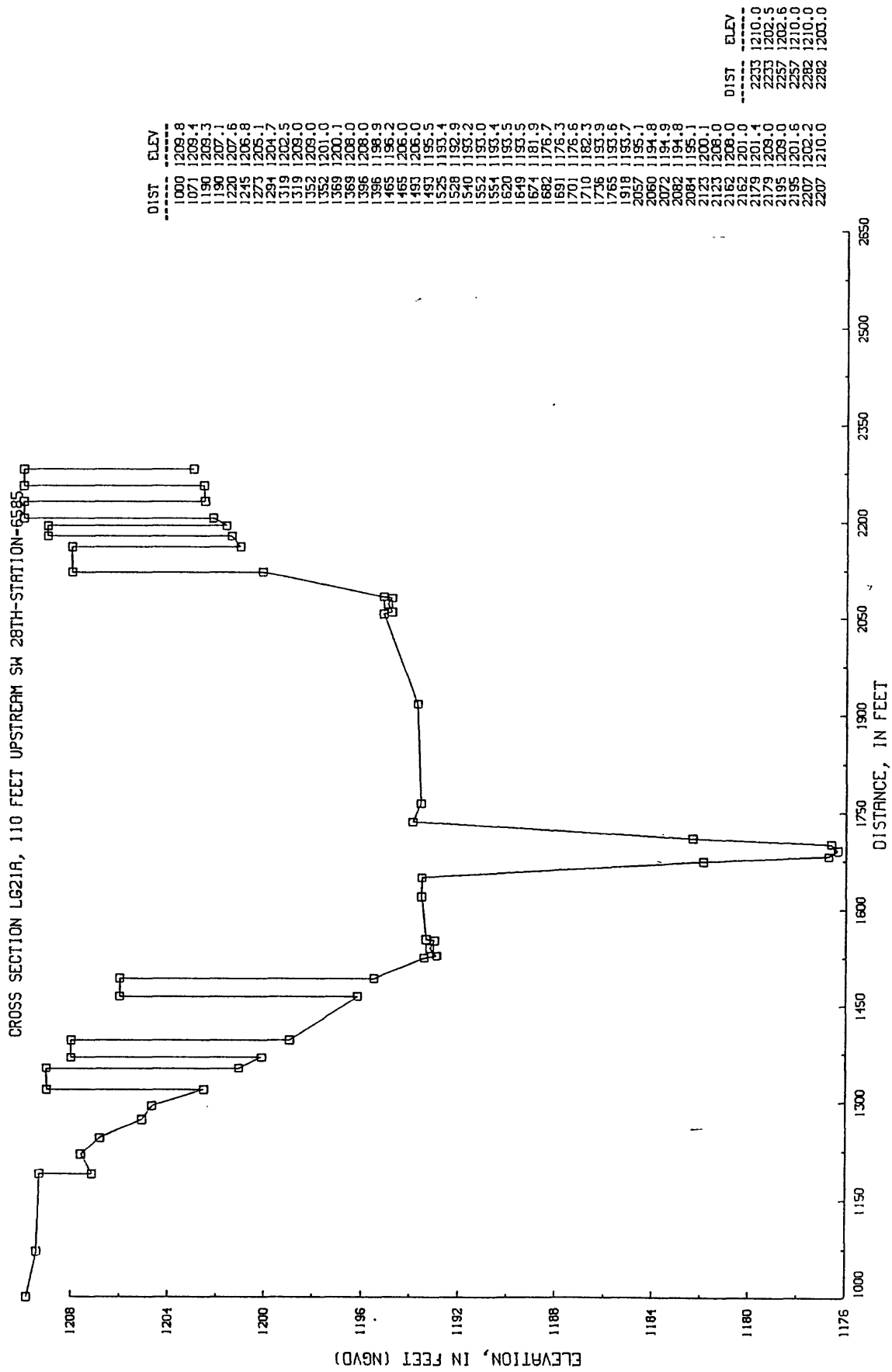
LIGHTNING CREEK AT SW29TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION LG21R, SOUTH SIDE SW 28TH - STATION - 6455



Appendix 7-3. Plot of cross section 21R, Lightning Creek at SW 29th Street (site 7).

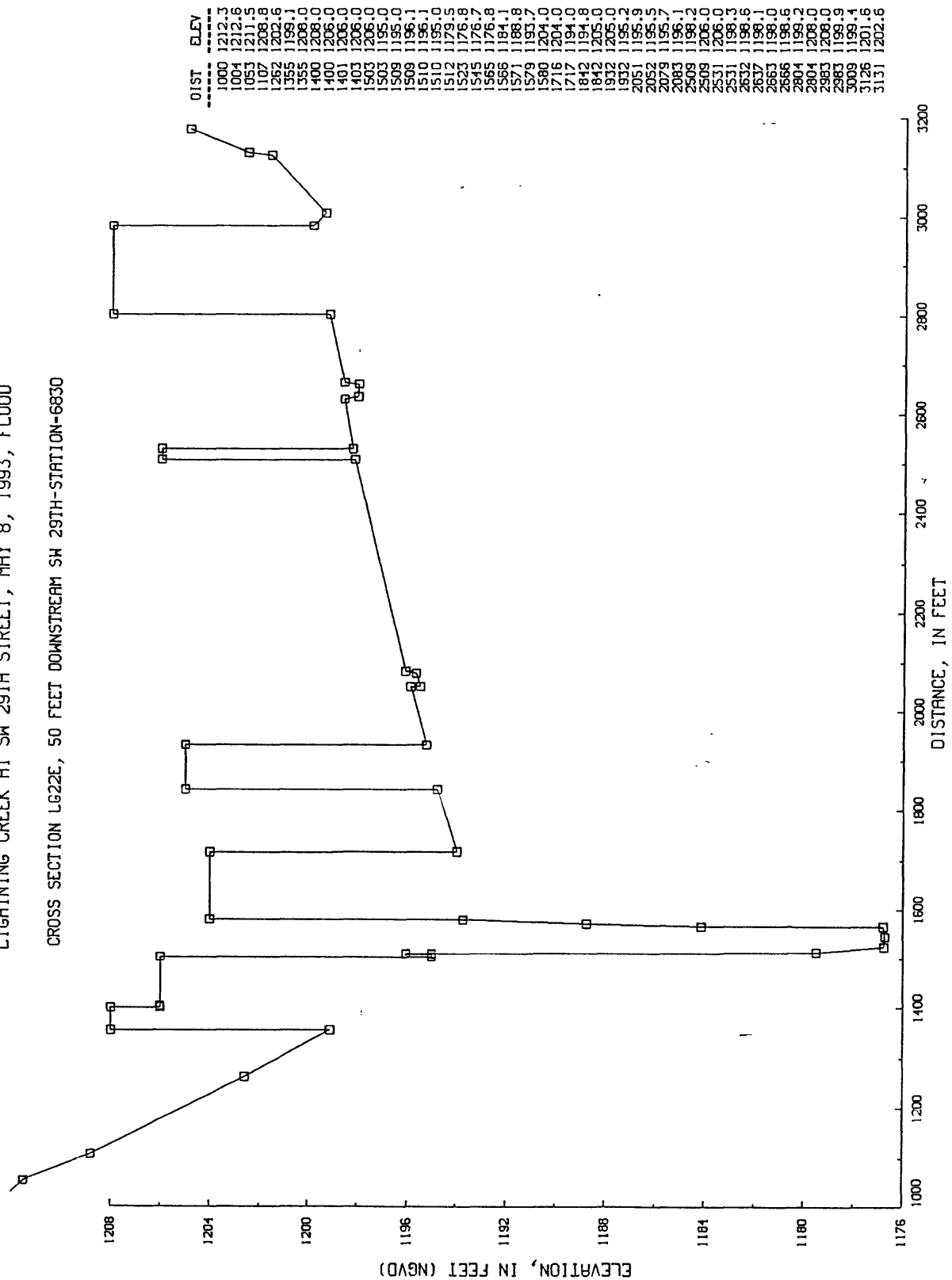
LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD



Appendix 7-4. Plot of cross section 21A, Lightning Creek at SW 29th Street (site 7).

LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

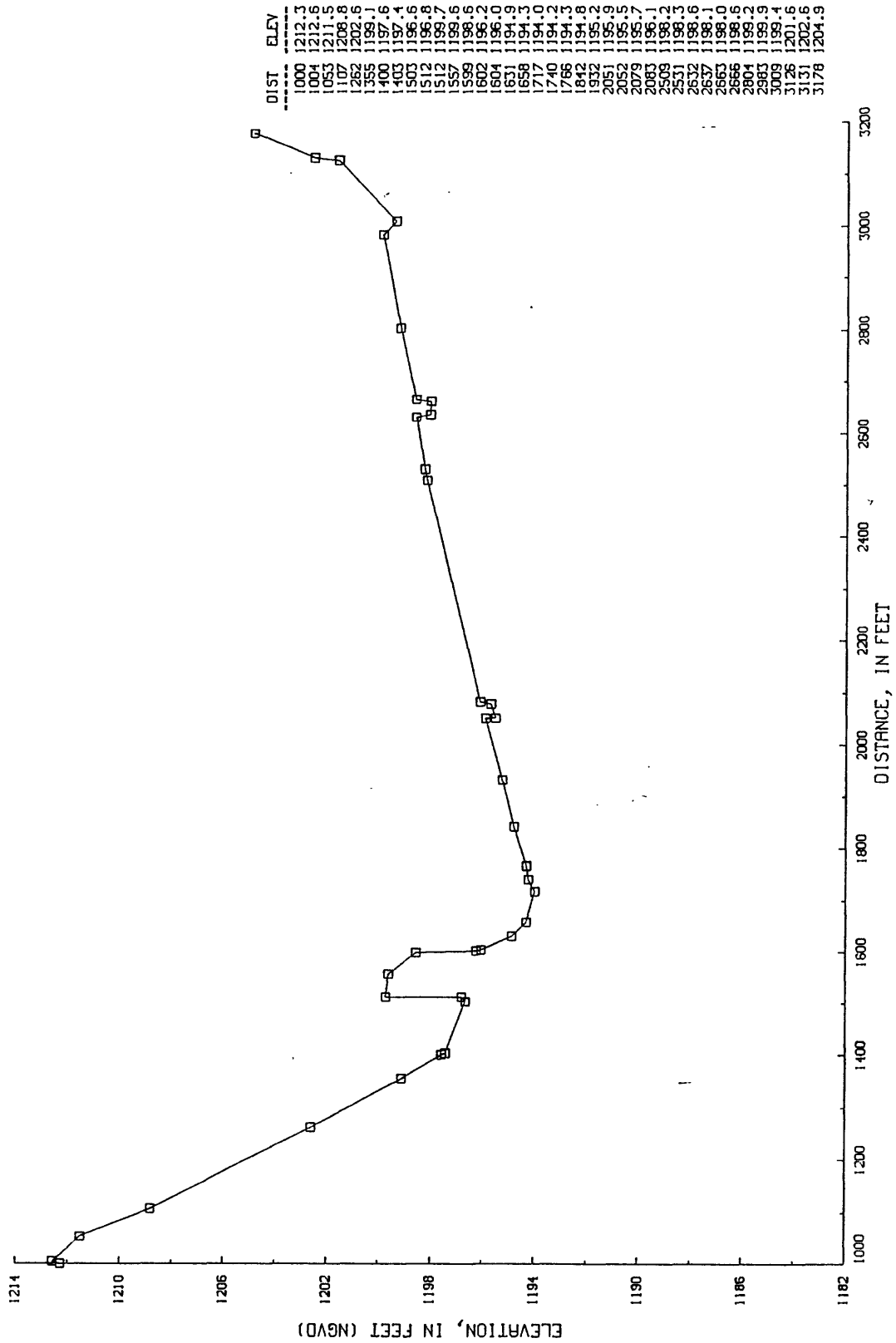
CROSS SECTION LG22E, 50 FEET DOWNSTREAM SW 29TH-STATION-6830



Appendix 7-5. Plot of cross section 22E, Lightning Creek at SW 29th Street (site 7).

LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

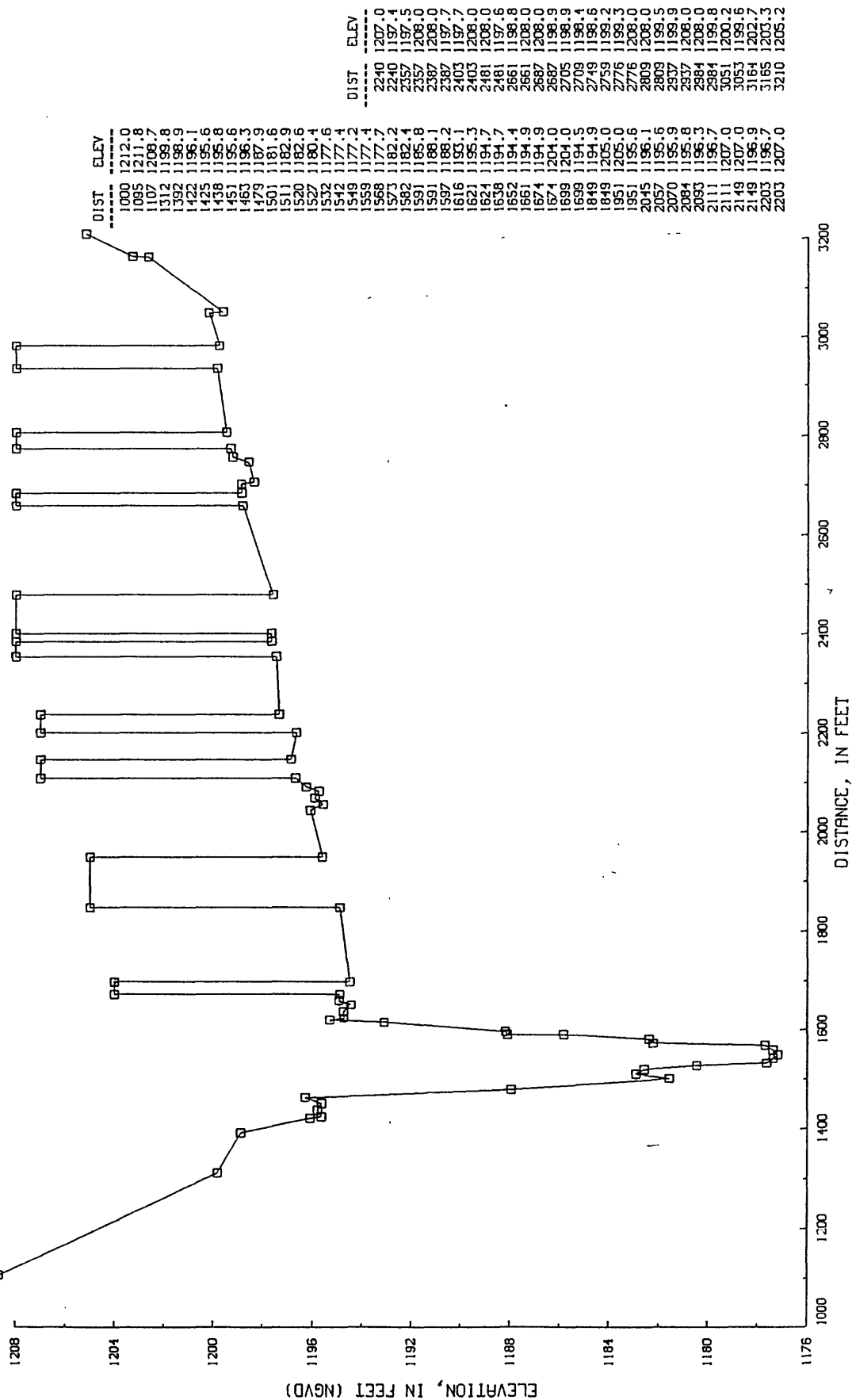
CROSS SECTION LG22R, NORTH SIDE SW 29TH - STATION - 6850



Appendix 7-6. Plot of cross section 22R, Lightning Creek at SW 29th Street (site 7).

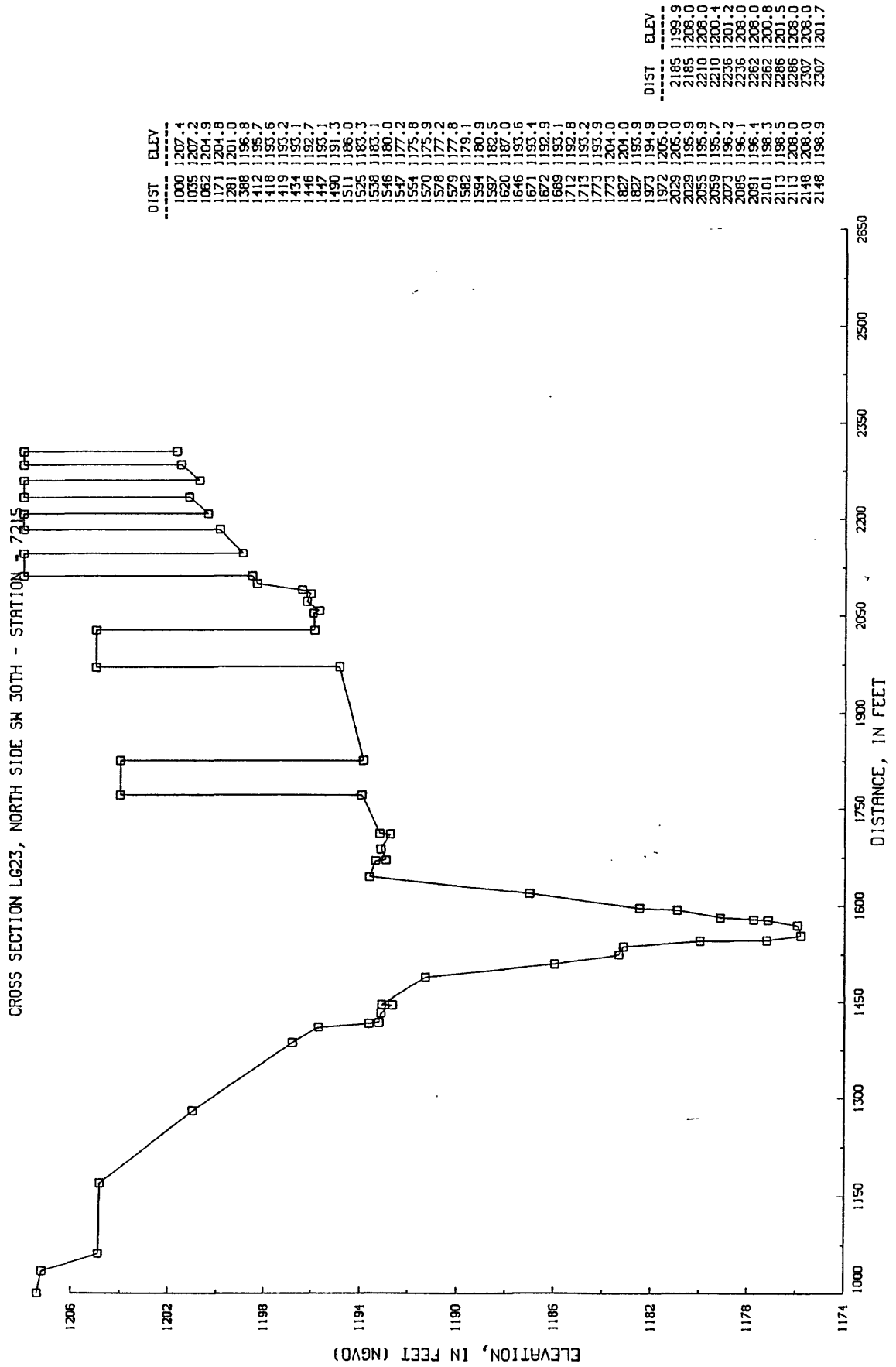
LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION LG22A, UPSTREAM SW 29TH - STATION - 7035



Appendix 7-7. Plot of cross section 22A, Lightning Creek at SW 29th Street (site 7).

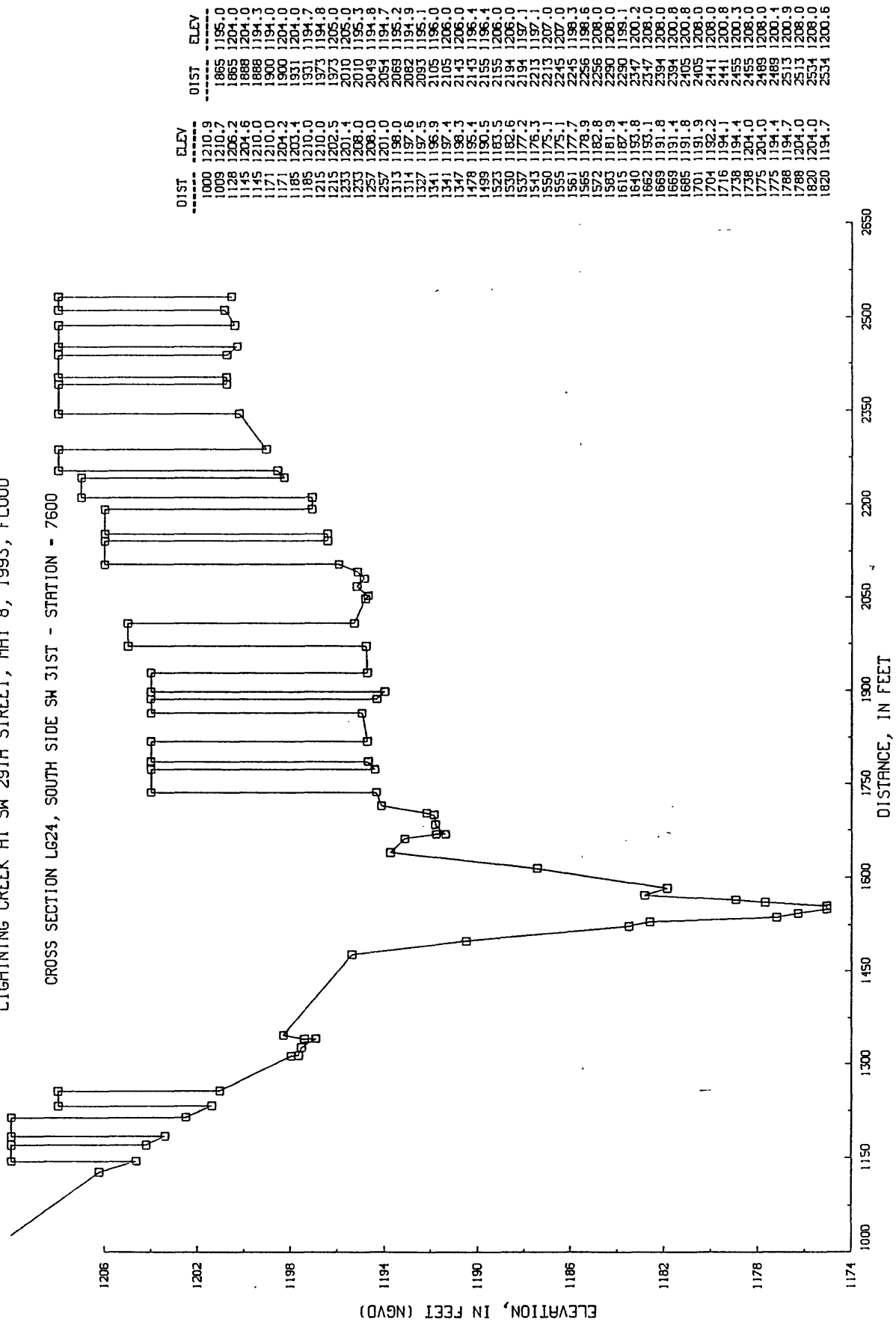
LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD



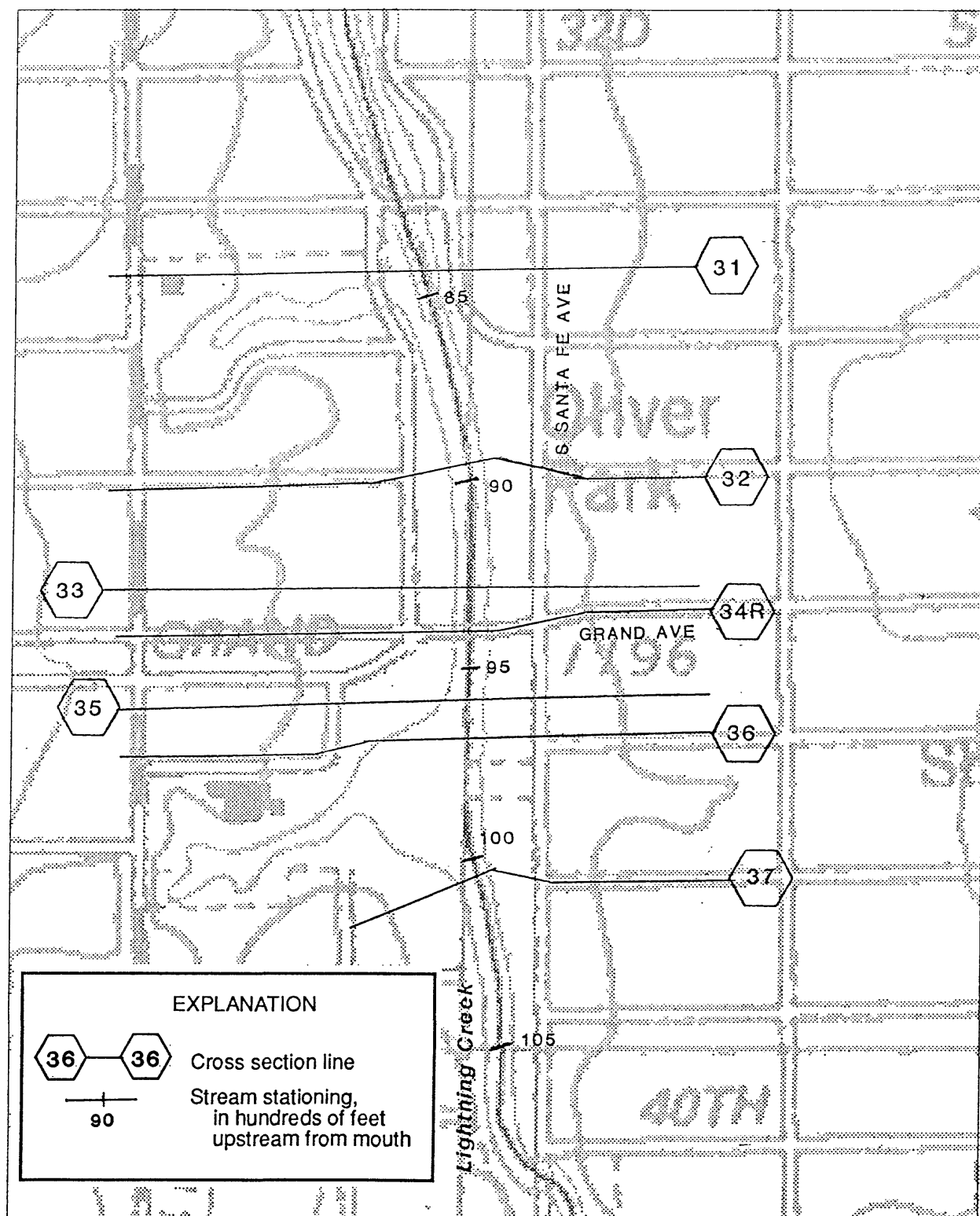
Appendix 7-8. Plot of cross section 23, Lightning Creek at SW 29th Street (site 7).

LIGHTNING CREEK AT SW 29TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION LG24, SOUTH SIDE SW 31ST - STATION - 7600



Appendix 7-9. Plot of cross section 24, Lightning Creek at SW 29th Street (site 7).



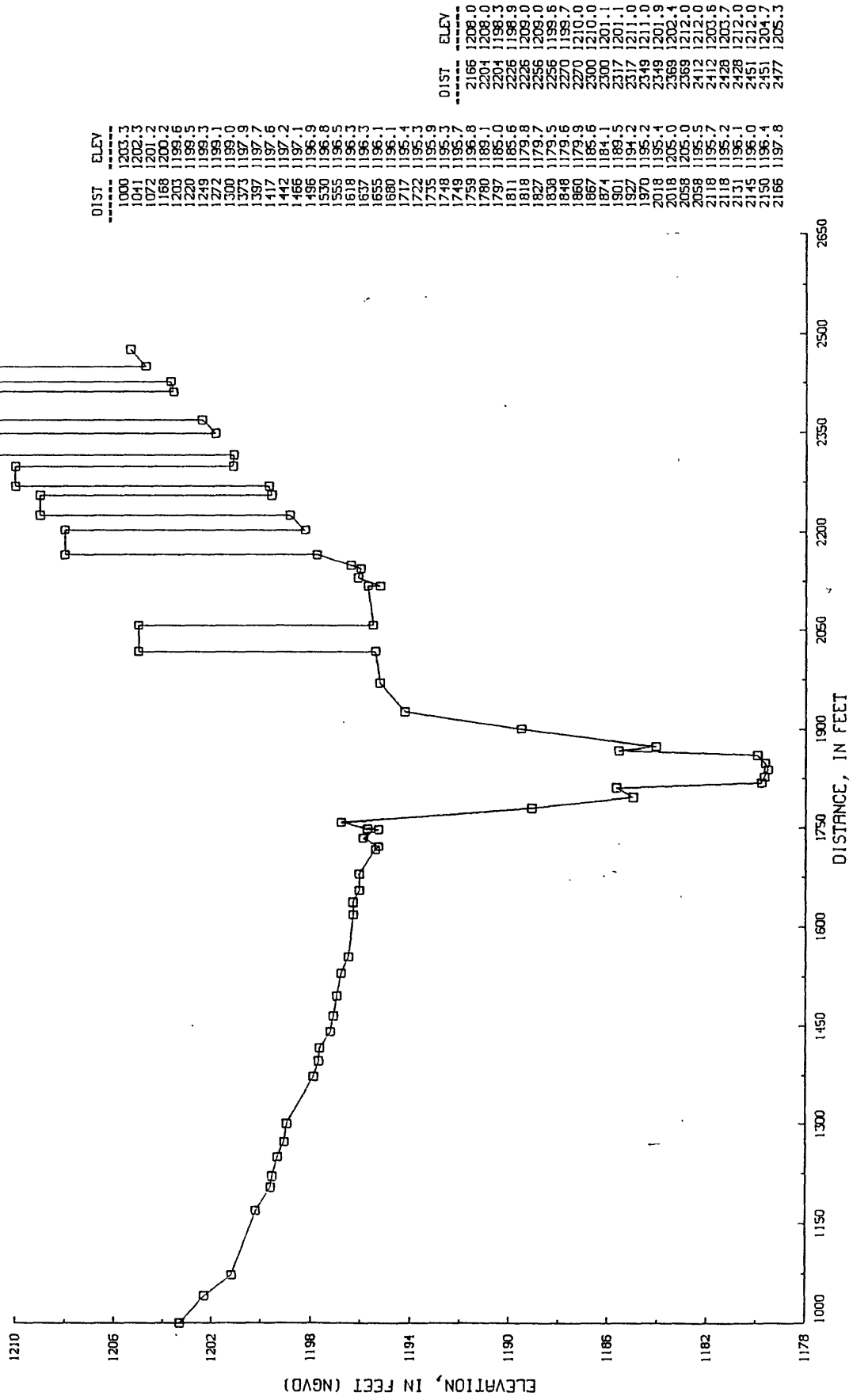
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 8-1. Location of study cross sections on Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

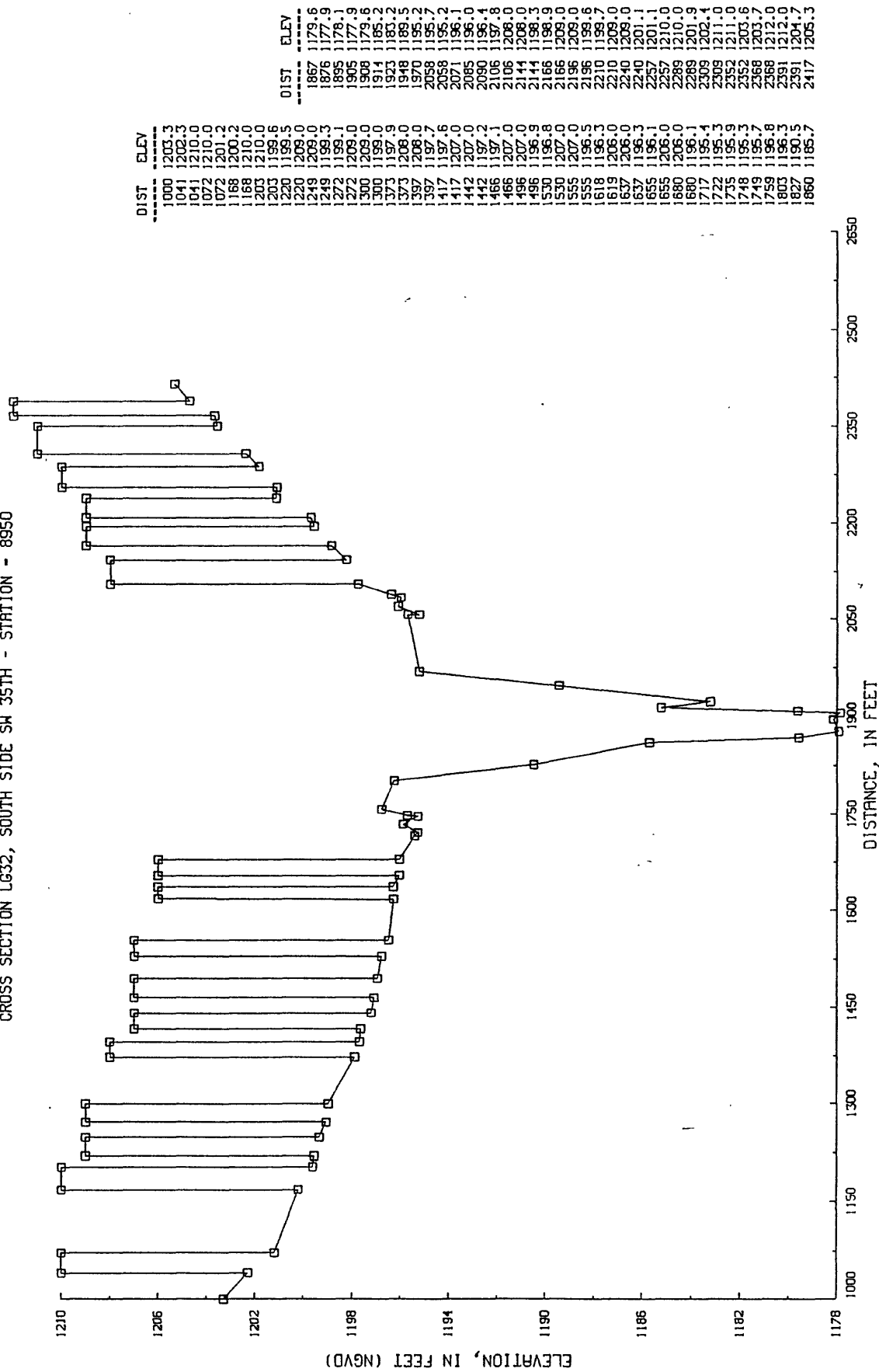
CROSS SECTION LG31, UPSTREAM SW 33RD BRIDGE - STATION - 8430



Appendix 8-2. Plot of cross section 31, Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

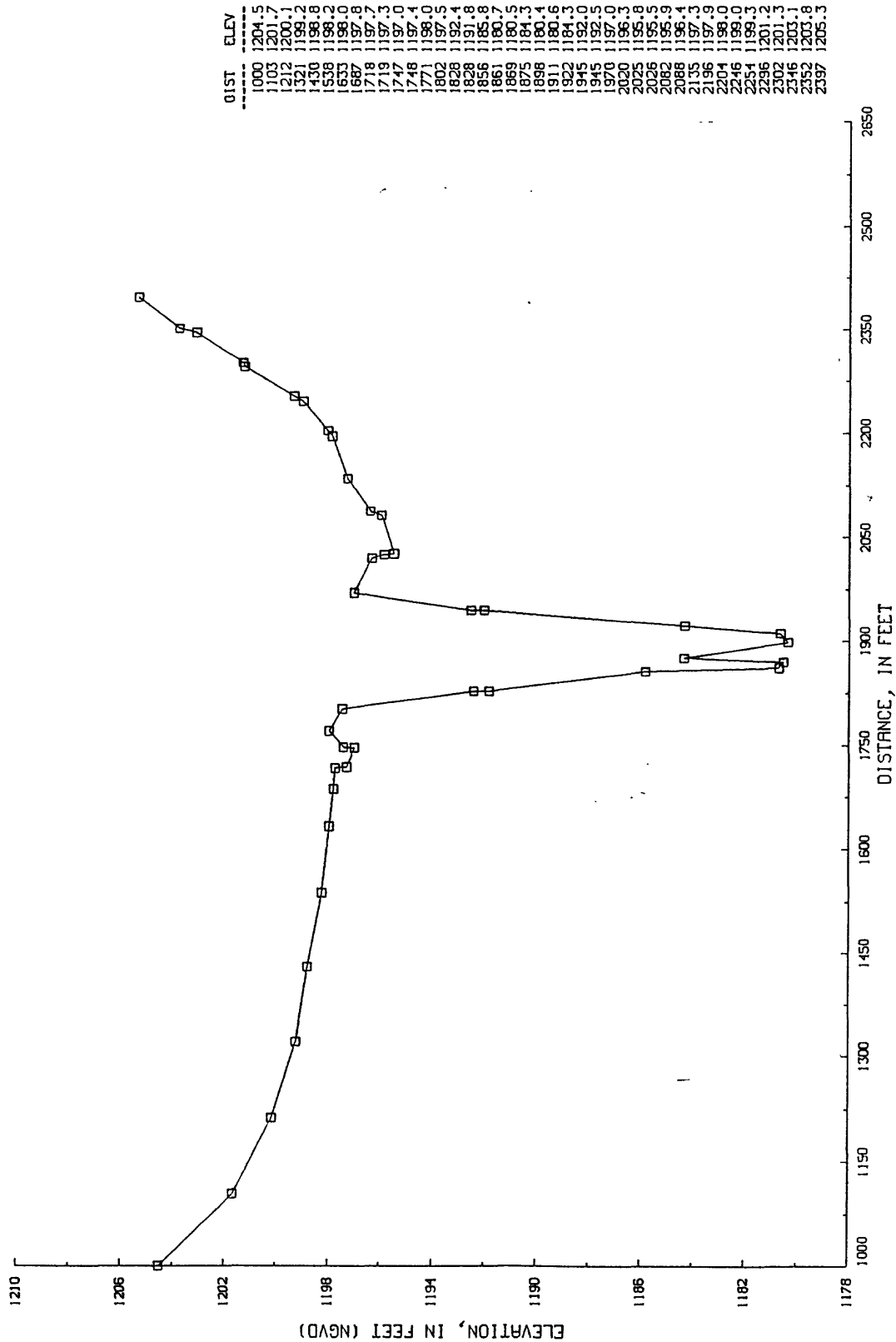
CROSS SECTION LG32, SOUTH SIDE SW 35TH - STATION - 8950



Appendix 8-3. Plot of cross section 32, Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

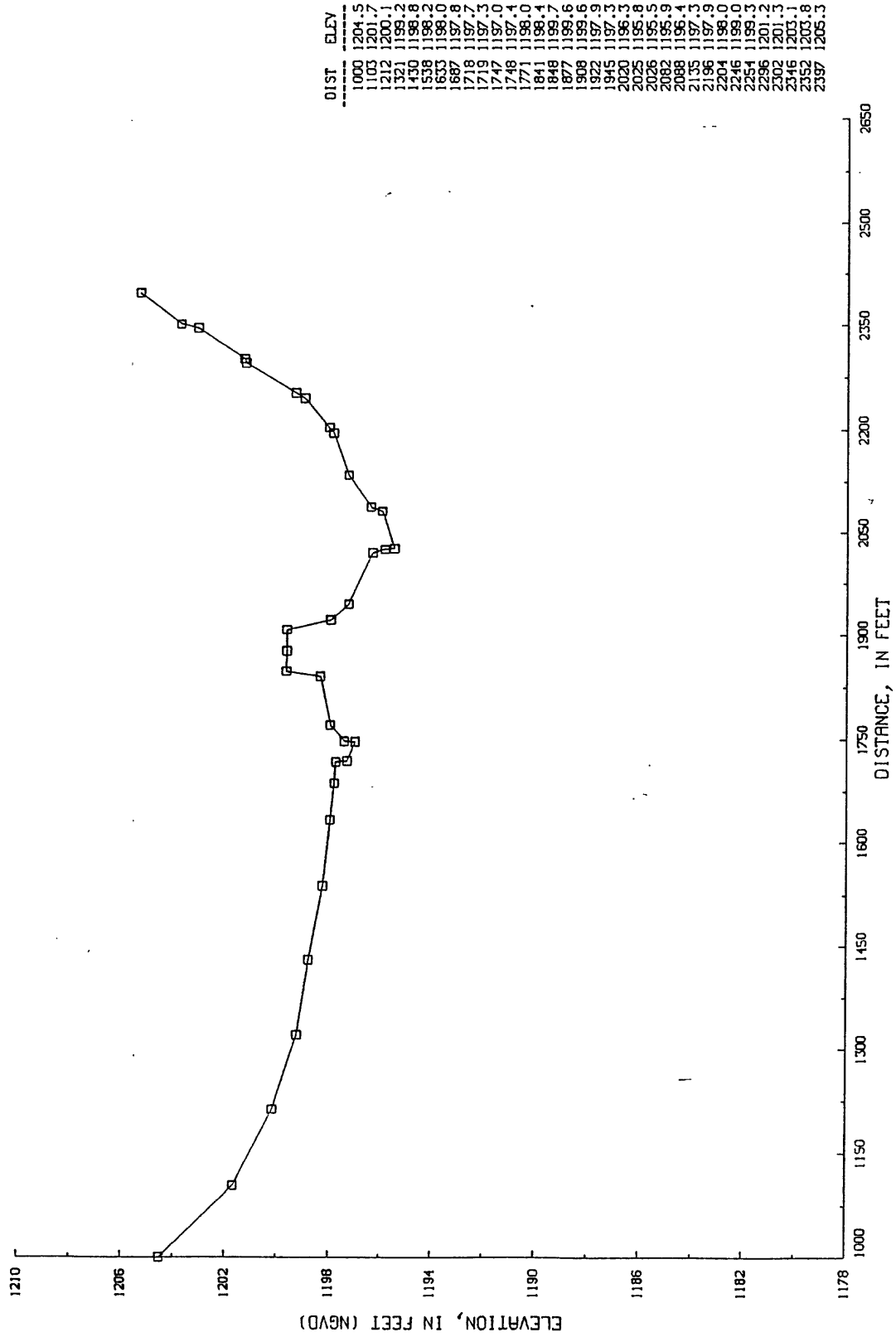
CROSS SECTION LG33, DOWNSTREAM GRAND - STATION - 9230



Appendix 8-4. Plot of cross section 33, Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

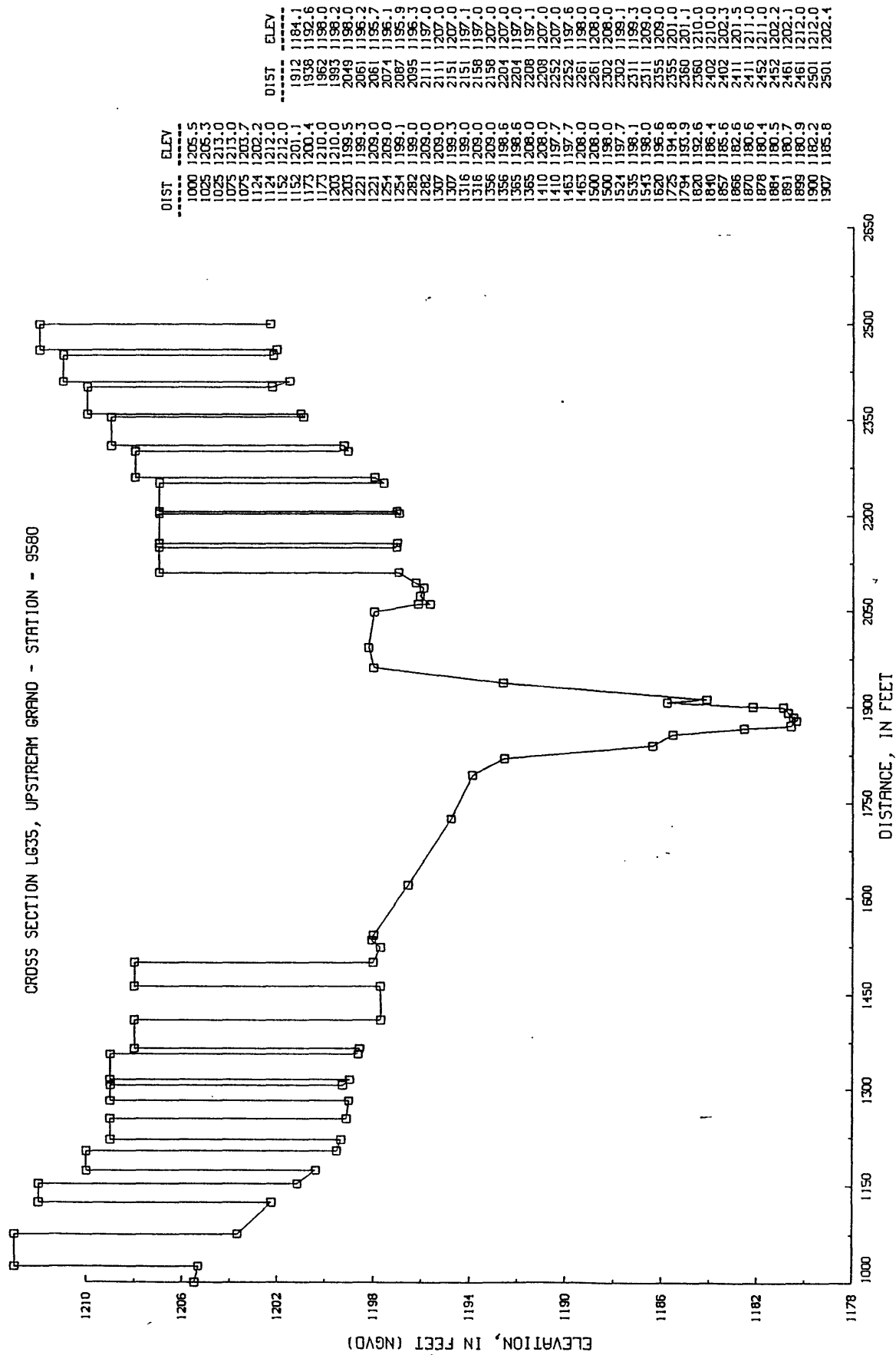
CROSS SECTION LG34R, NORTH SIDE GRAND - STATION - 9360



Appendix 8-5. Plot of cross section 34R, Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

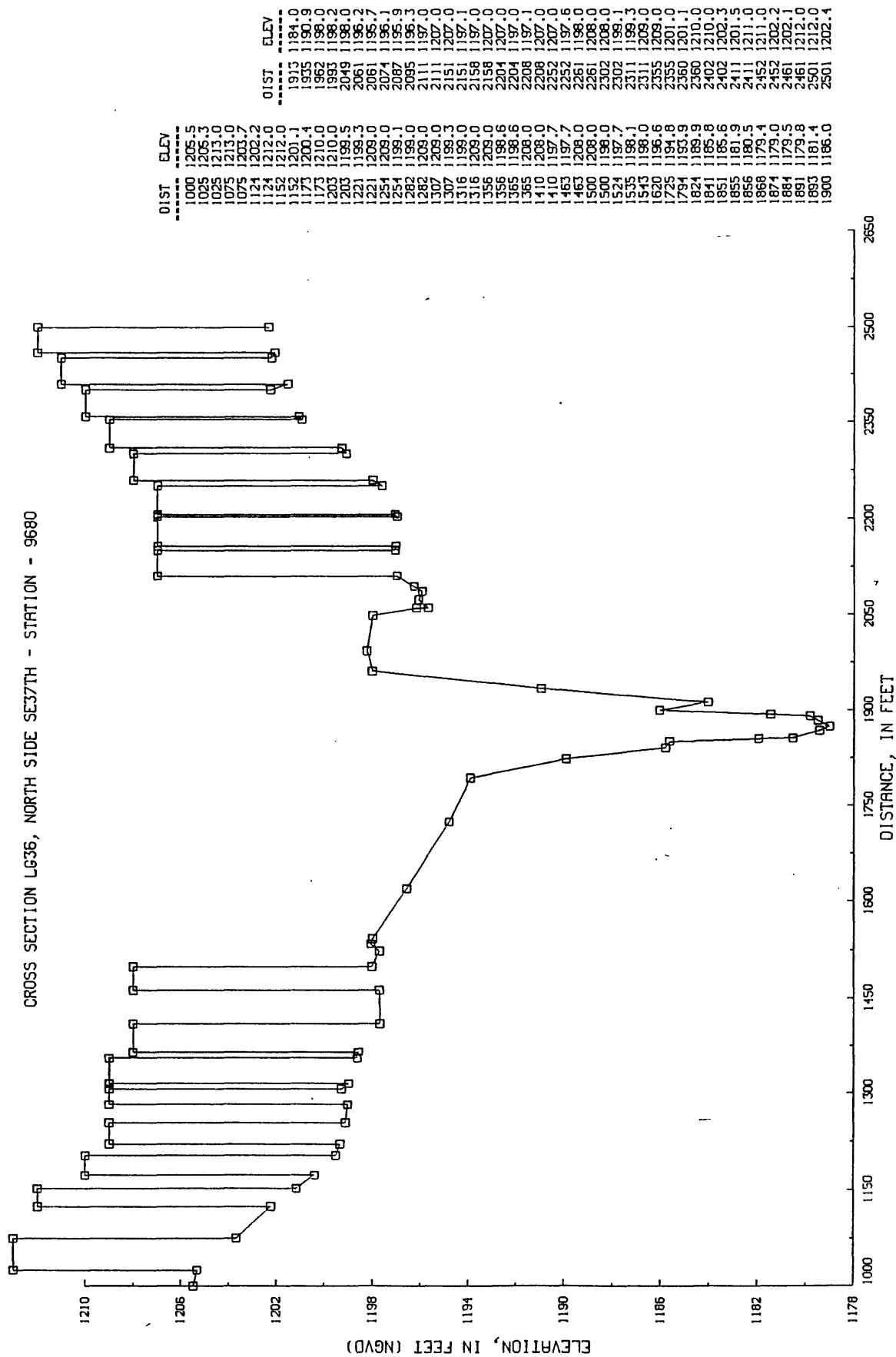
CROSS SECTION L635, UPSTREAM GRAND - STATION - 9580



Appendix 8-6. Plot of cross section 35, Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

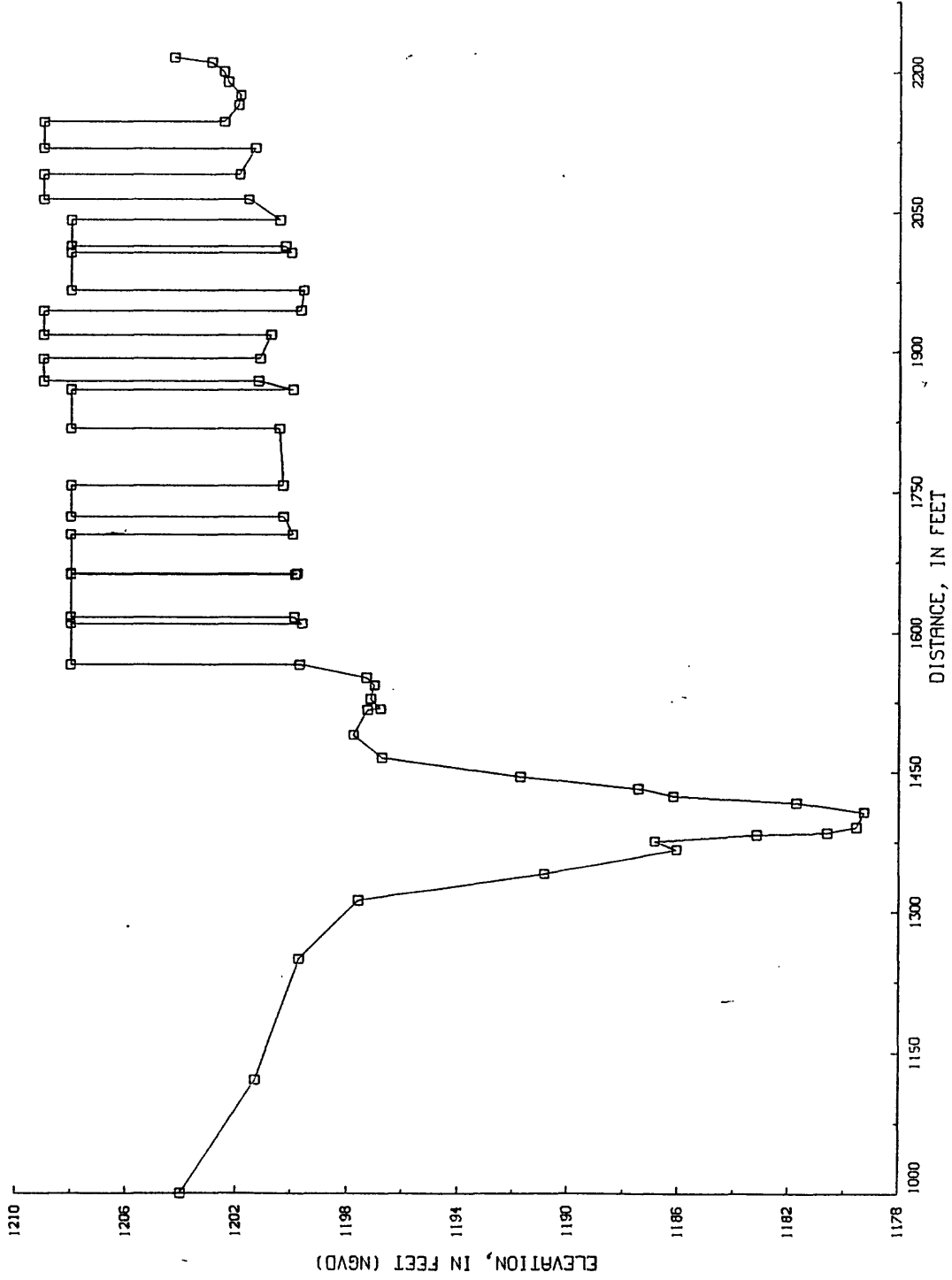
CROSS SECTION LG36, NORTH SIDE SE37TH - STATION - 9680



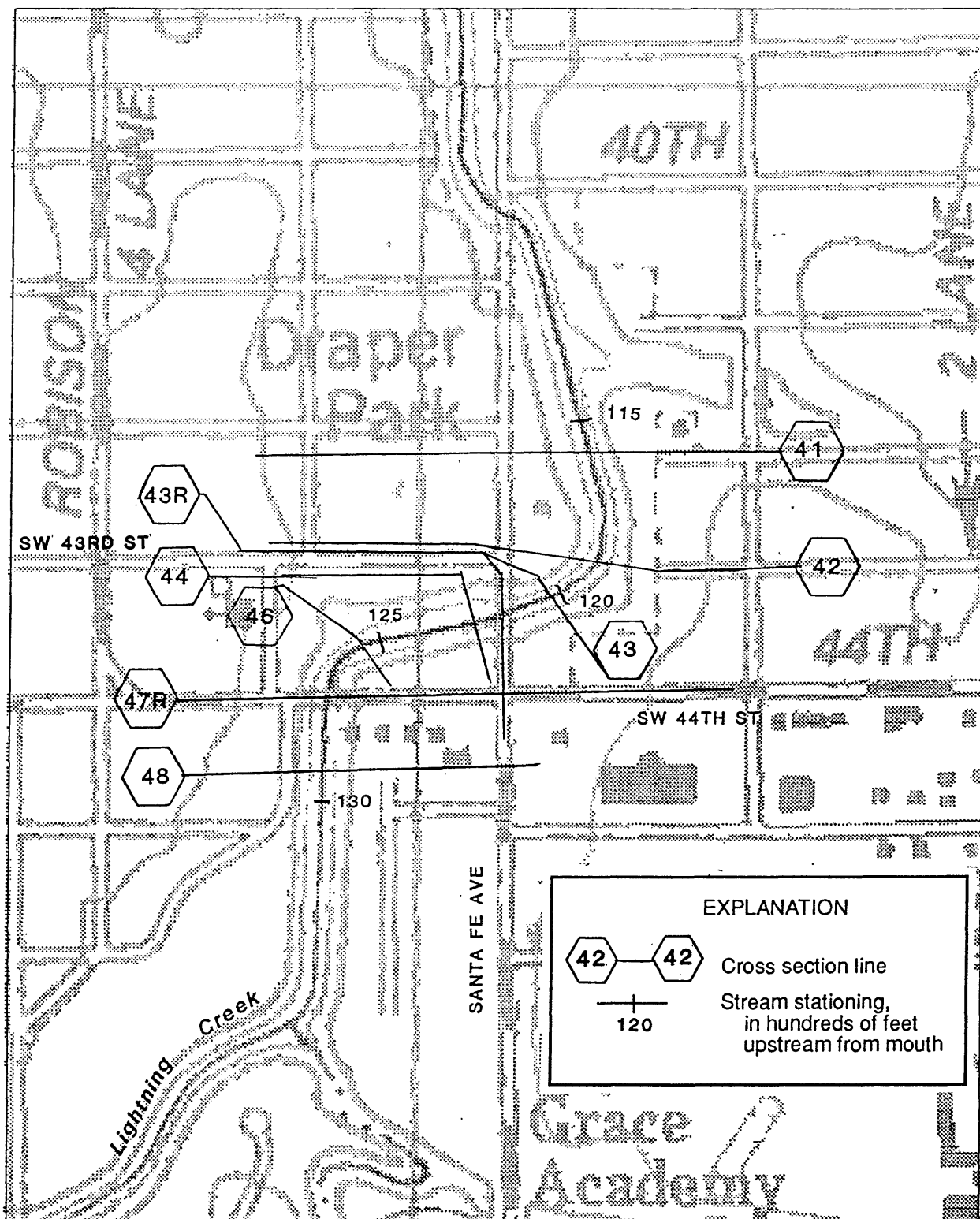
Appendix 8-7. Plot of cross section 36, Lightning Creek at Grand Avenue (site 8).

LIGHTNING CREEK AT GRAND AVENUE, MAY 8, 1993, FLOOD

CROSS SECTION LG37, SOUTH SIDE SW 38TH - STATION - 10045



Appendix 8-8. Plot of cross section 37, Lightning Creek at Grand Avenue (site 8).



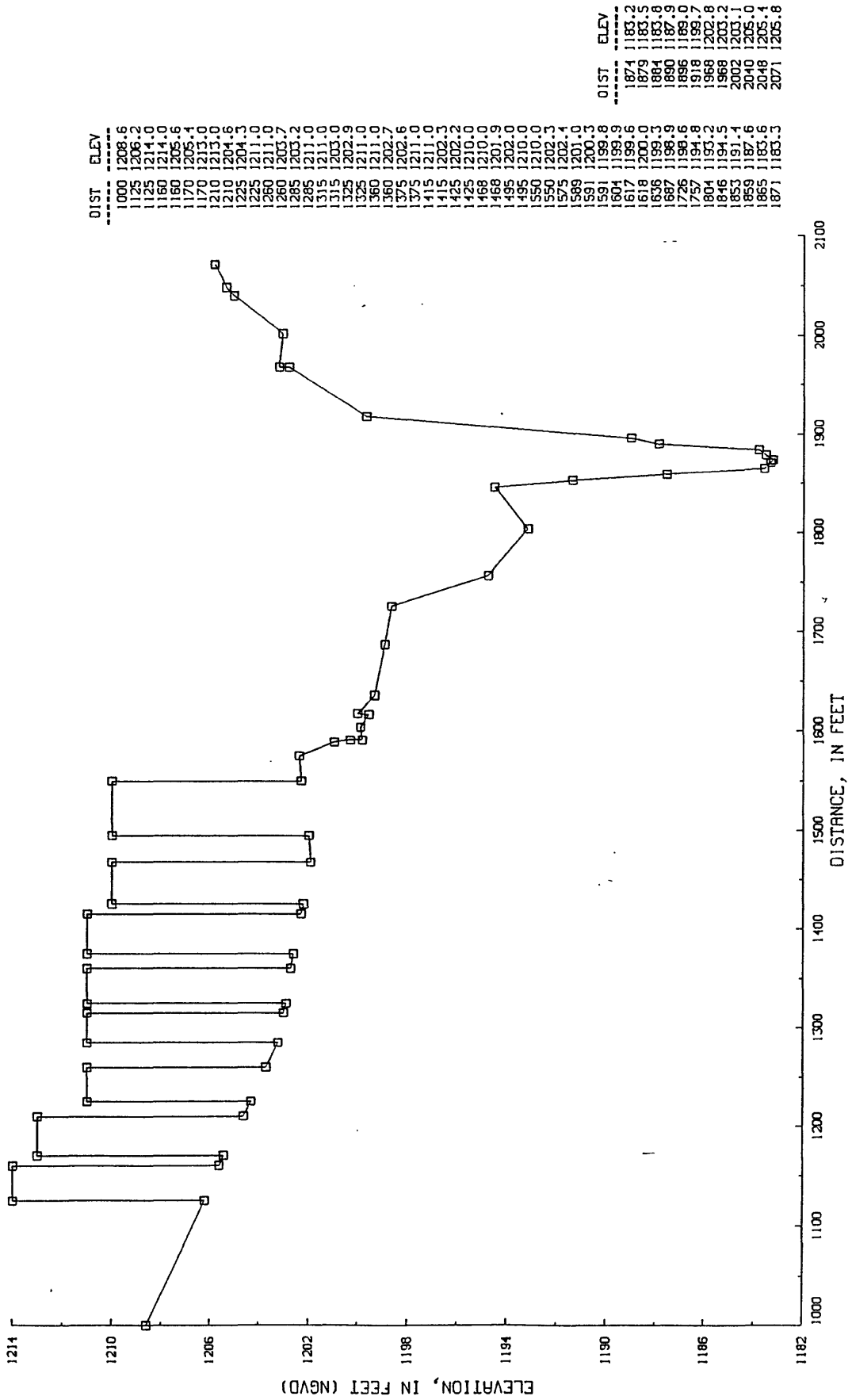
Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

0 100 FEET
 0 50 100 METERS

Appendix 9-1. Location of study cross sections on Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

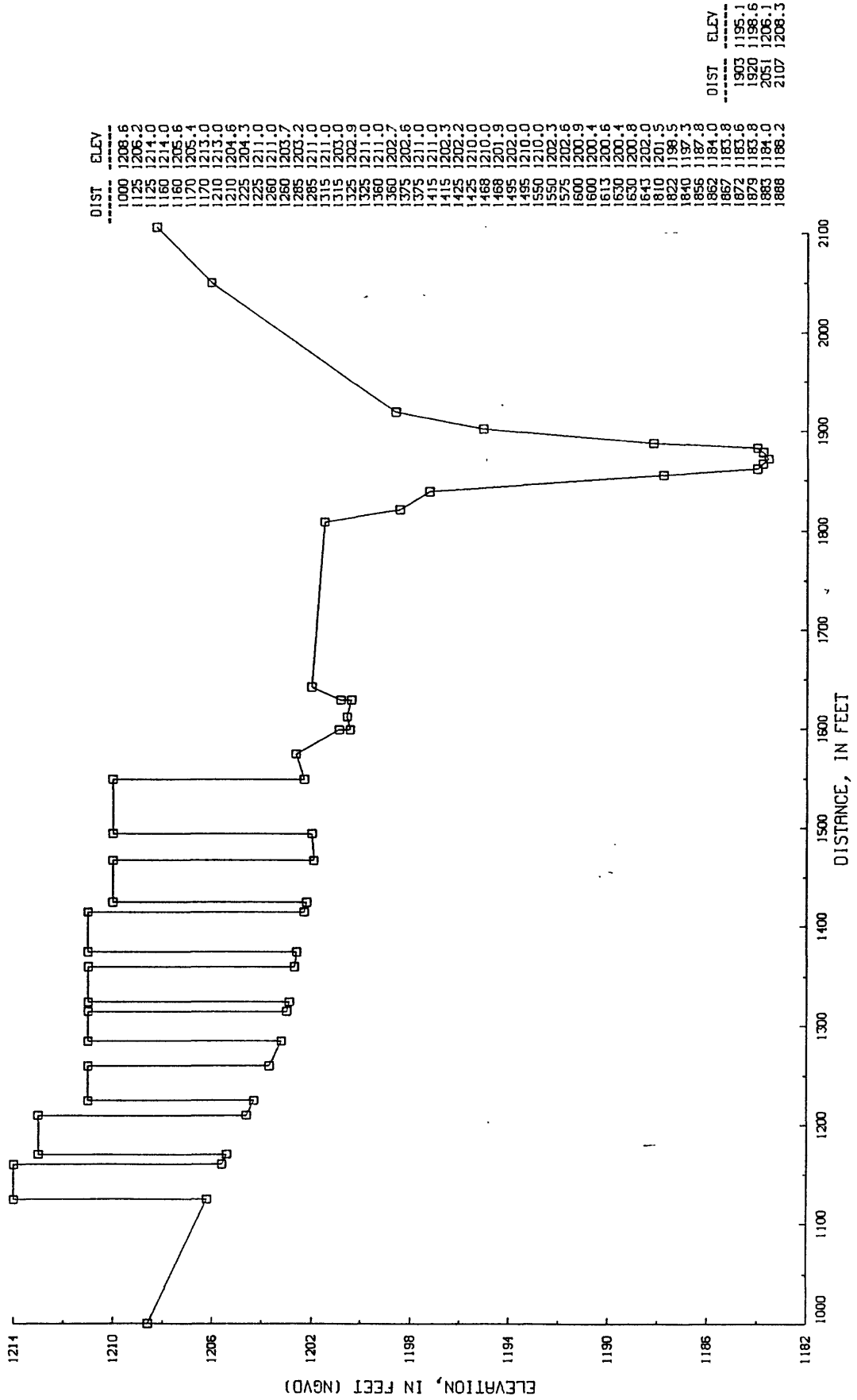
CROSS SECTION LG41, SW 42ND/DRAPER PARK - STATION-11590



Appendix 9-2. Plot of cross section 41, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

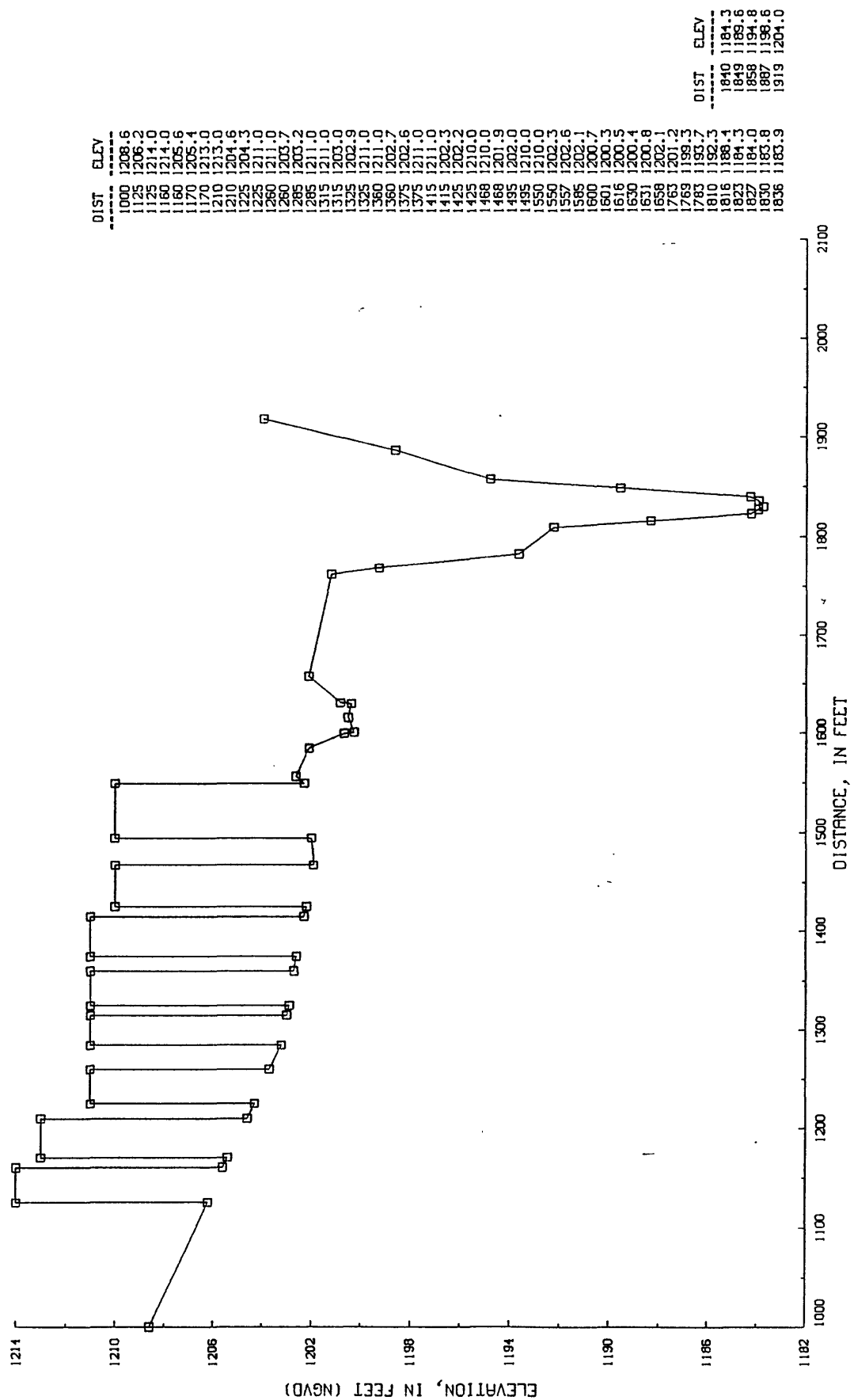
CROSS SECTION LG42, SW 43RD/DRAPER PARK - STATION - 11840



Appendix 9-3. Plot of cross section 42, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

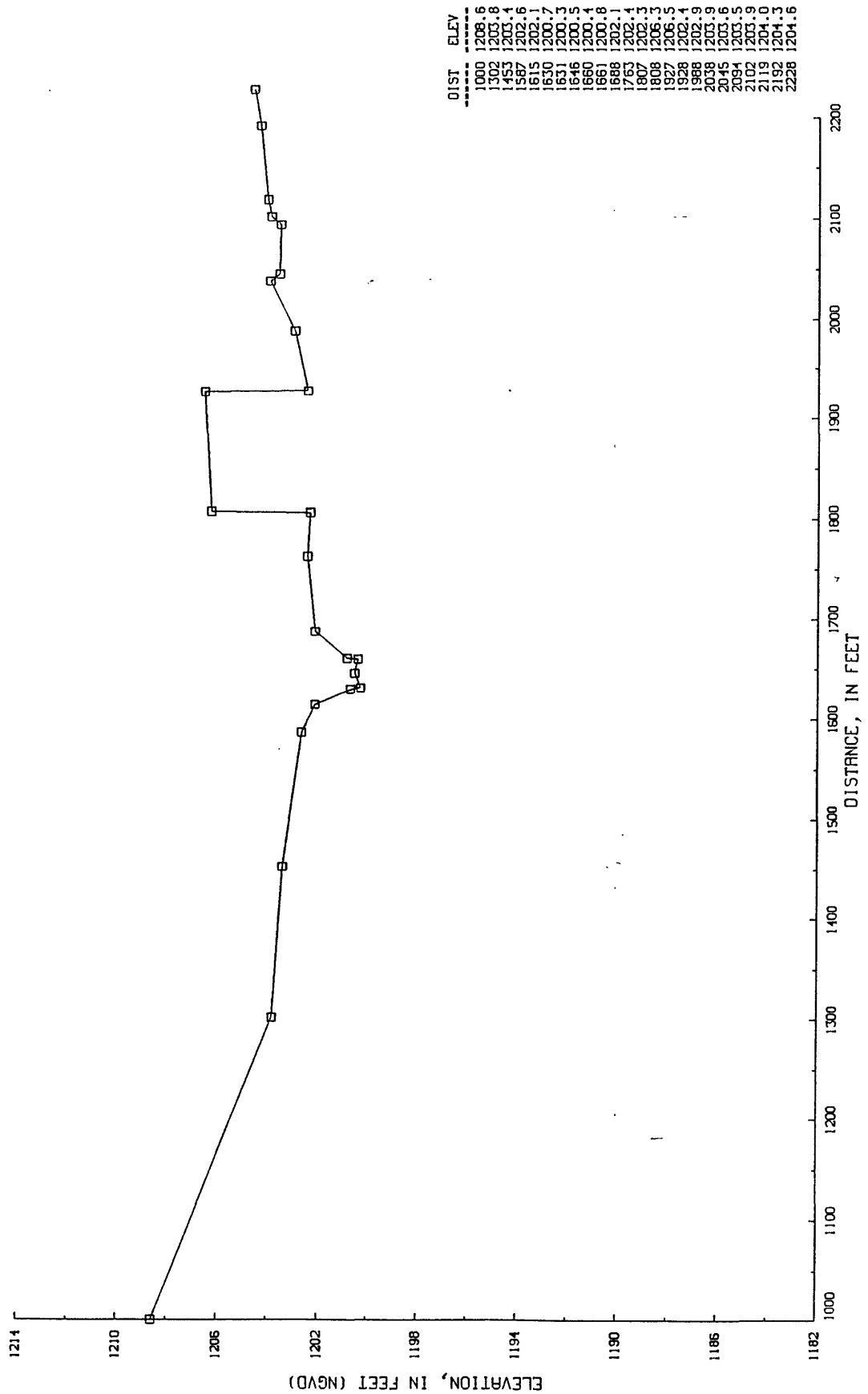
CROSS SECTION LG43, 100 FEET DOWNSTREAM SANTA FE-STATION-12035



Appendix 9-4. Plot of cross section 43, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

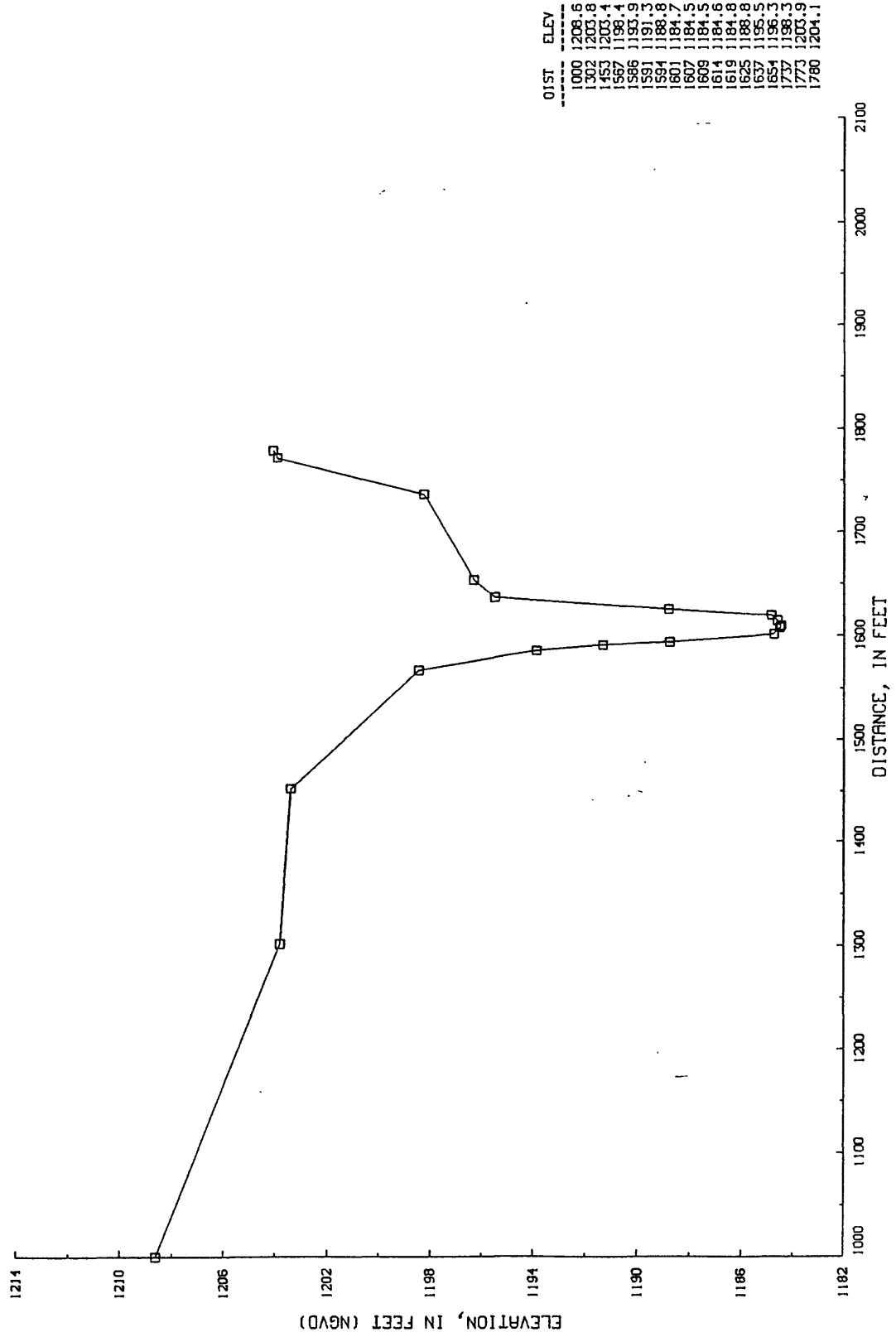
CROSS SECTION LG43R, EAST SIDE SANTA FE - STATION - 12160



Appendix 9-5. Plot of cross section 43R, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

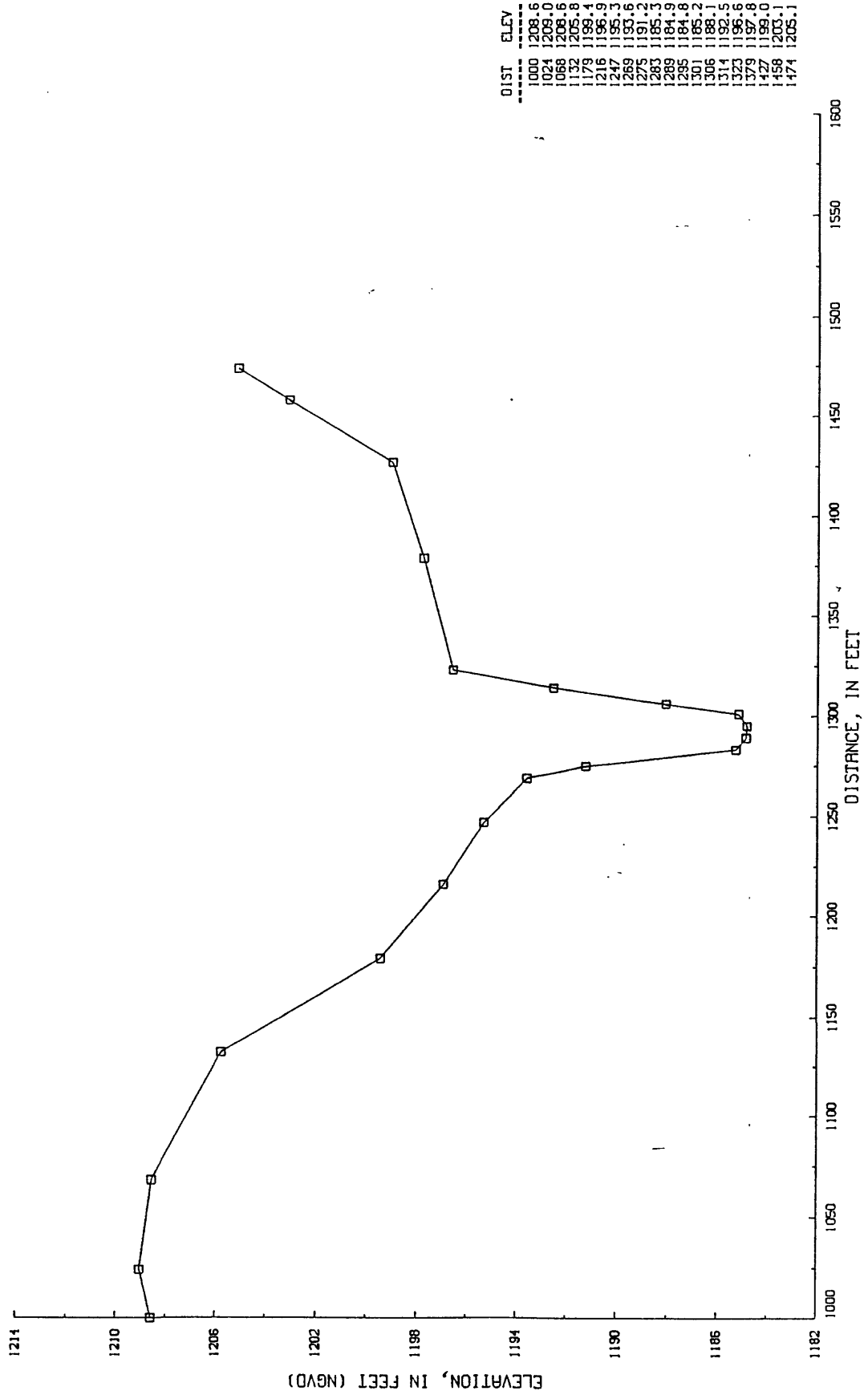
CROSS SECTION L044, 110 FEET UPSTREAM SANTA FE-STATION-12290



Appendix 9-6. Plot of cross section 44, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

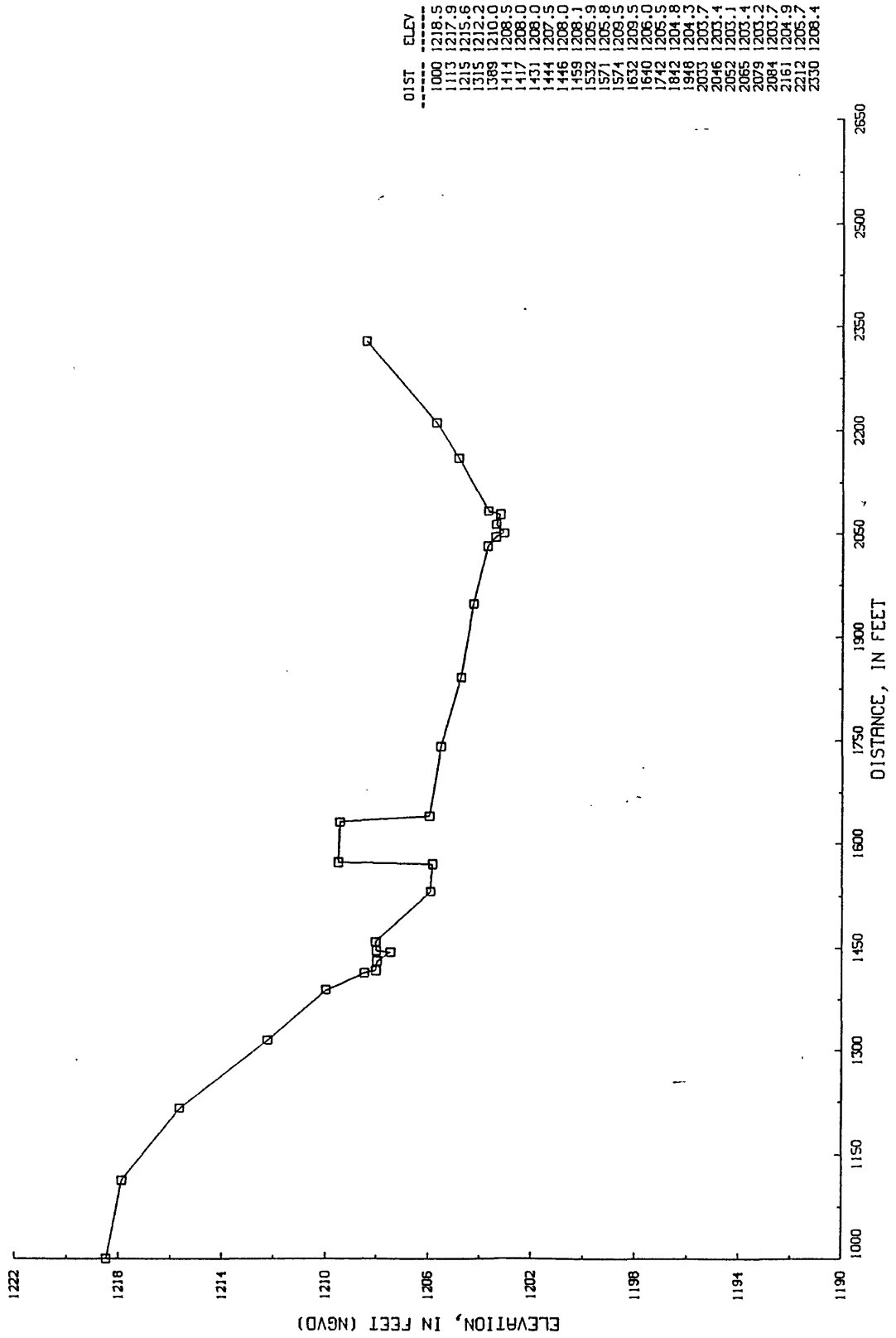
CROSS SECTION LG46, 150 FEET DOWNSTREAM SW 44TH-STATION-12545



Appendix 9-7. Plot of cross section 46, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

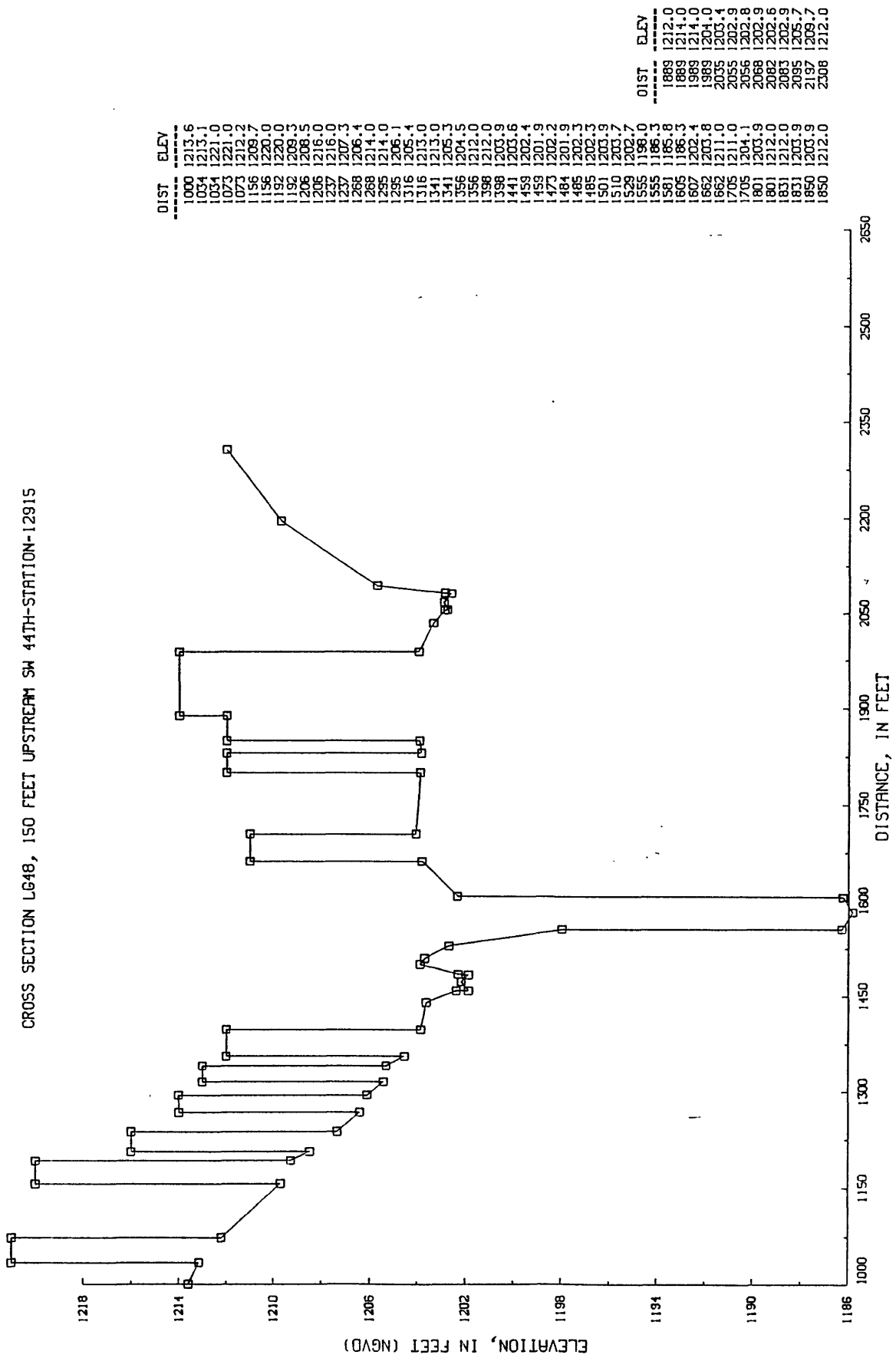
CROSS SECTION LG47R, NORTH SIDE SW 44TH - STATION - 12732



Appendix 9-8. Plot of cross section 47R, Lightning Creek at SW 44th Street (site 9).

LIGHTNING CREEK AT SW 44TH STREET, MAY 8, 1993, FLOOD

CROSS SECTION LG48, 150 FEET UPSTREAM SW 44TH-STATION-12915



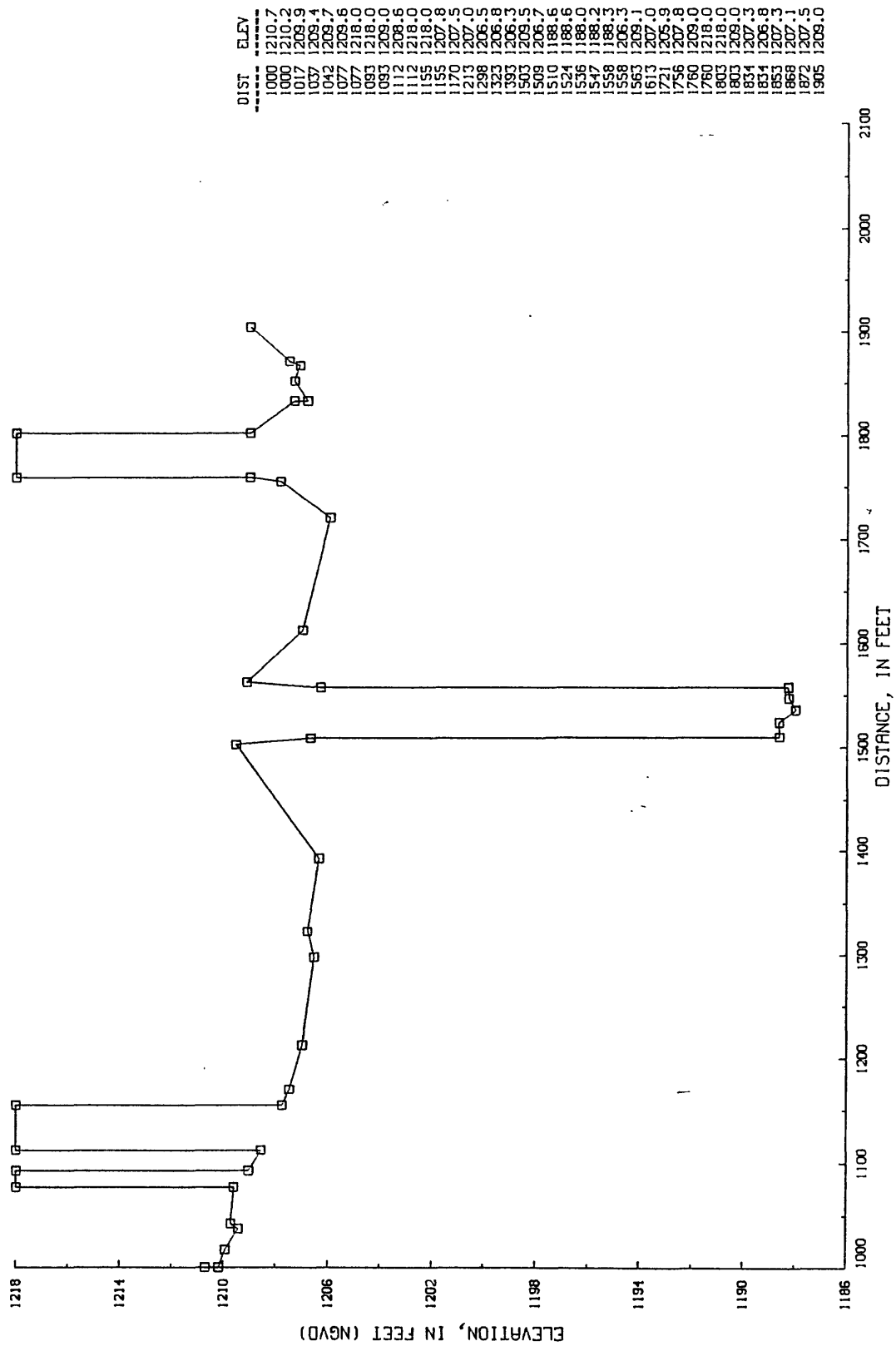
Appendix 9-9. Plot of cross section 48, Lightning Creek at SW 44th Street (site 9).



Base from U.S. Geological Survey Digital Raster Graphic, 1:24,000, 1986
 Projection: Oklahoma Coordinate System, north zone
 (Lambert Conformal Conic)

Appendix 10-1. Location of study cross sections on Lightning Creek at Sage Street (site 10), and SW 51st Street (site 11).

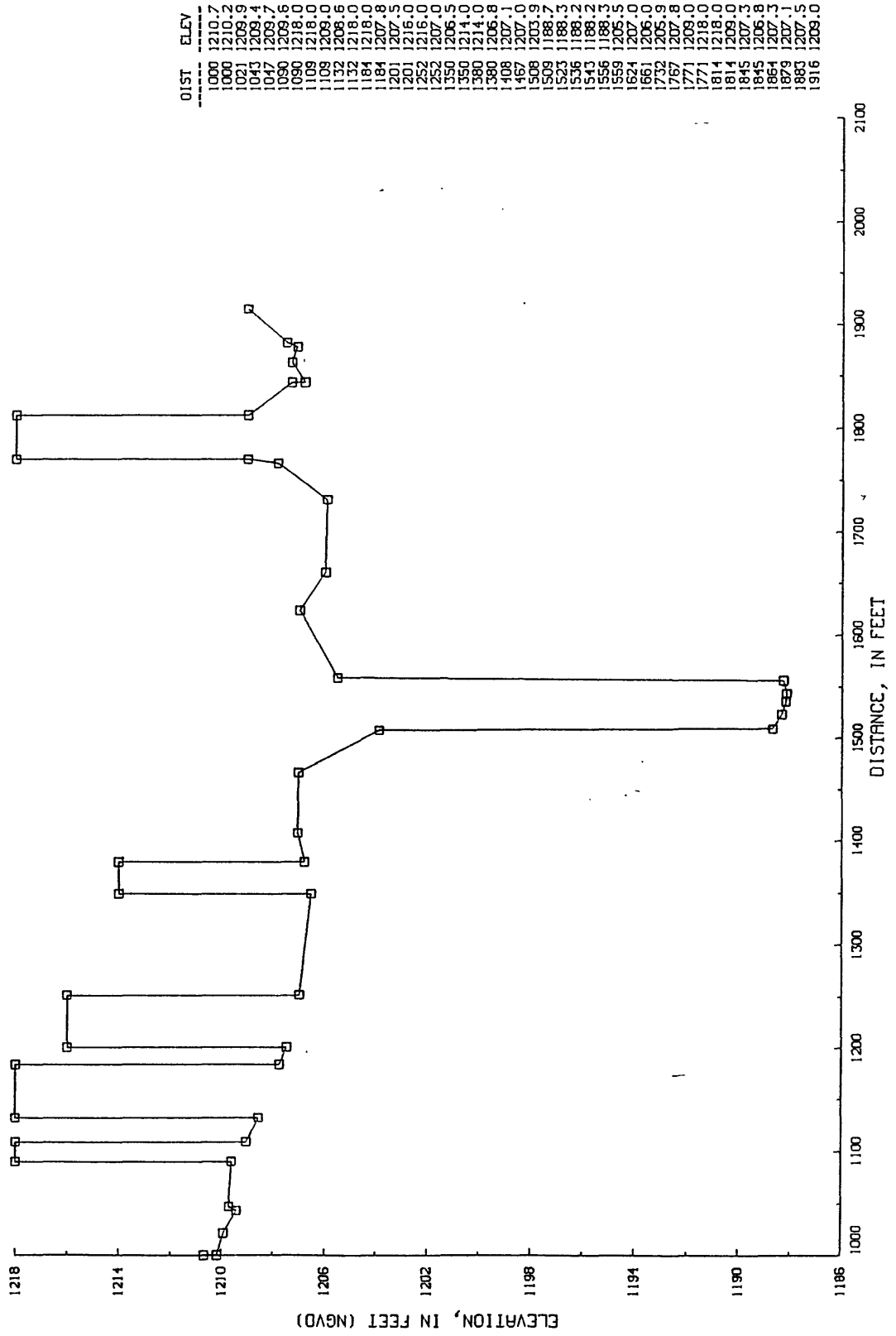
LIGHTNING CREEK AT SAGE STREET, MAY 8, 1993, FLOOD
CROSS SECTION 1051, 300 FEET DOWNSTREAM SAGE - STATION-14150



Appendix 10-2. Plot of cross section 51, Lightning Creek at Sage Street (site 10).

LIGHTNING CREEK AT SAGE STREET, MAY 8, 1993, FLOOD

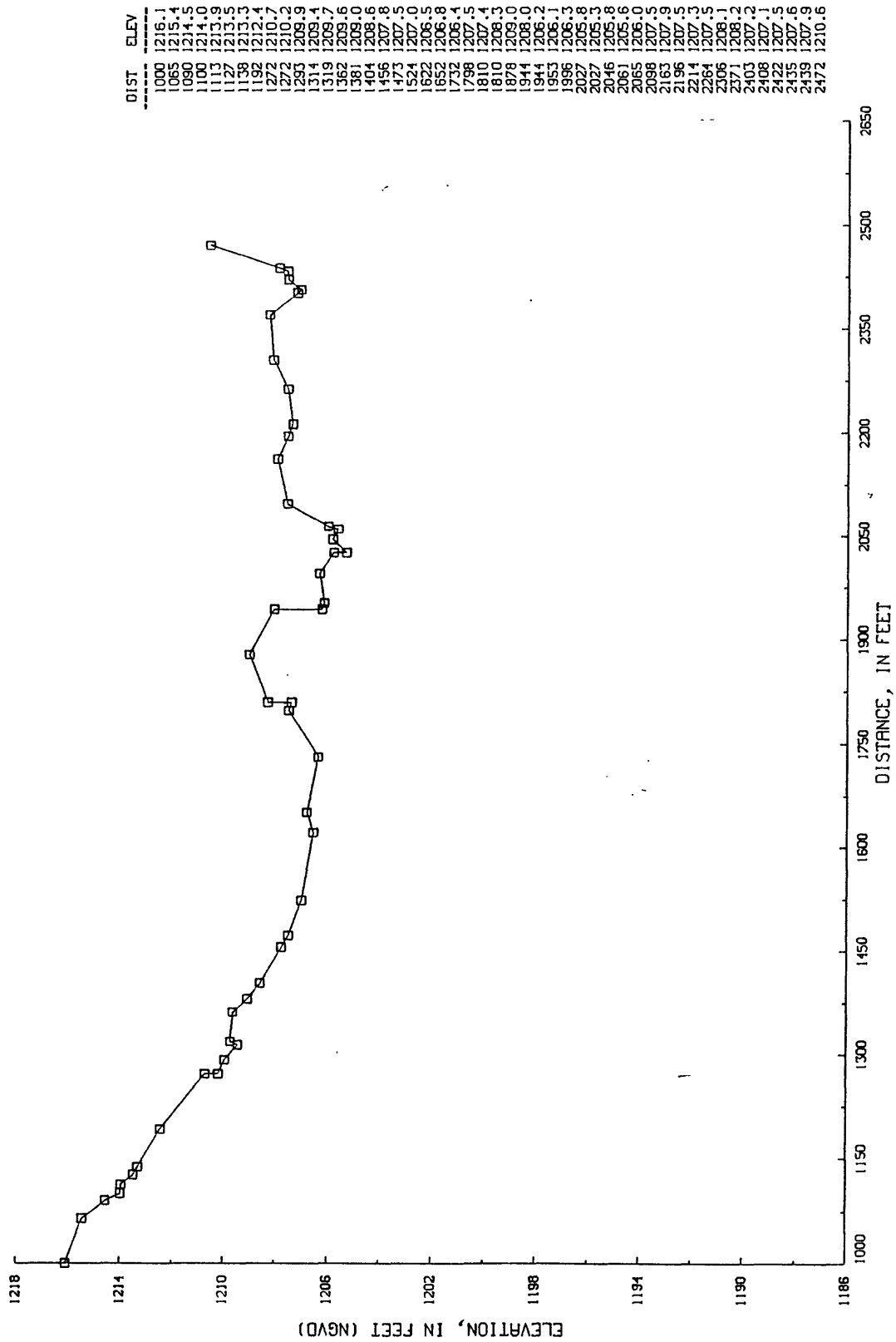
CROSS SECTION L952E, 180 FEET DOWNSTREAM SAGE-STATION-14285



Appendix 10-3. Plot of cross section 52E, Lightning Creek at Sage Street (site 10).

LIGHTNING CREEK AT SAGE STREET, MAY 8, 1993, FLOOD

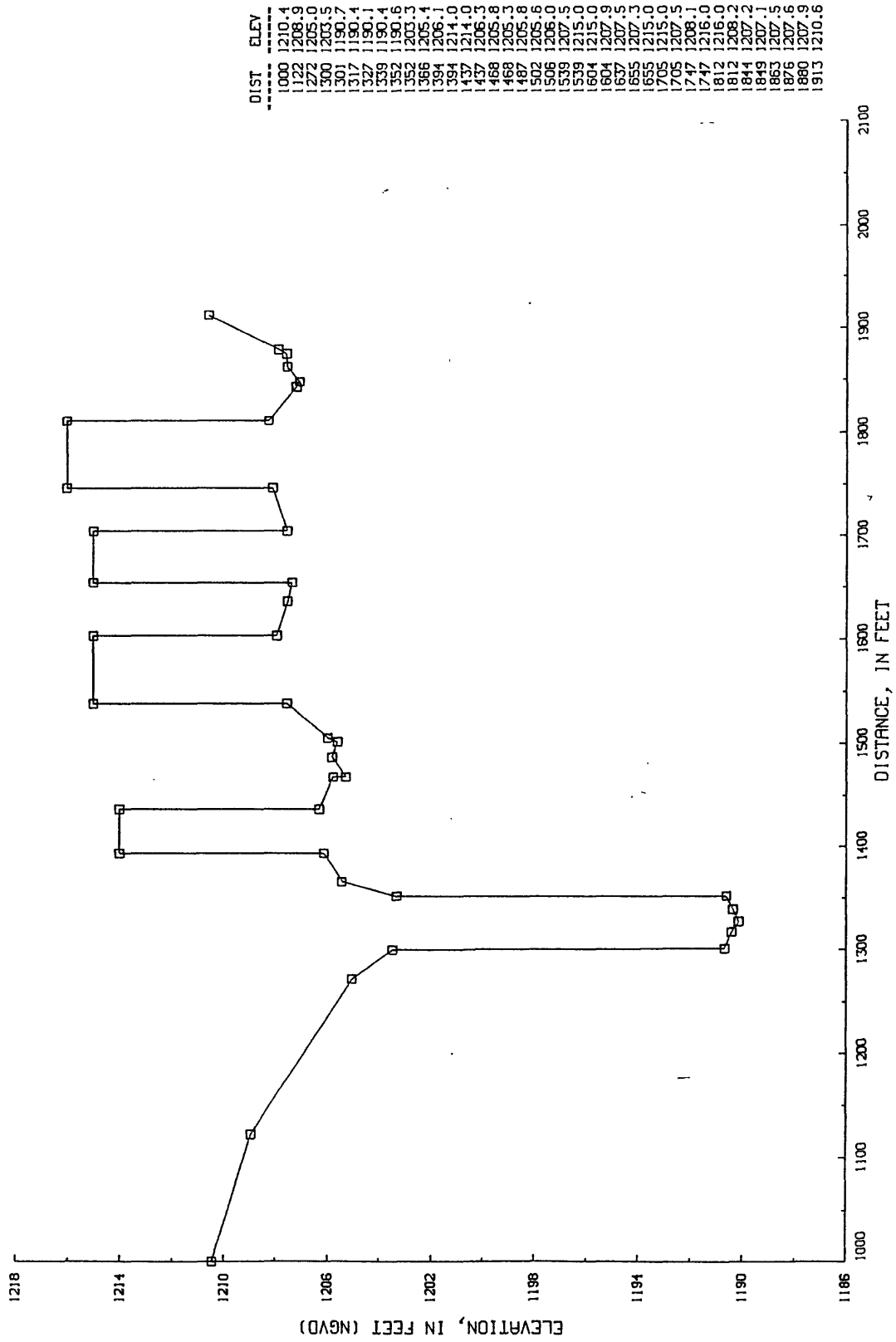
CROSS SECTION LG52R, EAST SIDE SAGE - STATION - 14482



Appendix 10-4. Plot of cross section 52R, Lightning Creek at Sage Street (site 10).

LIGHTNING CREEK AT SAGE STREET, MAY 8, 1993, FLOOD

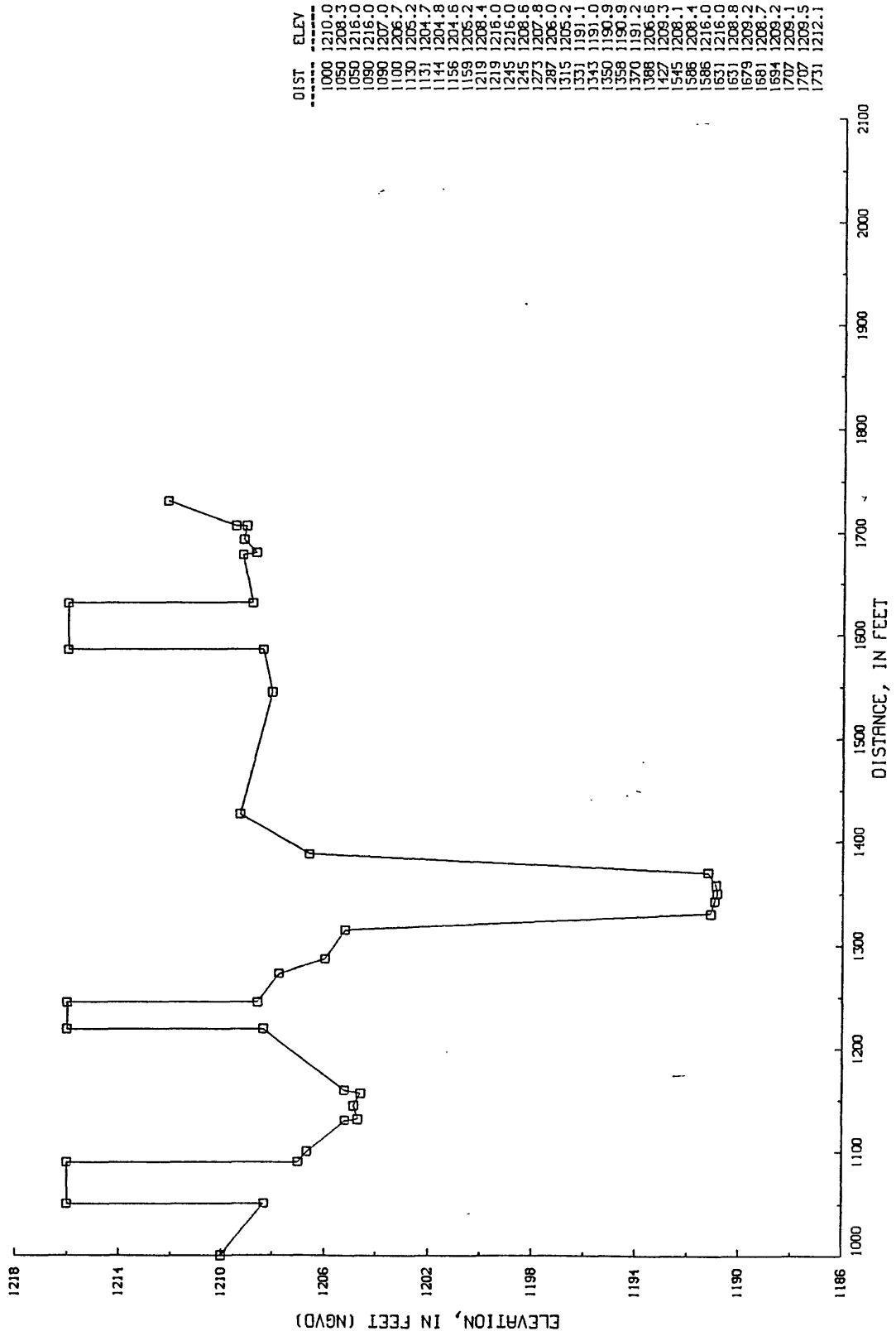
CROSS SECTION L652A, 155 FEET UPSTREAM SAGE - STATION-14655



Appendix 10-5. Plot of cross section 52A, Lightning Creek at Sage Street (site 10).

LIGHTNING CREEK AT SW 51ST STREET, MAY 8, 1993, FLOOD

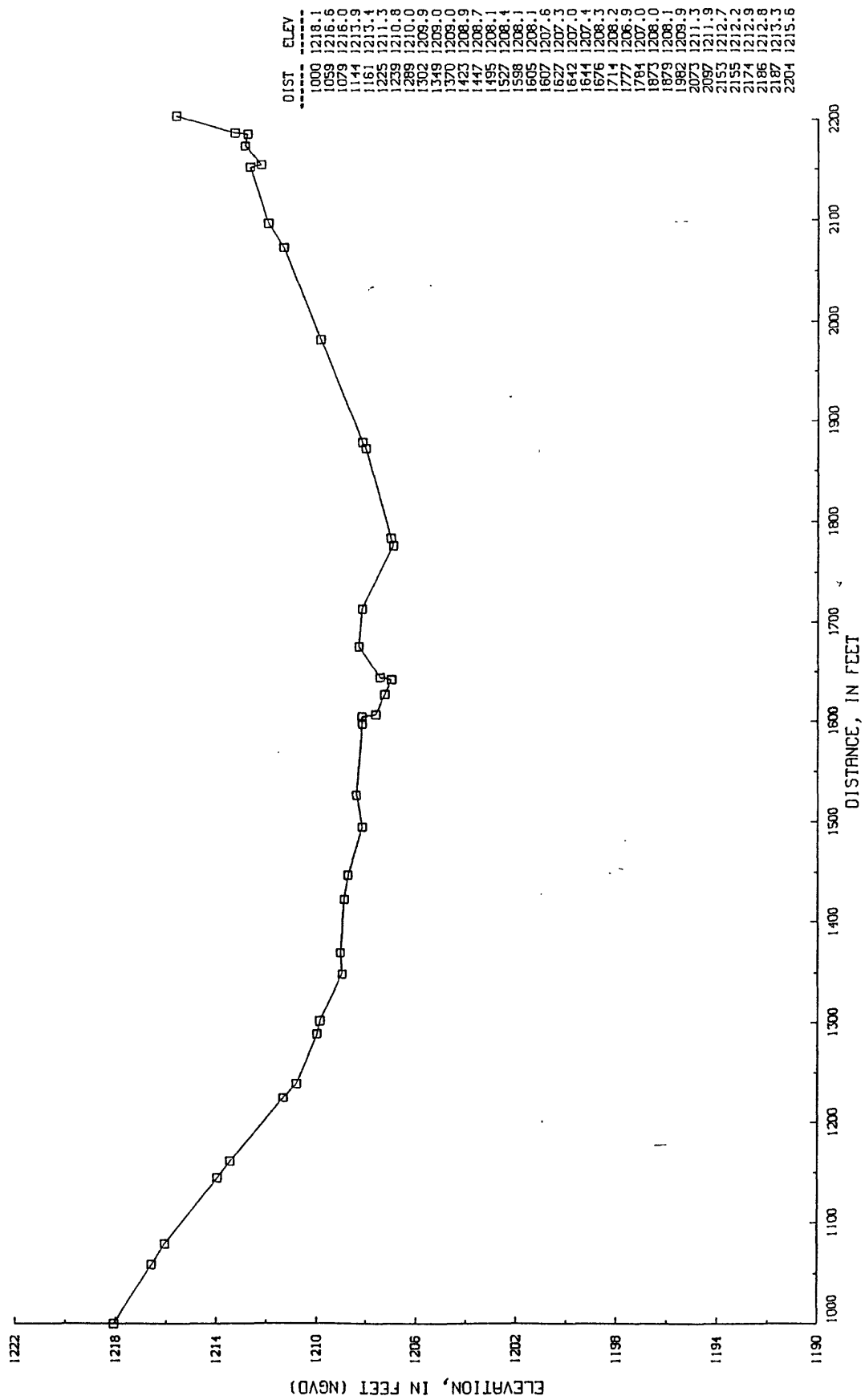
CROSS SECTION L054E, 235 FEET DOWNSTREAM SW 51ST-STATION-15345



Appendix 10-6. Plot of cross section 54E, Lightning Creek at SW 51st Street (site 11).

LIGHTNING CREEK AT SW51ST STREET, MAY 8, 1993, FLOOD

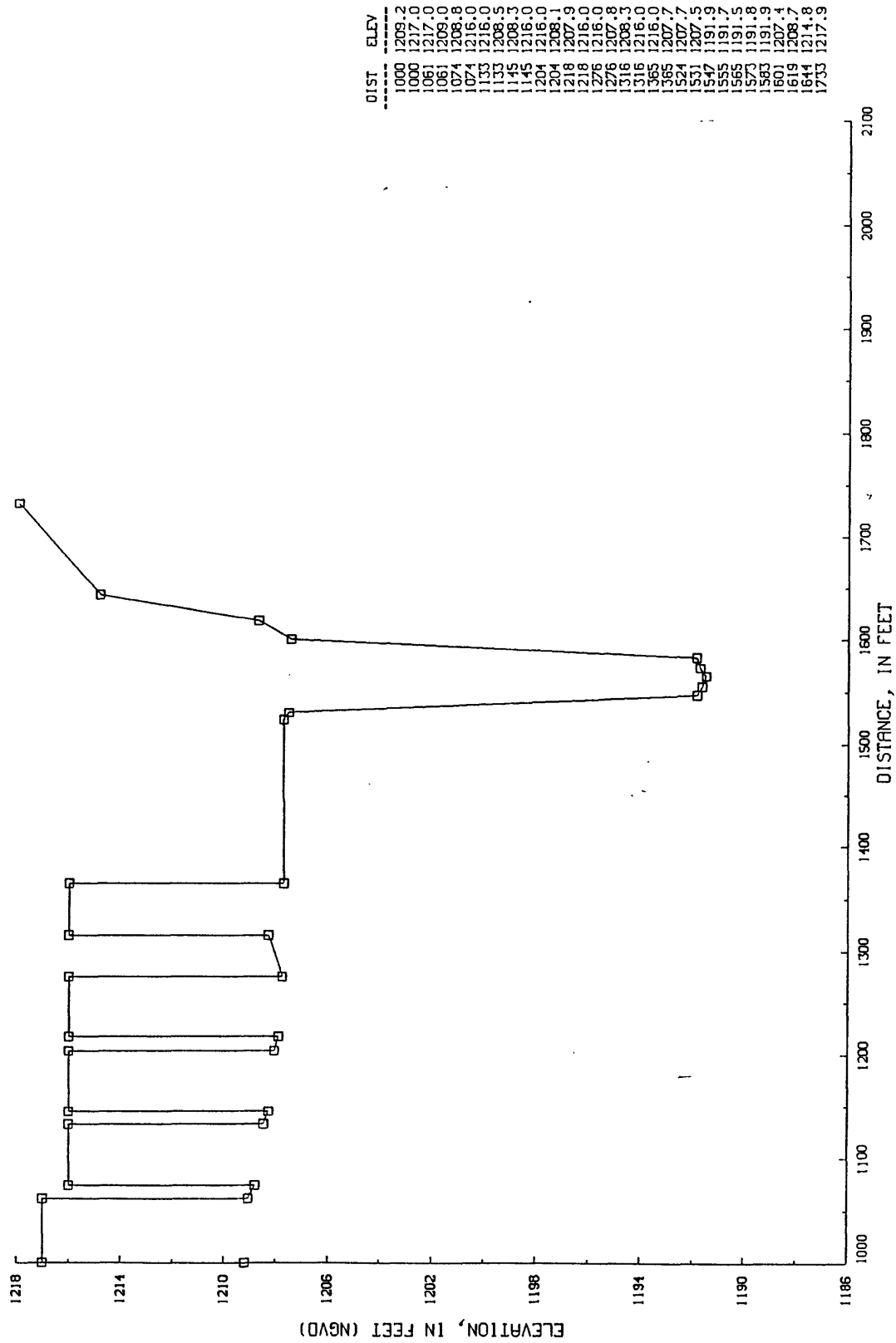
CROSS SECTION LG54R, NORTH SIDE SW 51ST - STATION - 15600



Appendix 10-7. Plot of cross section 54R, Lightning Creek at SW 51st Street (site 11).

LIGHTNING CREEK AT SW 51ST STREET, MAY 8, 1993, FLOOD

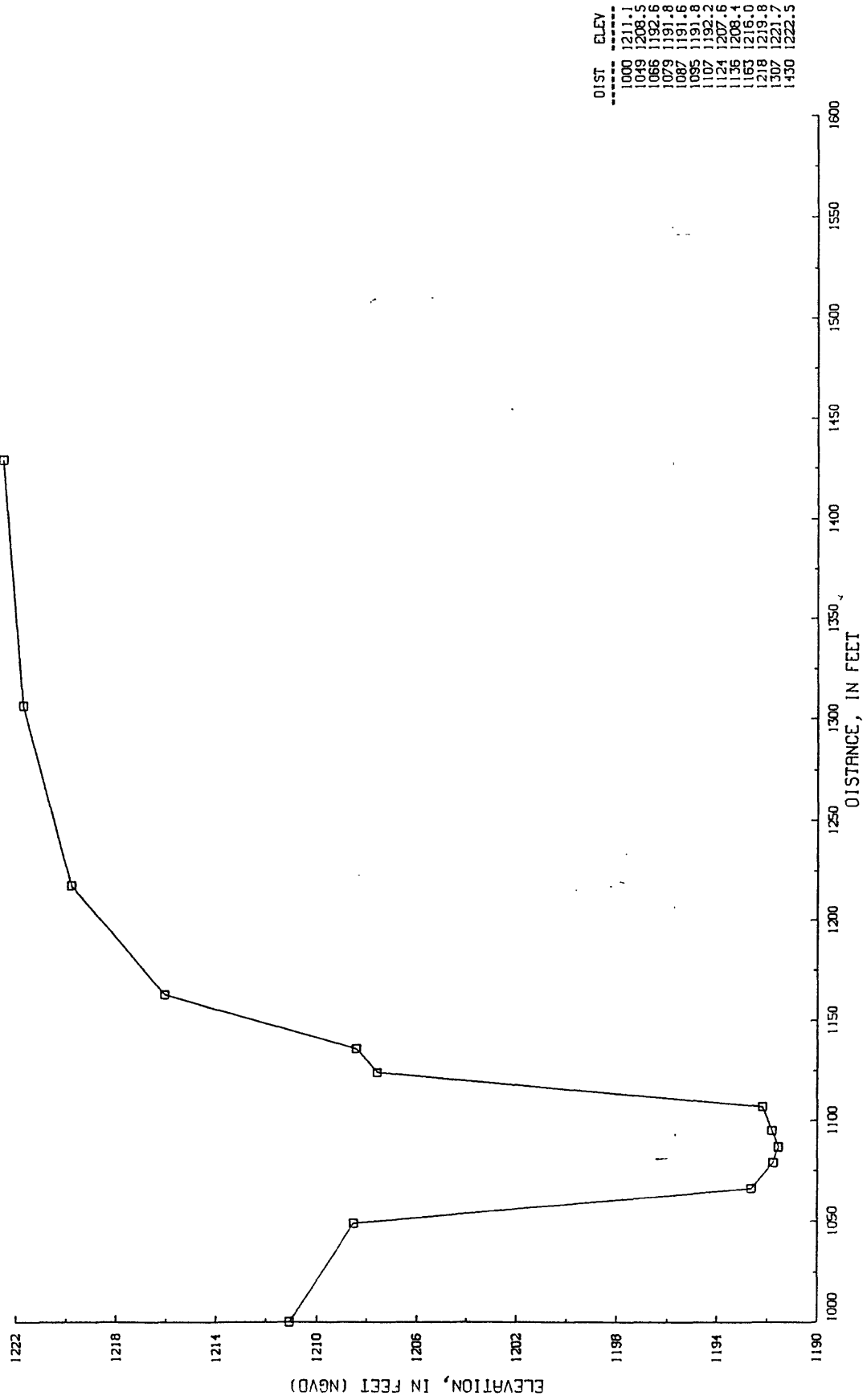
CROSS SECTION L654R, 400 FEET UPSTREAM SW 51ST-STATION-16000



Appendix 10-8. Plot of cross section 54A, Lightning Creek at SW 51st Street (site 11).

LIGHTNING CREEK AT SW 51ST STREET, MAY 8, 1993, FLOOD

CROSS SECTION LG55, 570 FEET UPSTREAM SW 51ST-STATION-16190



Appendix 10-9. Plot of cross section 55, Lightning Creek at SW 51st Street (site 11).