Summary of Bridge Scour Analyses at Selected Sites in Colorado, 1991-93

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U.S. GEOLOGICAL SURVEY

Open-File Report 95-296

Prepared in cooperation with the

COLORADO DEPARTMENT OF TRANSPORTATION

Denver, Colorado
1995

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
millimeter (mm)	0.03937	inch
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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Abstract

Scour depths were estimated for 220 bridge structures in Colorado as part of a cooperative agreement between the U.S. Geological Survey and the Colorado Department of Transportation. Methods of computation and analysis used are recommended by the Federal Highway Administration. Sites were selected for analysis by the U.S. Geological Survey and the Colorado Department of Transportation based on a screening process of 3,610 State-owned bridges for susceptibility to scour during extreme flood events.

Magnitudes of the 100-year and 500-year flood events were computed from regionalized regression equations developed for Colorado in previously published reports. Water-surface profiles were computed for the 100-year and 500-year flood events using the Water-Surface PROfile (WSPRO) computation program. Variables were selected from the WSPRO output and used in the scour equations recommended by the Federal Highway Administration. Computed scour depths for the bridge sites and selected data collected during field surveys were tabulated.

INTRODUCTION

Stream stability and, potentially, bridge stability are affected by geomorphic and hydraulic factors (Lagasse and others, 1990). Stream behavior depends on the apparent stability of the stream at the bridge and on the associated hydraulic characteristics of the stream and the bridge geometry. Streams can be classified qualitatively based on their geomorphic properties observed in the field or from aerial photographs. A more quantitative method used to assess bridge stability and scour analysis is described in Richardson and others (1991). Scour analysis requires evaluation of the hydraulic factors that characterize streamflow and channel conditions at the bridge. Hydraulic factors are determined from computation of the water-surface profile for a given flood magnitude through the bridge. The water-surface profile through the bridge is a result of gradually varied flow over long distances and rapidly varied flow at obstructions in or near the bridge. Channel conditions can be defined from observations and data collected during a field survey of the bridge site.

The U.S. Geological Survey (USGS), in cooperation with the Colorado Department of Transportation (CDOT), began a study in 1991 to evaluate scour potential at bridge sites in Colorado. The purpose of this study was to aid CDOT in fulfilling requirements set forth by the Federal Highway Administration (FHWA) to evaluate all bridges on the Federal Aid System in Colorado for bridge stability related to scour. The sites selected for scour analysis were determined by a screening process. An initial screening by CDOT of 3,610 State-owned bridges for susceptibility to scour during an extreme flood event eliminated 2,122 bridges that did not span water or that crossed controlled waterways such as irrigation ditches. A secondary screening process of the remaining 1,488 bridges by CDOT, using Laursen's abutment-scour equations and Chang's pier-scour equation (Richardson and others, 1991) and by using a USGS ranking procedure, further decreased the number of bridges that might be scour susceptible. The 220 bridge sites analyzed were selected from the list of sites remaining after the secondary screening process (fig. 1). A copy of the Colorado State highway map, which was provided by CDOT, is in Appendix 1 in the pocket at the back of the report. The map can be used as an aid in locating the bridge sites using the highway route number and the CDOT structure ID.

A model, Water-Surface PROfile computations (WSPRO), was used to compute the profiles for the 100- and 500-year flood events through the bridge reaches (Shearman, 1990). Profile computations for open-channel flow are compatible with conventional techniques used in existing step-backwater models. Profile computations for free-surface flow through bridges are based on relatively recent developments in bridge-backwater analysis and recognize the effect of bridge-geometry variations. Magnitudes of the 100- and 500-year floods at the bridge sites were determined from regionalized regression equations that define the flood-frequency relations for a given area. Scour equations used in the analyses are recommended by FHWA and are described in Richardson and others (1991).

A separate phase of the project was collection of scour data at a limited number of sites during selected flow events. Baseline cross sections were determined during the low-flow period prior to the runoff peak in the spring of the year at most sites. Thirty cross sections at six sites were measured during 1991–93 that indicate scour, channel aggradation, and thalweg migration. Stream-channel cross-section plots for various streamflows at each site are included in Appendix 2.

This report summarizes scour computations for 220 bridge sites analyzed during 1991–93. Data included are pertinent bridge and channel information, the computed scour depths at each site, and an example of a bridge scour analysis. Final determination of the severity of total scour related to bridge stability was outside the scope of this project.

METHODS OF DATA COLLECTION

Channel cross-section geometry and related bridge-geometry features were determined for input to WSPRO using standard field-surveying techniques (Benson and Dalrymple, 1967). Reference points were established and an arbitrary datum assigned. Any existing reference marks on the bridges were included in the surveys. Ground elevations and pertinent bridge-point elevations were then determined using differential leveling techniques (Rayner and Schmidt, 1963). Horizontal control was established by setting the initial azimuth of the surveying instrument to magnetic north or approximate true north as the reference. Angles from the reference were recorded at all surveyed points to locate them in the horizontal plane. Independent checks were made on select points periodically during the survey to maintain the vertical datum and horizontal control.

Surveyed cross sections were located one bridge width upstream from the bridge (approach section), at the downstream side of the bridge (bridge section), and one bridge width downstream from the bridge (exit section). Additional cross sections were surveyed downstream from the exit section if there were substantial changes in channel geometry or bed slope through the stream reach (fig. 2). At sites where dense vegetation or deep channels prohibited surveys of all cross sections, a representative cross section was surveyed and field observations made of the channel geometry through the stream reach. The representative cross sections were then used to define the cross sections required by WSPRO.

Channel roughness coefficients were assigned to each cross section, and its subareas if needed, based on experience of the field crew and guidelines from selected references (Jarrett, 1985; Arcement and Schneider, 1989). Values of d50 (median particle diameter) for the bed material were determined by visual estimates or by estimated pebble counts (Wolman, 1954).

Bridge-geometry features that were surveyed included abutment corners to define orientation of the bridge to the flow, wingwall ends to determine the angle from the road embankment, pier centerlines to measure pier skew to the flow, low-steel (chord) elevations, roadway embankment widths, roadway embankment slopes, and road centerline elevations. Selected data collected during the field surveys are listed in table 1.

BRIDGE SCOUR RESULTS

Discharge Computations

Magnitudes of the flood events that had an exceedance probability of 0.01 and 0.002 were computed for each bridge site. These flood events commonly are termed the 100- and 500-year floods. Regionalized regression equations for these flood events are published in several reports for Colorado that apply to different physiographic regions statewide (for example, McCain and Jarrett, 1976; Kircher and others, 1985). Application of the equations is limited by drainage-basin area and the physiographic location of the bridge. Equations for the 100- and 500-year flood in the northern and southern plateaus and the mountains are reported in Kircher and others (1985). Equations for the foothills area (the area in the South Platte River Basin between 5,000- and 8,000-ft elevation and where the drainage-basin area below 8,000-ft elevation is between 2 and 50 mi^2) are reported in Jarrett and Costa (1988). The 100-year flood for sites in the eastern plains was computed from data provided by Livingston and Minges (1987) for drainage areas less than 20 mi^2. Equation information in McCain and Jarrett (1976) was used for the 100-year flood for drainage-basin areas greater than 20 mi^2 and for the 500-year flood on the eastern plains for all drainage-area sizes.

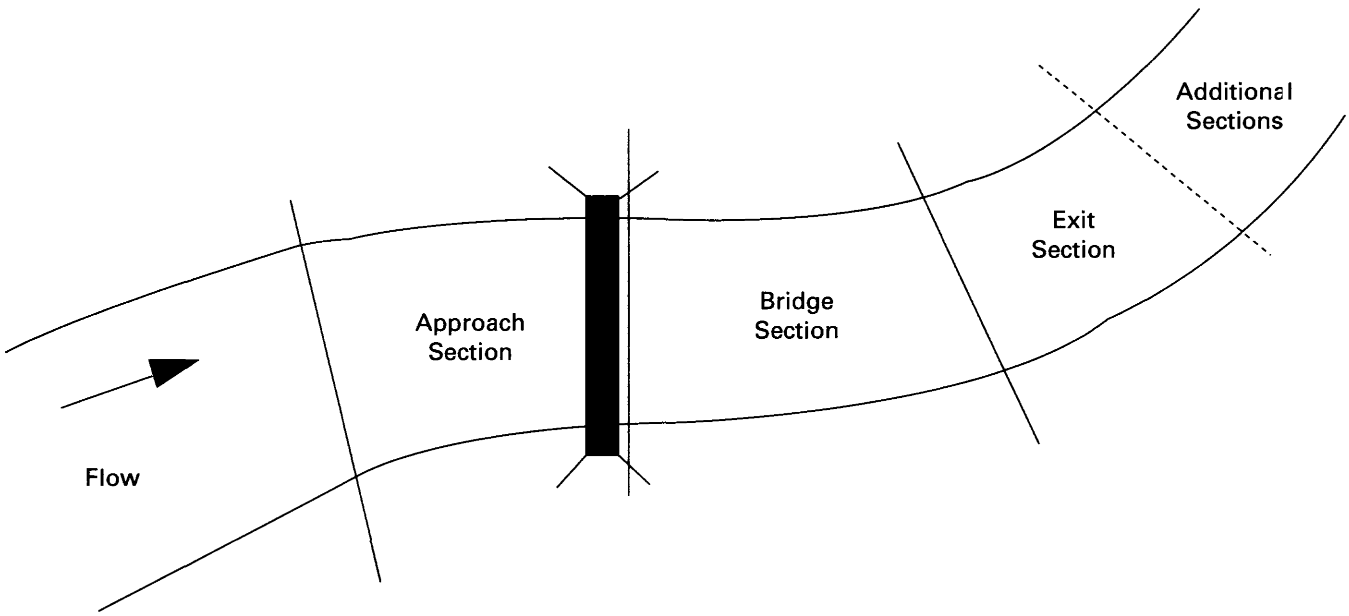


Figure 2. Typical plan view of a bridge survey.

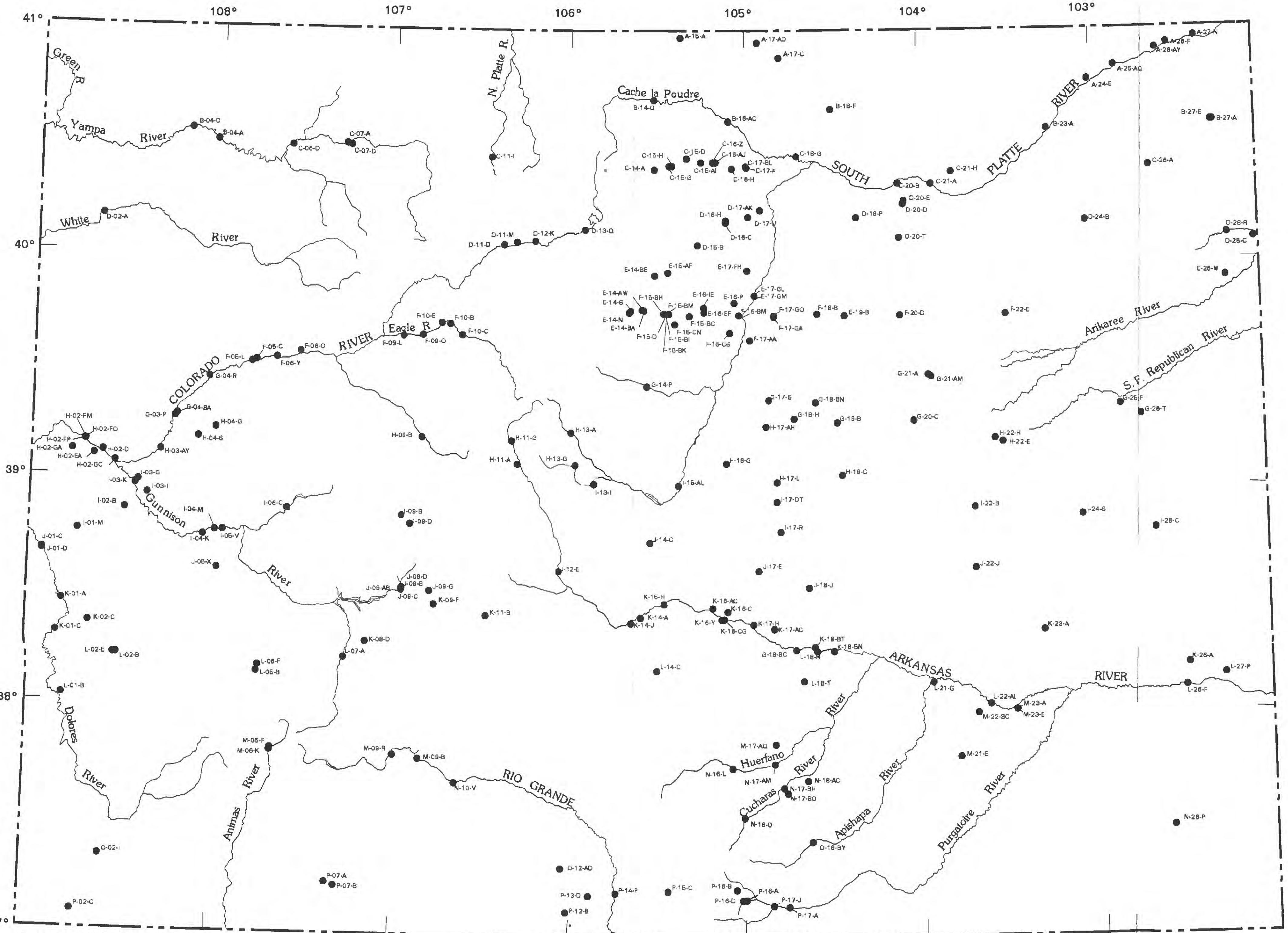
The applicable equations and input parameters were determined for each bridge site. Input parameters for the various equations include average-basin precipitation, in inches; channel slope, in foot per foot or feet per mile; drainage area, in square miles; drainage area below 8,000-ft elevation, in square miles; and the mean basin slope, in foot per foot.

Drainage-basin areas were supplied by CDOT, if available. Various-scale topographic maps were used to compute drainage-basin areas not supplied by CDOT. Channel slope was computed from topographic maps for the channel reach at the bridge site. Values for mean basin slope were selected from Richter and others (1984) or were computed using described techniques. Precipitation values also were selected from Richter and others (1984) or were computed using described techniques and the Colorado Average Annual Precipitation 1951–80 map prepared by the Colorado Climate Center (U.S. Geological Survey, 1980).

Water-Surface Profiles

Water-surface profiles for the 100- and 500-year flood discharges were computed using WSPRO, a model for Water-Surface PROfile computations (Shearman, 1990) that uses the field-surveyed data. Stream-channel geometry was input from cross-section plots and information from the field surveys. In instances where computed water-surface elevations were higher than the surveyed cross-section endpoints, the cross sections were extended based on field observations of channel geometry or data from topographic maps. Field-selected roughness coefficients were used in the initial computations. Roughness coefficients were weighted based on channel conveyance, and a single value was used for the section when the cross-section shape indicated subdivision was unnecessary. Unnecessary subdivision of a cross section affects the hydraulic radius term in the computations. A composite roughness value less than the field-selected value for the main channel could be computed (R.H. Tice, U.S. Geological Survey, written commun., 1970). When pronounced changes in roughness coefficients occurred in a cross section, the section was subdivided at the roughness change, regardless of cross-sectional shape.

Bridge type was assigned according to one of six types defined in the WSPRO documentation (Shearman and others, 1985). Effects of piers and bridge geometry on the hydraulic properties in the bridge section were accounted for in the computations. Cross-sectional flow properties for the specified water-surface elevation and the associated streamflow used in the scour analysis were generated by WSPRO.



Base from U.S. Geological Survey
1:100,000 Digital Line Graphs
Lambert projection
Standard Parallels 33° and 45°, central meridian -105°30′

0 25 50 75 MILES
0 25 50 75 KILOMETERS

Explanation

● N-26-P Colorado Department of Transportation Structure ID

Figure 1. Location of bridge sites.

Table 1. Bridge and channel information for 1991–93

[CDOT, Colorado Department of Transportation; mi^2, square miles; pier type, 1 = square nose, 2 = round nose, 3 = sharp nose, 4 = square piles, 5 = round piles; abutment type, 1 = vertical, 2 = sloping; n/a, not applicable]

CDOT structure ID (fig. 1)	CDOT route number	Drainage area (mi^2)	Number of piers	Pier type	Skew angle (degrees)	Abutment type	Riprap present	Predominant bed material observed
B–27–A	6	150	6	4	10	1	Yes	Sand/silt
F–09–O	6	120	2	1	25	1	No	Gravel/cobble
N–16–O	12	146	1	1	0	1	No	Gravel
P–16–D	12	50	0	n/a	10	2	No	Gravel/cobble
P–17–A	12	35.3	3	3	0	1	No	Coarse sand
P–17–J	12	550	2	3	0	1	No	Cobble
F–05–C	13	217	2	3	5	1	No	Gravel/sand
C–11–I	14	60	3	5	0	1	No	Gravel
H–19–C	24	2.0	1	4	30	1	No	Sand/silt
I–15–AL	24	100	1	2	0	1	No	Gravel/cobble
E–17–FH	25	35	1	3	20	1	Yes	Silt/sand
H–17–AH	25	50	1	3	40	1	Yes	Silt/gravel
C–15–AI	34	287	2	3	15	1	No	Sand/gravel
C–16–AJ	34	4.0	3	4	10	1	No	Sand
D–13–Q	34	300	2	3	35	1	No	Gravel
D–24–B	34	76	5	1	10	1	No	Sand/gravel
D–28–C	34	6.0	2	5	10	1	No	Silt
D–15–B	36	7.0	2	3	0	2	Yes	Sand/gravel
D–11–M	40	177	3	5	0	1	No	Gravel/cobble
G–21–A	40	6.0	3	4	40	1	No	Sand/gravel
H–22–E	40	12	1	5	0	1	No	Sand/silt
H–22–H	40	12	4	5	40	1	No	Sand/gravel
I–03–I	50	133	3	3	0	1	No	Gravel/cobble
K–16–AC	50	430	2	3	0	1	No	Sand/gravel
C–21–H	52	88	6	5	0	1	No	Silt
L–05–B	62	125	1	3	0	1	No	Gravel/cobble
H–16–G	67	62	2	1	varied	1	No	Sand/gravel
F–15–D	70	285	2	3	65	1	No	Gravel/cobble
G–04–R	70	190	0	n/a	0	1	Yes	Gravel/silt
H–11–A	82	120	2	1	40	1	No	Gravel/cobble
C–18–G	85	1,650	3	3	25	1	No	Silt/gravel
F–16–BM	88	16.4	2	1	varied	1	Yes	Sand/gravel
M–06–F	110	25	0	n/a	0	1	No	Cobble/gravel
J–09–G	114	636	3	5	0	1	Yes	Gravel
F–16–CS	121	243	3	3	varied	2	Yes	Gravel/sand
F–10–B	131	646	1	2	0	2	Yes	Cobble/gravel
I–09–D	135	108	1	3	0	1	No	Cobble/gravel
A–24–E	138	70	2	5	20	1	No	Silt
A–25–AQ	138	77	1	3	15	1	No	Sand/silt
I–03–K	141	100	1	3	0	1	Yes	Gravel/silt
J–01–D	141	10	1	3	0	1	Yes	Sand/cobble
L–02–B	141	263	2	1	15	1	No	Cobble/sand
C–20–B	144	12,500	26	5	35	1	Yes	Silt/sand

Table 1. Bridge and channel information for 1991–93--Continued

CDOT structure ID (fig. 1)	CDOT route number	Drainage area (mi^2)	Number of piers	Pier type	Skew angle (degrees)	Abutment type	Riprap present	Predominant bed material observed
C–21–A	144	12,598	16	5	varied	1	Yes	Silt/sand
B–16–AC	287	1,116	4	2	0	1	No	Sand/gravel
C–16–H	287	505	2	3	10	1	No	Sand/silt
D–16–H	287	500	2	4	0	1	No	Sand
H–04–G	330	33	1	1	5	1	No	Cobble/boulder
H–02–EA	340	6.0	1	4	10	1	No	Sand
D–28–R	385	84	3	5	5	1	No	Silt/sand
F–09–L	6	100	0	n/a	5	1	No	Gravel
F–10–C	6	40	0	n/a	0	1	No	Cobble/boulder
F–10–E	6	630	0	n/a	0	1	No	Cobble
F–15–BC	6	390	2	3	20	2	Yes	Gravel/cobble
P–16–A	12	50	0	n/a	10	1	No	Gravel/cobble
P–16–B	12	16	0	n/a	20	2	No	Gravel/cobble
C–06–D	13	1,750	3	3	0	2	No	Gravel
H–11–G	24	15	0	n/a	30	2	No	Gravel/cobble
I–13–I	24	100	0	n/a	20	1	No	Silt
C–17–F	25	571	2	1	0	2	Yes	Gravel/cobble
G–17–S	25	76	3	3	0	2	Yes	Sand/silt
I–17–DT	25	210	5	1	0	2	Yes	Sand
L–18–T	25	213	3	3	20	2	Yes	Gravel/sand
O–18–BY	25	132	4	3	0	2	Yes	Gravel/sand
C–15–D	34	85	2	2	0	1	Yes	Gravel/cobble
C–15–G	34	191	2	3	10	1	Yes	Cobble/gravel
C–15–H	34	178	1	3	30	1	Yes	Cobble/gravel
C–14–A	36	137	0	n/a	40	1	Yes	Gravel/cobble
E–19–B	36	229	32	5	0	1	No	Sand/silt
F–20–D	36	565	5	3	0	2	Yes	Sand/silt
B–04–A	40	3,410	3	3	0	1, 2	No	Gravel/cobble
C–07–A	40	1,430	2	2	0	1	Yes	Gravel/cobble
D–12–K	40	38	0	n/a	10	1	No	Cobble
E–14–N	40	65	0	n/a	30	1	No	Gravel/cobble
E–14–S	40	65	2	1	0	2	Yes	Cobble/boulder
F–15–CN	40	275	1	3	0	2	Yes	Gravel/cobble
F–15–GA	40	41	2	3	0	2	Yes	Cobble/boulder
F–15–GO	40	41	2	3	0	2	Yes	Cobble/boulder
I–24–S	40	18	2	3	35	1	No	Silt
J–09–AB	50	1,024	2	3	0	1	Yes	Cobble/gravel
J–09–B	50	1,024	2	3	0	1	No	Cobble/gravel
J–09–C	50	1,024	0	n/a	0	1	No	Cobble/gravel
J–09–D	50	1,024	0	n/a	15	1	Yes	Cobble/gravel
K–14–A	50	150	0	n/a	5	1	Yes	Gravel/sand
K–14–J	50	23	1	1	0	1	No	Coarse sand
K–15–H	50	2.2	0	n/a	0	1	No	Sand/gravel
K–16–C	50	74	3	1, 3	0	1	Yes	Gravel/cobble
D–17–AK	66	900	5	3	70	2	Yes	Sand/gravel

Table 1. Bridge and channel information for 1991–93--Continued

CDOT structure ID (fig. 1)	CDOT route number	Drainage area (mi^2)	Number of piers	Pier type	Skew angle (degrees)	Abutment type	Riprap present	Predominant bed material observed
K–16–CG	67	3,677	2	3	5	1	Yes	Gravel/cobble
L–14–C	69	30	0	n/a	10	1	No	Silt
E–14–AW	70	195	6	3	15	2	Yes	Gravel/cobble
E–14–BA	70	205	2	3	0	2	Yes	Gravel/cobble
F–15–BI	70	565	2	3	0	2	Yes	Gravel/sand
F–15–BK	70	565	2	3	0	2	Yes	Gravel/sand
G–21–AM	70	6.0	2	1	0	1	Yes	Silt/sand
H–02–FM	70	35	2	3	0	1	No	Sand/gravel
H–02–FO	70	142	2	3	10	1	Yes	Gravel
H–02–FP	70	142	2	3	0	1	Yes	Gravel
H–03–AY	70	8,650	6	2	0	2	Yes	Cobble/boulder
J–22–J	71	99	2	3	0	1	Yes	Silt/sand
E–17–GL	76	4,045	6	3	0	2	No	Sand/gravel
E–17–GM	76	4,045	6	3	0	2	No	Sand/gravel
H–09–B	82	50	4	1	0	2	No	Cobble/boulder
A–17–C	85	12	2	1	0	2	Yes	Sand
K–01–C	90	2,024	0	n/a	0	1	Yes	Gravel
I–05–V	92	5,420	2	3	15	1	No	Gravel
E–16–IE	93	11	1	4	0	1	No	Alluvium
E–16–P	95	570	2	3	10	2	No	Gravel
K–23–A	96	429	2	3	0	1	No	Fine sand
L–02–E	97	1,069	2	1	15	1	No	Gravel/cobble
E–14–BE	119	46	0	n/a	30	1	Yes	Gravel/cobble
K–01–A	141	3,755	3	3	0	1	No	Cobble/sand
K–08–D	149	340	2	3	0	1	Yes	Cobble
L–07–A	149	320	2	3	0	2	Yes	Cobble
M–09–B	149	780	4	3	0	1	Yes	Cobble/gravel
P–15–C	159	240	2	2	30	1	No	Gravel/cobble
P–02–C	160	76	3	1, 3	0	2	Yes	Gravel
P–07–A	160	371	2	3	0	1	Yes	Cobble
I–06–C	187	600	3	3	30	1	Yes	Gravel/cobble
L–18–R	227	4,910	5	3	10	2	No	Sand
K–18–BN	233	4,925	5	3	20	2	No	Sand
G–14–P	285	130	0	n/a	10	1	No	Gravel/cobble
H–13–A	285	75	0	n/a	0	1	No	Gravel/cobble
P–12–B	285	359	3	3	15	2	Yes	Alluvium
A–15–A	287	50	2	3	0	2	Yes	Sand/silt
J–12–E	291	1,110	2	4	15	2	No	Sand/gravel
B–04–D	318	3,557	3	3	0	1	No	Gravel
H–02–GC	340	16,800	8	3	varied	1	Yes	Cobble/gravel
L–06–F	550	17	2	5	0	1	Yes	Gravel
M–06–K	550	49	2	3	0	2	No	Cobble/gravel
B–23–A	6	753	6	5	0	1	No	Silt
D–20–D	6	675	16	5	0	1	No	Silt
E–16–EF	6	392	2	3	0	1	Yes	Cobble

Table 1. Bridge and channel information for 1991–93--Continued

CDOT structure ID (fig. 1)	CDOT route number	Drainage area (mi²)	Number of piers	Pier type	Skew angle (degrees)	Abutment type	Riprap present	Predominant bed material observed
H–02–D	6	15	0	n/a	0	1	No	Gravel
D–11–D	9	1,020	4	2	20	1	No	Sand/silt
J–14–C	9	5.2	1	5	0	1	No	Sand/gravel
M–22–BC	10	460	2	3	0	1	Yes	Gravel
N–18–AC	10	530	2	3	0	1	Yes	Gravel/cobble
B–14–O	14	220	0	n/a	10	1	Yes	Cobble
B–18–F	14	71	2	3	0	2	No	Sand/silt
A–17–AD	25	132	2	3	10	2	Yes	Gravel/sand
C–17–BL	25	553	2	2	0	1	Yes	Gravel/cobble
D–17–U	25	890	11	5	0	1	Yes	Sand
H–17–L	25	12	2	3	0	1, 2	Yes	Sand
J–18–J	25	15	3	3	10	1	Yes	Sand/gravel
M–17–AQ	25	25	2	3	0	1	Yes	Gravel/silt
N–17–AM	25	634	3	3	5	2	Yes	Sand/gravel
N–17–BH	25	14	2	3	0	2	Yes	Sand/gravel
N–17–BO	25	65	2	3	0	2	Yes	Sand/silt
C–16–Z	34	291	2	2	0	1	No	Gravel
D–20–E	34	680	3	1	15	1	No	Silt
F–18–B	36	230	15	5	10	1	Yes	Sand
F–22–E	36	2.0	6	5	0	1	Yes	Silt
C–07–D	40	80	3	1	0	1	No	Gravel
I–26–C	40	104	2	3	0	2	Yes	Silt
I–03–G	50	12	2	3	0	1	Yes	Sand/silt
I–04–K	50	5,500	3	3	5	2	Yes	Gravel/cobble
K–11–B	50	12	2	5	0	1	No	Silt
K–17–H	50	209	2	4	0	2	Yes	Gravel/cobble
K–17–AC	50	103	2	3	5	2	Yes	Sand/gravel
L–21–G	50	1,088	5	5	0	2	No	Sand/silt
L–22–AL	50	400	2	2	15	2	No	Sand/silt
L–26–F	50	230	4	3	0	2	Yes	Gravel/silt
M–23–A	50	9.5	3	5	0	2	Yes	Gravel/silt
M–23–E	50	9.5	2	3	5	2	Yes	Gravel/silt
D–20–T	52	22	2	3	0	1	Yes	Fine sand
C–26–A	59	95	6	5	0	1	Yes	Sand
G–25–F	59	120	2	3	0	1	Yes	Sand
D–02–A	64	34	2	4	0	2	Yes	Sand
I–04–M	65	5,421	2	3	5	2	Yes	Gravel/cobble
N–16–L	69	70	0	n/a	0	1, 2	Yes	Gravel/silt
F–05–L	70	6,970	4	3	varied	2	Yes	Gravel/cobble
F–06–O	70	172	0	n/a	0	2	Yes	Cobble/boulder
F–06–Y	70	6,640	4	3	10	2	Yes	Gravel/cobble
F–15–BH	70	267	2	1, 3	0	1	Yes	Cobble/boulder
F–15–BM	70	270	3	3	0	1	Yes	Cobble/boulder
G–03–P	70	7,370	3	3	0	2	No	Cobble/gravel
G–04–BA	70	7,370	3	3	0	2	Yes	Cobble/gravel

Table 1. Bridge and channel information for 1991–93--Continued

CDOT structure ID (fig. 1)	CDOT route number	Drainage area (mi²)	Number of piers	Pier type	Skew angle (degrees)	Abutment type	Riprap present	Predominant bed material observed
G–26–T	70	62	2	3	0	2	Yes	Sand
I–22–B	71	77	14	5	15	2	Yes	Sand/silt
E–15–AF	72	75	0	n/a	0	1	Yes	Cobble/boulder
D–19–P	76	194	3	3	0	2	Yes	Fine sand/silt
G–18–BC	83	48	2	3	0	2	Yes	Sand/silt
G–18–H	83	48	2	3	0	1	Yes	Silt
I–17–R	85	477	3	2	30	2	Yes	Alluvium
G–18–BN	86	62	3	3	0	2	Yes	Sand
G–19–B	86	106	2	3	0	1	No	Sand
G–20–C	86	10	2	3	10	1	Yes	Fine sand
K–18–BT	96	925	9	3	0	1, 2	Yes	Sand
K–26–A	96	1,749	8	3	0	1	No	Sand/gravel
K–09–F	114	331	0	n/a	0	1	No	Gravel
J–17–E	115	17	0	n/a	0	1	No	Sand/gravel
K–16–Y	115	45	0	n/a	25	1	No	Gravel/sand
I–09–B	135	94	2	3	0	2	Yes	Gravel/cobble
A–26–AY	138	83	1	3	0	1	No	Sand/gravel
A–26–F	138	12	3	5	80	1	No	Fine sand
A–27–N	138	3,100	0	n/a	0	1	No	Fine sand
I–01–M	141	10	0	n/a	0	1	No	Cobble/boulder
I–02–B	141	24	3	5	0	2	Yes	Coarse sand
J–01–C	141	4,188	3	3	0	1, 2	Yes	Gravel/cobble
K–02–C	141	1,475	1	3	0	1, 2	No	Cobble/boulder
L–01–B	141	10	2	3	0	2	Yes	Sand/bedrock
P–13–D	142	341	4	5	5	1	Yes	Sand/gravel
P–14–P	142	7,700	2	3	0	1	No	Gravel/cobble
M–09–R	149	566	1	2	5	2	Yes	Gravel/cobble
N–10–V	160	216	1	3	5	2	Yes	Gravel/cobble
O–02–I	160	119	2	3	0	2	Yes	Cobble
P–07–B	160	67	2	3	0	2	Yes	Cobble/boulder
F–17–AA	177	16	2	3	0	1	Yes	Gravel/sand
H–13–G	285	90	2	5	0	1	No	Sand
D–16–C	287	76	0	n/a	0	1	No	Gravel
N–26–P	287	24	2	3	0	2	Yes	Sand/silt
H–04–S	330	484	1	3	0	2	Yes	Cobble/boulder
H–02–GA	340	17,100	5	3	0	2	Yes	Gravel/cobble
J–05–X	348	920	1	3	0	1	No	Gravel/cobble
M–21–E	350	1.6	1	3	0	1	No	Gravel/cobble
O–12–AD	371	142	2	3	30	2	Yes	Sand/gravel
E–28–W	385	36	0	n/a	5	1	Yes	Fine sand
L–27–P	385	36	2	3	0	1	No	Silt
B–27–E	387	234	3	4	0	1	No	Sand/silt

Scour Analyses

Scour is the depth a streambed is lowered below a natural level or an assumed datum. Depth of scour was estimated using the recommended equations given in FHWA Hydraulic Engineering Circular 18 (HEC–18) (Richardson and others, 1991) for contraction, pier, and abutment scour. Variables used in the scour equations were determined using options in WSPRO to generate velocity-area distributions for 20 streamtubes in the bridge cross section (fig. 3). Streamtubes are imaginary tubes bounded by streamlines. Since the discharge between streamlines is constant, each streamtube carries an equal discharge. The velocity/area distributions were computed using a specified water-surface elevation and specified discharge. The specified water-surface elevation is a close approximation of the water-surface elevation at the upstream bridge opening. This specified elevation is computed by (1) subtracting the friction losses between the approach section and bridge section from the constricted-profile water-surface elevation at the approach section or by (2) adding the constricted-profile water-surface elevation in the bridge section and the "other losses" term between the bridge section and the approach section. The "other losses" term represents energy losses other than losses due to friction between the approach and bridge sections. The term is computed by WSPRO and is found under the column heading "HO" in the WSPRO output (see Appendix 3) for the approach section. The 50 sites evaluated during 1991 were analyzed using procedure 1 to compute an upstream bridge-opening water-surface elevation. The 170 sites evaluated during 1992–93 were evaluated using procedure 2 to compute an upstream bridge-opening water-surface elevation.

The specified discharge to compute the velocity/area distribution was equal to the computed 100- and 500-year floods unless road overflow or pressure flow was indicated by initial WSPRO computations. Pressure flow occurs when the bridge deck intersects the flow or becomes submerged. Flow classes are summarized in table 2.

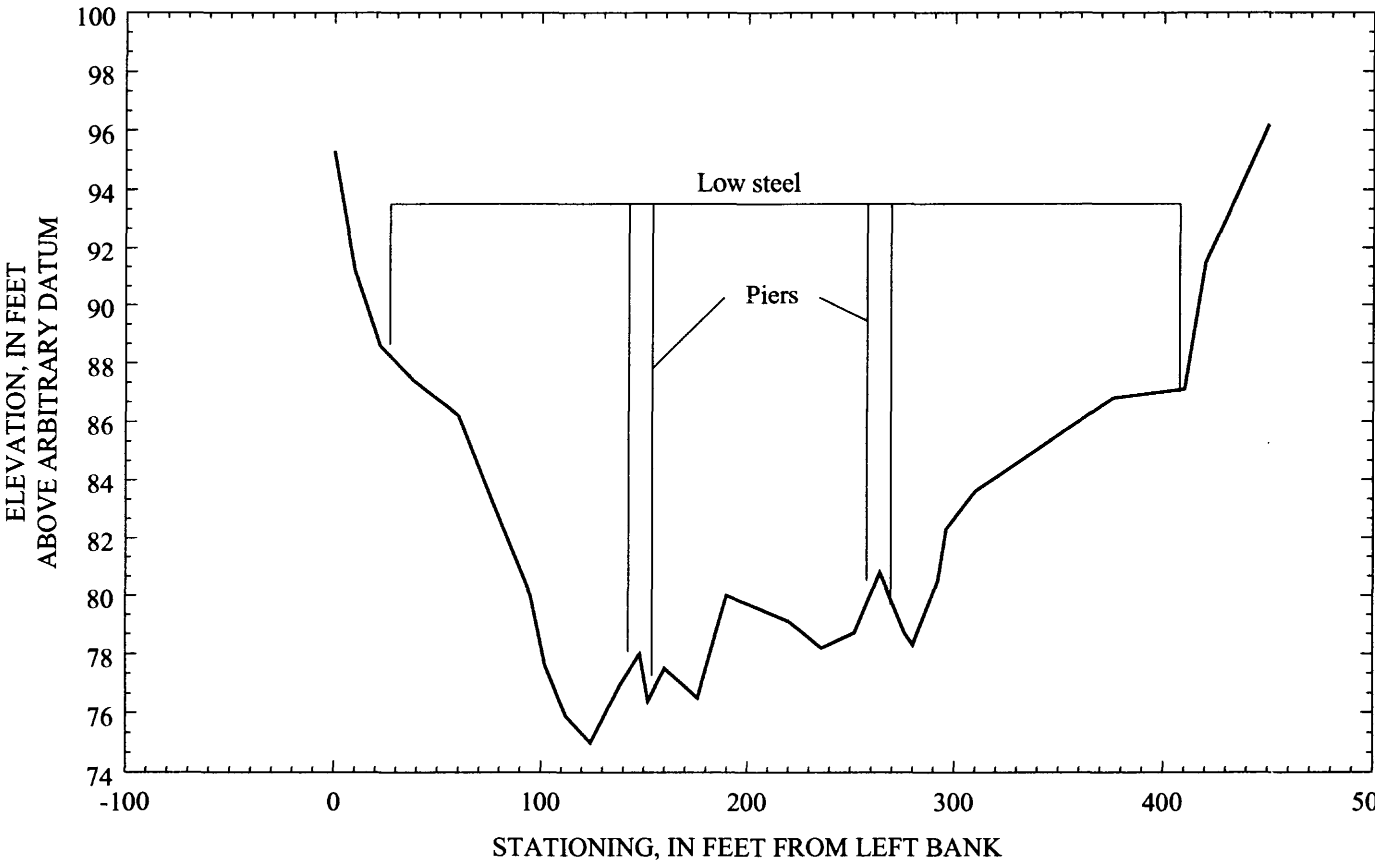


Figure 3. Typical bridge cross section.

Table 2. Summary of flow classes for a single bridge opening (modified from Shearman, 1990)

[Free surface, no contact or insubstantial contact of the water surface and low steel; orifice, only the upstream water surface is in contact with low steel; submerged orifice, water surface is in contact with low steel for the full flow length through the bridge; hds, water surface immediately downstream from the bridge; Yls, low-steel elevation; hus, water surface immediately upstream from the bridge; Ymin, minimum embankment elevation]

Class no.	Flow class	Relative elevations		
(a) Flow only through the bridge opening				
1	Free surface	hds < Yls	hus < Yls	hus <Y min
2	Orifice	hds < Yls	hus > Yls	hus < Ymin
3	Submerged orifice	hds > Yls	hus > Yls	hus < Ymin
(b) Combination of flow through the bridge opening and weir flow over the road grade				
4	Free surface	hds < Yls	hus < Yls	hus > Ymin
5	Orifice	hds < Yls	hus > Yls	hus > Ymin
6	Submerged orifice	hds > Yls	hus > Yls	hus > Ymin

Variations of the two procedures mentioned previously were used when road overflow or pressure flow was indicated. The elevation of low steel and the streamflow computed by WSPRO for the bridge opening were specified to compute velocity/area distributions for sites analyzed in 1991. For sites analyzed in 1991, scour was calculated for the discharge and flow class listed in table 3. The discharge specified (table 3) was that of the 100-year or 500-year flood that would pass through the bridge opening; discharge specified for the 500-year flood might be larger than, smaller than, or equal to the discharge specified for the 100-year flood, depending on how the flow class (table 2) changed between the two flood discharges. The discharge specified for sites analyzed during 1992–93, when road overflow or pressure flow was indicated, was determined by incrementally increasing the discharge being routed through the bridge until a change in flow type from free surface to pressure flow was noted in the WSPRO output (table 4). The maximum discharge that could be routed through the bridge before a change in flow type occurred was used to generate the velocity/area distribution for scour analysis; therefore, all scour computations for sites analyzed in 1992–93 were for free-surface flow conditions. The upstream bridge-opening water-surface elevation was computed using the maximum discharge determined and the corresponding water-surface elevations. The discharge used for each site also is included in table 4.

Contraction scour was computed using Laursen's equation for long contractions (Richardson and others, 1991). This equation estimates the depth of scour in the contracted section (commonly the bridge section). It assumes that bed material is being transported in the main channel but not in the overbank zones.

Pier-scour depths were estimated using the Colorado State University equation (Richardson and others, 1991). The equation estimates equilibrium scour depths. The maximum subsection depth and 90 percent of the maximum subsection velocity from the velocity/area distributions for the bridge opening were used in the equation. The maximum velocity was not used in the equation because, typically, piers are not located in the thalweg where the maximum velocity usually occurs. The computed scour depth was assumed to apply to all piers in the bridge section regardless of their location in the channel. This allows for the potential of the thalweg shifting and for greater scour to occur at a pier not currently located near the thalweg.

Equations for abutment scour are for the worst-case conditions. They will predict the maximum scour that could occur for an abutment projecting into the flow with velocities and depths upstream from the abutment similar to those in the main channel. Froehlich's equation for live-bed scour (Richardson and others, 1991) was used in the analyses with variables determined from WSPRO output.

Computed scour depths are listed in tables 3 and 4. Scour depths were not computed when the water-surface elevation determined for the upstream bridge opening did not contact the piers or abutments.

In order to evaluate bridge integrity, total scour-depth estimates require that a relation be established between the arbitrary datum used in the field survey and sea-level datum used on the original bridge plans. This relation can be established if a common point can be identified from both surveys. If an accurate elevation of low steel, top of pier, or top of abutment (for example) can be identified, arbitrary datum is subtracted from sea-level datum for that point. The difference then can be subtracted from sea-level datum for the pier footing bases, abutment footings, and other pertinent elevations to determine their arbitrary datum elevations. Determination of this relation is not possible in most instances because reference mark datums have not been maintained.

When a relation can be established, elevations of the pier footing bases and abutment footing bases are plotted to an arbitrary datum on a plot of the cross section showing locations of the bridge abutments and piers. Total scour is computed by adding contraction scour and pier or abutment scour or both. Lines of estimated total scour are drawn on the cross-section plot. The lines of total scour depth are then compared to the footing elevations to determine if the depth of total scour is deeper than the base of the footings. An example of a complete scour analysis is included in Appendix 3.

Table 3. Summary of computed scour depths for 1991

[Q100, magnitude of 100-year flood; Q500, magnitude of 500-year flood; --, same as Q100 or Q500 value; n/a, not applicable]

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths				Flow class (from table 2)
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)	
B–27–A	23,200		11,600	17	3	18	18	6
		50,300	7,800	26	3	27	27	6
F–09–O	1,540		--	0	9	11	10	1
		1,860	--	0	9	12	11	1
N–16–O	28,600		7,950	33	24	32	32	6
		49,700	7,360	42	23	29	29	6
P–16–D	11,800		3,240	29	n/a	22	22	6
		21,200	3,240	40	n/a	30	30	6
P–17–A	13,700		--	12	11	50	31	1
		26,800	16,900	35	11	57	37	5
P–17–J	32,800		11,900	41	6	107	88	5
		52,800	12,900	50	6	112	92	5
F–05–C	2,150		--	0	3	1	1	1
		2,660	--	0	4	1	1	1
C–11–I	680		--	0	5	n/a	n/a	1
		870	--	0	6	n/a	n/a	1
H–19–C	2,300		--	1	12	0	n/a	1
		7,780	5,470	8	17	0	0	6
I–15–AL	975		--	0	3	0	0	1
		1,240	--	0	3	0	0	1
E–17–FH	14,800		9,820	11	6	0	0	6
		26,800	9,440	16	6	0	0	6
H–17–AH	8,730		--	0	6	25	33	1
		19,500	--	5	7	42	52	1
C–15–AI	17,600		--	4	14	0	0	2
		34,300	23,200	13	16	0	0	6
C–16–AJ	5,200		--	0	5	n/a	0	1
		10,500	--	2	5	n/a	0	1

Table 3. Summary of computed scour depths for 1991--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths				Flow class (from table 2)
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)	
D–13–Q	3,220		--	1	3	0	n/a	1
		3,770	--	1	3	0	n/a	1
D–24–B	17,300		--	2	5	0	0	1
		37,500	17,700	7	5	0	0	6
D–28–C	6,400		4,540	82	13	17	17	5
		12,500	5,000	67	13	23	23	5
D–15–B	1,610		--	2	4	n/a	n/a	1
		3,190	--	3	5	n/a	n/a	1
D–11–M	1,970		--	1	3	0	0	1
		2,360	--	1	3	0	0	1
G–21–A	5,870		--	6	11	15	15	1
		12,500	10,900	14	14	20	20	6
H–22–E	9,660		2,200	42	4	25	25	6
		16,900	2,100	54	4	33	33	6
H–22–H	9,660		3,310	6	4	18	18	6
		16,900	2,650	10	3	22	22	6
I–03–I	1,000		--	0	3	n/a	3	1
		1,250	--	0	4	n/a	4	1
K–16–AC	4,420		--	1	4	0	0	1
		8,540	--	2	4	0	0	1
C–21–H	22,900		14,200	5	3	33	33	6
		39,900	15,400	8	3	42	42	6
L–05–B	1,910		--	2	5	0	0	1
		2,300	--	2	5	0	0	1
H–16–G	604		--	0	3	7	2	1
		936	--	1	4	9	4	3
F–15–D	3,370		--	1	5	0	0	1
		3,880	--	2	5	0	0	1

Table 3. Summary of computed scour depths for 1991--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths: Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)	Flow class (from table 2)
G–04–R	3,020		--	1	n/a	6	8	1
		4,620	--	2	n/a	10	12	1
H–11–A	1,960		--	1	7	8	0	1
		2,240	--	1	7	9	0	1
C–18–G	27,000		11,500	10	5	29	29	6
		36,100	9,600	11	11	34	34	6
F–16–BM	3,350		--	1	11	12	n/a	1
		6,990	--	2	13	24	n/a	1
M–06–F	1,140		--	1	n/a	0	0	2
		1,580	--	1	n/a	0	0	2
J–09–G	2,590		--	1	3	9	n/a	1
		3,120	--	2	3	11	n/a	1
F–16–CS	20,200		16,700	21	5	19	18	6
		41,800	17,600	23	6	22	18	6
F–10–B	6,330		--	2	10	0	0	1
		7,480	--	3	10	0	0	1
I–09–D	1,640		--	0	4	0	0	1
		1,910	--	0	4	0	0	1
A–24–E	26,000		3,730	32	4	21	21	6
		36,200	3,630	38	4	24	24	6
A–25–AQ	17,000		2,490	54	3	25	25	5
		37,700	2,720	72	3	37	37	6
I–03–K	920		--	0	2	n/a	0	1
		1,200	--	0	3	n/a	1	1
J–01–D	905		--	0	6	0	0	1
		1,260	--	0	6	0	0	1
L–02–B	5,660		--	0	11	10	9	1
		7,780	--	0	11	12	12	1

Table 3. Summary of computed scour depths for 1991--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths				Flow class (from table 2)
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)	
C–20–B	42,000		--	0	3	28	28	3
		80,000	47,500	2	3	34	34	6
C–21–A	42,500		38,500	6	4	0	38	4
		80,000	48,900	8	4	56	56	6
B–16–AC	10,500		--	2	5	n/a	n/a	1
		14,000	--	2	6	n/a	n/a	1
C–16–H	28,100		12,700	15	6	51	51	6
		68,200	11,400	27	6	81	81	6
D–16–H	8,120		--	0	6	9	16	1
		12,600	--	5	7	12	19	3
H–04–G	545		--	1	7	13	11	1
		685	--	2	8	14	11	1
H–02–EA	45		--	0	2	n/a	n/a	1
		69	--	0	3	n/a	n/a	1
D–28–R	27,400		7,000	19	4	4	9	6
		39,100	6,700	22	4	4	9	6

Table 4. Summary of computed scour depths for 1992–93

[Q100, magnitude of 100-year flood; Q500, magnitude of 500-year flood; --, same as Q100 or Q500 value; n/a, not applicable]

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
F–09–L	1,510		--	0.1	n/a	6.2	5.8
		1,780	--	0.3	n/a	7.4	6.8
F–10–C	817		--	0.1	n/a	11.7	12.3
		954	--	0.2	n/a	12.3	13.0
F–10–E	5,480		--	0	n/a	3.2	3.8
		6,430	--	0	n/a	3.8	5.4
F–15–BC	4,140		--	2.9	7.6	n/a	n/a
		4,780	--	2.3	8.1	n/a	n/a
P–16–A	11,300		1,700	10.0	n/a	11.4	8.4
		21,200	--	n/a	n/a	n/a	n/a
P–16–B	284		--	2.3	n/a	10.6	1.7
		430	--	2.5	n/a	12.0	2.4
C–06–D	10,000		--	0.2	3.7	n/a	n/a
		12,000	--	0.1	3.8	n/a	n/a
H–11–G	484		--	16.1	n/a	7.7	6.4
		549	--	17.1	n/a	8.2	6.7
I–13–I	1,130		--	18.3	n/a	23.0	23.4
		1,400	--	23.3	n/a	26.8	26.9
C–17–F	50,800		16,000	0	7.7	28.8	30.4
		89,500	--	n/a	n/a	n/a	n/a
G–17–S	12,500		--	0.2	5.8	10.4	4.2
		28,600	25,000	0.5	7.2	16.6	9.0
I–17–DT	15,500		--	0	7.7	31.8	27.4
		28,200	--	0	9.1	45.2	38.7
L–18–T	32,400		18,000	29.7	6.6	26.9	35.0
		58,500	--	n/a	n/a	n/a	n/a
O–18–BY	25,600		22,200	7.4	12.9	20.2	17.9
		47,600	--	n/a	n/a	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
C–15–D	3,820		--	0.1	4.5	16.1	8.6
		8,290	--	1.4	5.7	25.7	15.3
C–15–G	2,460		--	0.2	5.1	10.3	10.8
		2,860	--	0.3	5.3	10.3	10.8
C–15–H	2,400		--	0.4	4.5	n/a	10.1
		2,770	--	0.3	4.7	n/a	10.6
C–14–A	2,060		--	0	n/a	13.3	12.5
		2,300	--	0	n/a	14.9	12.7
E–19–B	29,500		--	n/a	n/a	n/a	n/a
		60,300	--	3.9	3.4	n/a	n/a
F–20–D	42,500		--	23.7	5.3	30.7	15.2
		89,100	63,000	41.7	6.0	14.8	11.5
B–04–A	17,700		--	1.3	5.2	n/a	n/a
		20,000	--	2.2	5.2	n/a	2.6
C–07–A	9,660		--	0	5.4	n/a	n/a
		11,500	--	0	5.6	n/a	n/a
D–12–K	672		--	0.8	n/a	n/a	1.6
		809	--	0.8	n/a	1.0	2.3
E–14–N	2,120		--	3.5	n/a	14.7	12.2
		2,450	--	4.2	n/a	14.3	12.9
E–14–S	1,270		--	5.9	5.6	n/a	n/a
		1,450	--	6.0	5.8	n/a	n/a
F–15–CN	3,280		--	3.8	6.2	n/a	n/a
		3,790	--	3.8	6.4	n/a	n/a
F–15–GA	7,360		--	0.1	5.2	n/a	n/a
		16,200	--	0	6.0	n/a	n/a
F–15–GO	7,360		--	0.1	5.2	n/a	n/a
		16,200	--	0	6.0	n/a	n/a
I–24–S	11,800		5,520	0	10.6	18.4	16.4
		20,100	--	n/a	n/a	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
J–09–AB	9,830		6,850	0	4.6	7.7	n/a
		12,100	7,970	0	4.7	9.1	n/a
J–09–B	2,980		--	1.1	3.6	10.8	5.9
		4,130	--	1.6	3.9	13.7	8.8
J–09–C	2,980		--	1.1	n/a	10.8	5.9
		4,130	--	1.6	n/a	13.7	8.8
J–09–D	9,830		6,850	0	n/a	7.7	n/a
		12,100	7,970	0	n/a	9.1	n/a
K–14–A	23,000		2,450	1.2	n/a	2.8	7.8
		44,500	--	n/a	n/a	n/a	n/a
K–14–J	400		--	0.4	6.1	3.4	n/a
		1,000	--	0.6	6.6	5.2	n/a
K–15–H	3,000		--	n/a	n/a	n/a	n/a
		8,110	3,250	5.3	n/a	7.7	8.6
K–16–C	19,400		12,500	7.4	4.8	17.7	12.0
		37,000	--	n/a	n/a	n/a	n/a
D–17–AK	50,500		10,000	13.6	13.8	15.7	17.5
		92,100	--	n/a	n/a	n/a	n/a
K–16–CG	8,130		--	1.3	6.6	n/a	3.5
		9,260	--	1.7	6.8	n/a	5.8
L–14–C	310		--	3.0	n/a	2.9	3.5
		421	--	5.6	n/a	4.4	5.1
E–14–AW	2,720		--	4.6	9.8	n/a	n/a
		3,110	--	4.8	10.2	n/a	n/a
E–14–BA	2,820		--	2.5	6.3	n/a	n/a
		3,220	--	2.8	6.6	n/a	n/a
F–15–BI	3,240		--	1.6	5.1	n/a	n/a
		3,740	--	1.9	5.3	n/a	n/a
F–15–BK	3,240		--	0	9.3	n/a	n/a
		3,740	--	0	9.6	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
G–21–AM	5,160		--	1.2	4.6	5.5	1.8
		12,500	--	7.5	6.1	17.6	12.1
H–02–FM	222		--	0	2.7	n/a	n/a
		317	--	0	2.9	n/a	n/a
H–02–FO	886		--	0.2	3.7	n/a	n/a
		1,190	--	0.2	4.0	n/a	n/a
H–02–FP	886		--	0.2	3.7	n/a	n/a
		1,190	--	0.2	4.0	n/a	n/a
H–03–AY	33,800		--	0	7.1	n/a	n/a
		39,500	--	0	7.4	n/a	n/a
J–22–J	20,100		2,200	67.6	5.2	7.4	9.6
		42,100	--	n/a	n/a	n/a	n/a
E–17–GL	74,200		64,500	21.5	21.5	13.9	12.6
		141,000	--	n/a	n/a	n/a	n/a
E–17–GM	74,200		64,500	21.5	21.5	13.9	12.6
		141,000	--	n/a	n/a	n/a	n/a
H–09–B	1,050		--	n/a	8.3	n/a	n/a
		1,210	--	n/a	8.6	n/a	n/a
A–17–C	7,760		2,250	5.3	7.4	n/a	n/a
		16,900	--	n/a	n/a	n/a	n/a
K–01–C	18,600		--	5.4	n/a	19.2	8.7
		24,900	22,500	6.8	n/a	23.2	10.9
I–05–V	23,000		--	0	11.0	4.0	14.6
		27,100	--	0	11.5	7.2	17.5
E–16–IE	2,190		--	0.5	3.1	8.8	10.1
		4,430	--	1.7	3.8	13.8	15.0
E–16–P	15,700		13,500	0	9.9	10.6	13.7
		26,600	--	n/a	n/a	n/a	n/a
K–23–A	38,100		14,500	11.0	5.2	14.1	6.1
		79,100	--	n/a	n/a	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
L–02–E	10,700		--	0	18.4	n/a	n/a
		14,100	13,000	0.3	19.5	4.1	0
E–14–BE	850		--	1.2	n/a	7.6	10.6
		1,000	--	1.4	n/a	8.3	11.2
K–01–A	34,500		25,000	6.2	5.8	11.6	39.0
		47,100	--	n/a	n/a	n/a	n/a
K–08–D	3,000		--	2.4	4.3	16.6	12.8
		4,010	--	2.4	4.7	18.3	17.9
L–07–A	3,620		--	0.5	4.4	6.2	5.0
		4,180	--				
M–09–B	5,660		--	1.5	4.2	n/a	n/a
		6,700	--	2.3	4.2	n/a	n/a
P–15–C	960		--	0	2.3	2.9	3.2
		1,300	--	0	2.4	3.8	5.2
P–02–C	2,430		--	0	4.8	n/a	n/a
		3,360	--	0	5.0	n/a	n/a
P–07–A	9,130		--	2.3	4.9	5.6	4.3
		13,700	--	3.8	5.6	9.6	9.8
I–06–C	6,200		--	1.3	5.2	n/a	n/a
		7,300	--	1.0	5.2	n/a	n/a
L–18–R	101,000		90,000	0	11.6	19.7	18.9
		187,000	--	n/a	n/a	n/a	n/a
K–18–BN	101,000		52,000	19.3	10.5	15.5	n/a
		187,000	--	n/a	n/a	n/a	n/a
G–14–P	1,820		--	0	n/a	6.9	14.7
		2,130	--	0	n/a	7.8	15.4
H–13–A	1,180		--	1.8	n/a	8.5	11.4
		1,400	--	2.1	n/a	9.4	12.1
P–12–B	3,470		1,000	3.1	8.5	4.8	3.2
		4,700	--	n/a	n/a	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
A–15–A	8,730		--	6.6	7.7	9.3	8.8
		19,500	--	10.2	9.4	16.1	16.5
J–12–E	7,530		--	0.1	7.1	n/a	n/a
		8,910	--	0.2	7.4	n/a	n/a
B–04–D	17,500		--	0	4.1	n/a	n/a
		20,900	--	0.2	4.2	2.8	n/a
H–02–GC	53,900		--	1.9	5.7	35.2	n/a
		64,200	--	2.1	5.9	38.6	n/a
L–06–F	524		--	0.2	2.2	4.6	n/a
		597	--	0.2	2.3	5.2	n/a
M–06–K	1,150		--	3.8	3.3	10.2	n/a
		1,300	--	4.1	3.4	10.8	n/a
B–23–A	50,400		600	0.5	1.9	1.9	n/a
		101,000	--	n/a	n/a	n/a	n/a
D–20–D	47,000		17,500	0.9	2.9	13.2	11.1
		96,300	--	n/a	n/a	n/a	n/a
E–16–EF	7,380		--	0	7.1	13.6	14.6
		13,750	--	0	8.2	21.7	16.6
H–02–D	340		--	0	n/a	n/a	n/a
		440	--	0	n/a	n/a	n/a
D–11–D	6,860		--	0	5.8	n/a	n/a
		8,180	--	0	5.9	n/a	n/a
J–14–C	3,490		--	5.6	3.7	7.4	12.3
		6,850	3,560	5.9	3.7	7.6	12.5
M–22–BC	43,200		17,600	3.2	5.6	5.9	12.3
		77,800	--	n/a	n/a	n/a	n/a
N–18–AC	43,800		16,900	4.3	5.4	13.2	1.2
		82,900	--	n/a	n/a	n/a	n/a
B–14–O	3,470		--	0.7	n/a	11.9	14.6
		5,050	--	1.4	n/a	17.0	18.4

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
B–18–F	16,000		6,500	28.8	6.8	15.9	8.1
		36,400	--	n/a	n/a	n/a	n/a
A–17–AD	24,300		5,250	4.1	3.9	9.1	8.0
		47,600	--	n/a	n/a	n/a	n/a
C–17–BL	50,800		18,750	3.8	3.1	22.4	8.3
		89,500	--	n/a	n/a	n/a	n/a
D–17–U	45,500		14,500	0.1	3.8	10.0	10.9
		76,300	--	n/a	n/a	n/a	n/a
H–17–L	10,800		8,300	0	7.8	n/a	n/a
		16,900	--	n/a	n/a	n/a	n/a
J–18–J	12,100		5,900	1.9	6.6	7.2	21.4
		18,600	--	n/a	n/a	n/a	n/a
M–17–AQ	16,100		5,750	0.5	5.5	3.1	6.2
		23,200	--	n/a	n/a	n/a	n/a
N–17–AM	26,500		11,200	0	3.6	7.7	n/a
		46,900	--	n/a	n/a	n/a	n/a
N–17–BH	9,770		--	5.7	7.4	n/a	n/a
		18,000	--	11.7	8.5	n/a	n/a
N–17–BO	18,500		--	12.7	7.0	18.6	11.6
		35,000	24,600	19.0	7.5	23.1	16.3
C–16–Z	26,900		10,250	9.1	7.3	7.5	12.3
		64,900	--	n/a	n/a	n/a	n/a
D–20–E	47,100		2,500	3.9	3.0	10.4	16.5
		96,600	--	n/a	n/a	n/a	n/a
F–18–B	29,400		16,500	2.4	12.1	6.8	8.5
		60,600	--	n/a	n/a	n/a	n/a
F–22–E	2,090		--	0.7	2.2	0.9	n/a
		7,780	--	0.4	3.4	4.4	3.5
C–07–D	963		--	0	4.0	5.2	2.1
		1,220	--	0	4.3	6.1	2.9

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
I–26–C	19,600		5,030	5.0	4.5	6.6	17.6
		42,900	--	n/a	n/a	n/a	n/a
I–03–G	325		--	0	2.6	n/a	n/a
		436	--	0	2.7	n/a	n/a
I–04–K	23,200		--	0	5.1	9.4	8.7
		27,500	--	0	5.3	10.5	10.2
K–11–B	332		--	0.2	1.9	n/a	n/a
		394	--	0.2	2.0	n/a	n/a
K–17–H	20,100		--	50.7	9.4	27.6	31.7
		34,500	--	57.6	10.5	45.2	40.4
K–17–AC	24,100		21,000	26.5	12.2	14.1	21.2
		42,700	--	n/a	n/a	n/a	n/a
L–21–G	56,200		27,000	11.5	15.7	n/a	n/a
		110,000	--	n/a	n/a	n/a	n/a
L–22–AL	44,000		10,200	0	10.4	n/a	n/a
		78,900	--	n/a	n/a	n/a	n/a
L–26–F	28,400		21,500	10.9	4.4	8.6	18.5
		60,500	--	n/a	n/a	n/a	n/a
M–23–A	9,250		--	3.9	4.7	13.4	10.6
		15,200	14,650	0.2	5.3	n/a	11.1
M–23–E	9,250		--	3.5	7.2	n/a	9.1
		15,200	11,600	3.5	7.5	8.5	9.7
D–20–T	15,100		3,000	4.5	4.1	10.9	5.4
		21,900	--	n/a	n/a	n/a	n/a
C–26–A	18,200		7,000	1.7	2.7	10.6	10.4
		41,300	--	n/a	n/a	n/a	n/a
G–25–F	20,600		4,250	0.4	3.8	9.2	9.7
		45,600	--	n/a	n/a	n/a	n/a
D–02–A	310		--	0	1.8	0.8	0.7
		423	--	0	2.0	1.5	1.3

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
I–04–M	23,000		--	0	4.6	9.6	18.4
		27,100	--	0	4.8	11.4	19.6
N–16–L	20,600		2,600	2.7	n/a	11.7	8.9
		36,200	--	n/a	n/a	n/a	n/a
F–05–L	28,400		--	0	5.2	n/a	n/a
		33,100	--	0	5.3	n/a	n/a
F–06–O	2,040		--	0	n/a	n/a	n/a
		2,460	--	0	n/a	n/a	n/a
F–06–Y	27,200		--	0	7.9	n/a	5.7
		32,000	--	0	7.3	n/a	6.7
F–15–BH	3,210		--	1.3	6.7	n/a	n/a
		3,710	--	1.3	6.9	n/a	n/a
F–15–BM	3,240		--	6.5	6.0	n/a	n/a
		3,740	--	7.7	6.2	n/a	n/a
G–03–P	28,600		--	0	4.5	n/a	n/a
		32,100	--	0	4.6	n/a	n/a
G–04–BA	28,600		--	0	6.8	n/a	1.8
		32,100	--	0	6.7	n/a	2.8
G–26–T	15,300		4,750	0.2	3.8	2.5	9.7
		34,300	--	n/a	n/a	n/a	n/a
I–22–B	18,100		--	1.0	3.7	n/a	15.6
		37,700	32,500	2.3	4.3	n/a	25.9
E–15–AF	1,150		--	0	n/a	n/a	n/a
		1,370	--	0	n/a	n/a	n/a
D–19–P	26,300		8,250	3.1	2.5	3.7	7.2
		56,100	--	n/a	n/a	n/a	n/a
G–18–BC	14,700		6,000	12.6	8.0	6.3	7.6
		30,700	--	n/a	n/a	n/a	n/a
G–18–H	15,000		6,250	3.0	4.3	4.3	9.2
		30,700	--	n/a	n/a	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
I–17–R	23,800		--	0	12.4	11.8	n/a
		36,600	--	0	14.1	15.3	n/a
G–18–BN	15,900		15,000	3.2	4.2	9.8	11.7
		34,300	--	n/a	n/a	n/a	n/a
G–19–B	20,500		--	4.1	9.1	9.1	27.0
		43,300	22,500	4.7	9.0	9.8	28.5
G–20–C	8,320		3,750	0.3	4.3	4.6	4.0
		15,600	--	n/a	n/a	n/a	n/a
K–18–BT	64,900		--	3.8	12.9	n/a	n/a
		124,000	95,400	6.5	14.0	n/a	n/a
K–26–A	71,300		13,200	0.7	4.4	8.1	6.0
		145,000	--	n/a	n/a	n/a	n/a
K–09–F	2,940		2,600	0.5	n/a	3.7	2.9
		3,560	--	n/a	n/a	n/a	n/a
J–17–E	11,100		3,970	25.4	n/a	9.4	6.0
		19,600	--	n/a	n/a	n/a	n/a
K–16–Y	15,700		2,900	0	n/a	8.4	n/a
		29,900	--	n/a	n/a	n/a	n/a
I–09–B	1,510		--	0	3.6	n/a	n/a
		1,750	--	0	3.8	n/a	n/a
A–26–AY	18,700		500	3.1	2.1	2.2	2.2
		38,900	--	n/a	n/a	n/a	n/a
A–26–F	10,500		1,500	0	5.8	11.9	2.7
		16,900	--	n/a	n/a	n/a	n/a
A–27–N	96,500		1,000	3.3	n/a	8.7	5.0
		186,000	--	n/a	n/a	n/a	n/a
I–01–M	613		--	0.1	n/a	7.4	4.5
		851	--	0.2	n/a	8.6	5.6
I–02–B	195		--	0.3	1.9	n/a	n/a
		275	--	0.4	2.0	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
J–01–C	29,700		21,500	0	5.2	11.0	3.6
		39,300	--	n/a	n/a	n/a	n/a
K–02–C	13,600		--	0	7.0	n/a	n/a
		17,900	--	0	7.4	n/a	n/a
L–01–B	613		--	1.0	2.8	n/a	n/a
		851	--	1.2	3.2	n/a	n/a
P–13–D	3,070		--	5.0	2.4	4.3	4.5
		3,970	--	6.3	2.6	5.1	5.4
P–14–P	19,100		--	2.3	5.3	11.2	11.8
		28,700	24,600	2.5	5.6	12.7	13.3
M–09–R	4,180		--	0.4	4.5	7.8	n/a
		5,710	--	0.5	4.8	8.3	n/a
N–10–V	5,160		--	0	4.3	3.2	n/a
		7,320	--	0	4.7	4.8	n/a
O–02–I	2,700		--	0	4.4	3.4	0
		3,670	--	0	4.7	4.6	1.7
P–07–B	2,230		--	0	4.6	4.2	0
		3,080	--	0	4.9	5.4	2.1
F–17–AA	13,800		0	3.0	1.8	1.8	
		19,100	--	n/a	n/a	n/a	n/a
H–13–G	906		--	0	3.5	n/a	n/a
		1,160	--	0	3.7	n/a	n/a
D–16–C	4,030		3,000	1.8	n/a	16.0	8.1
		8,570	--	n/a	n/a	n/a	n/a
N–26–P	13,200		12,600	1.9	5.5	15.5	6.8
		22,700	--	n/a	n/a	n/a	n/a
H–04–S	3,860		--	0	4.5	n/a	n/a
		4,690	--	0	4.7	n/a	n/a
H–02–GA	54,400		--	0	5.0	n/a	n/a
		64,500	--	0	5.2	n/a	n/a

Table 4. Summary of computed scour depths for 1992–93--Continued

CDOT structure ID (fig. 1)	Q100 (cubic feet per second)	Q500 (cubic feet per second)	Discharge specified (cubic feet per second)	Computed scour depths			
				Contraction scour (feet)	Pier scour (feet)	Left abutment (feet)	Right abutment (feet)
J–05–X	4,450		--	0	3.4	n/a	n/a
		5,360	--	0.2	3.5	n/a	n/a
M–21–E	2,110		1,910	0	n/a	3.7	6.1
		7,070	--	n/a	n/a	n/a	n/a
O–12–AD	1,750		--	9.2	4.5	5.9	4.3
		2,420	--	11.9	5.0	7.4	5.5
E–28–W	12,400		9,000	0.3	n/a	7.8	0.2
		27,100	--	n/a	n/a	n/a	n/a
L–27–P	12,300		3,980	0.6	3.9	14.7	n/a
		27,100	--	n/a	n/a	n/a	n/a
B–27–E	27,400		7,750	1.4	9.3	11.2	12.5
		61,200	--	n/a	n/a	n/a	n/a

REFERENCES CITED

Arcement, G.J., Jr., and Schneider, V.R., 1989, Guide for selecting Manning's roughness coefficients for natural channels and flood plains: U.S. Geological Survey Water-Supply Paper 2339, 38 p.

Benson, M.A., and Dalrymple, Tate, 1967, General field and office procedures for indirect discharge measurements: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A1, 30 p.

Jarrett, R.D., 1985, Determination of roughness coefficients for streams in Colorado: U.S. Geological Survey Water-Resources Investigations Report 85–4004, 54 p.

Jarrett, R.D., and Costa, J.E., 1988, Evaluation of the flood hydrology in the Colorado Front Range using precipitation, streamflow, and paleoflood data for the Big Thompson River basin: U.S. Geological Survey Water-Resources Investigations Report 87–4117, 37 p.

Kircher, J.E., Choquette, A.F., and Richter, B.D., 1985, Estimation of natural streamflow characteristics in western Colorado: U.S. Geological Survey Water-Resources Investigations Report 85–4086, 28 p.

Lagasse, P.F., Schall, J.D., Johnson, F., Richardson, E.V., Richardson, J.R., and Chang, F., 1990, Stream stability at highway structures: Federal Highway Administration Hydraulic Engineering Circular 20, Publication FHWA–IP–90–014, 195 p.

Livingston, R.K., and Minges, D.R., 1987, Techniques for estimating regional flood characteristics of small rural watersheds in the plains region of eastern Colorado: U.S. Geological Survey Water-Resources Investigations Report 87–4094, 72 p.

McCain, J.F., and Jarrett, R.D., 1976, Manual for estimating flood characteristics of natural-flow streams in Colorado: Colorado Water Conservation Board, Technical Manual, no. 1, 68 p.

Rayner, W.H., and Schmidt, M.O., 1963, Fundamentals of surveying: New York, D. Van Nostrand Book Company, 525 p.

Richardson, E.V., Harrison, L.J., and Davis, S.R., 1991, Evaluating scour at bridges: Federal Highway Engineering Circular 18, Publication FHWA–IP–90–017, 103 p.

Richter, B.D., Kircher, J.E., Remmers, M.A., and Forst, B.A., 1984, Summary of basin and streamflow characteristics for selected basins in western Colorado and adjacent states: U.S. Geological Survey Open-File Report 84–137, 226 p.

Shearman, J.O., 1990, Users manual for WSPRO—A computer model for water-surface profile computations: Federal Highway Administration Publication FHWA–IP–89–027, 177 p.

Shearman, J.O., Kirby, W.H., Schneider, V.R., and Flippo, H.N., 1985, Bridge waterways analysis model—Research report: Federal Highway Administration Research Report FHWA–RD–86–108, 112 p.

U.S. Geological Survey, 1980, Colorado average annual precipitation, 1950–1980, *in* Colorado Climate Center, compiler: Fort Collins, Colorado State University, scale 1:500,000.

Wolman, M.G., 1954, A method of sampling coarse riverbed material: Transactions, American Geophysical Union, v. 35, no. 6, p. 951–956.

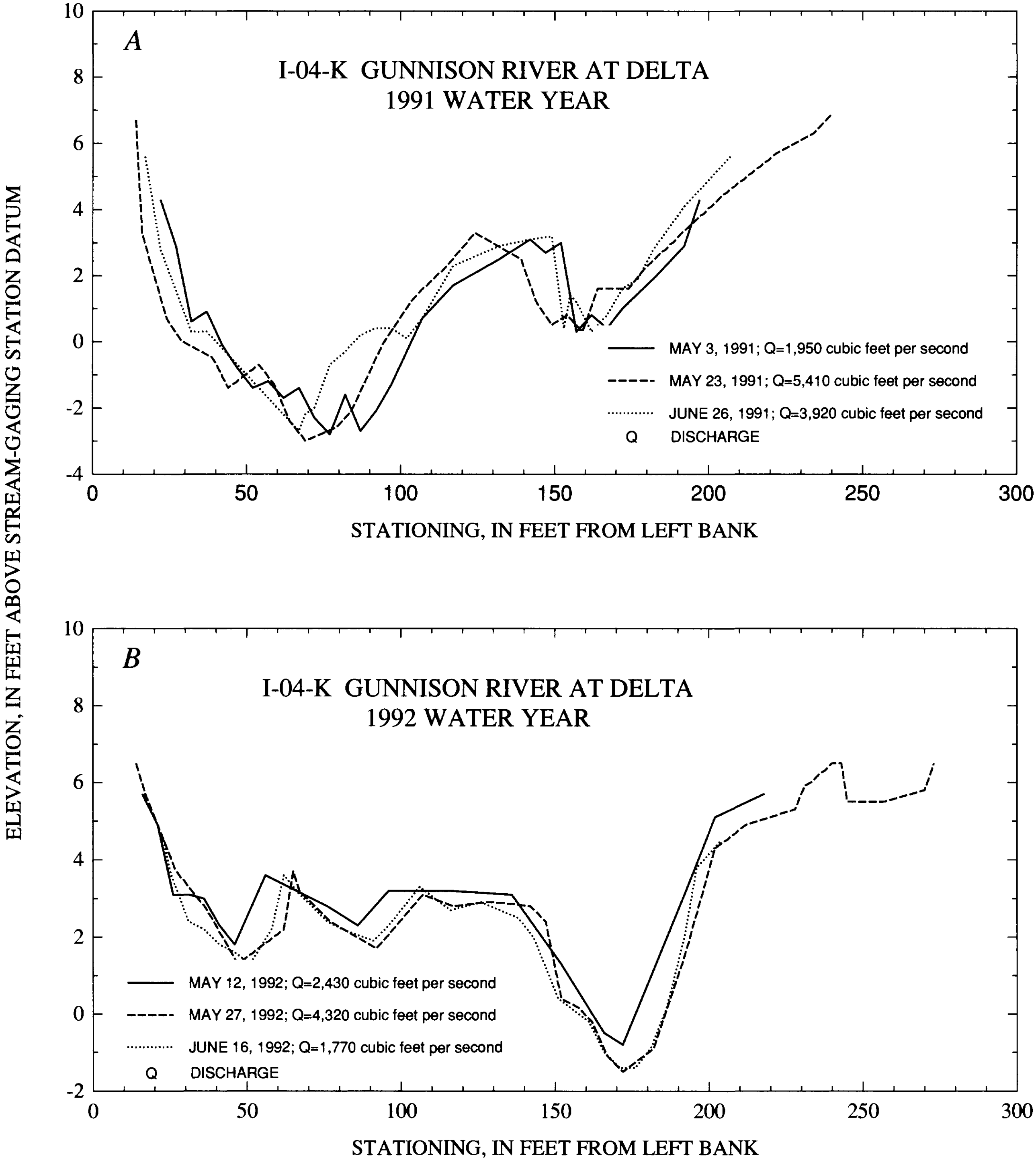
APPENDIXES

Appendix 1—Colorado State Highway Map

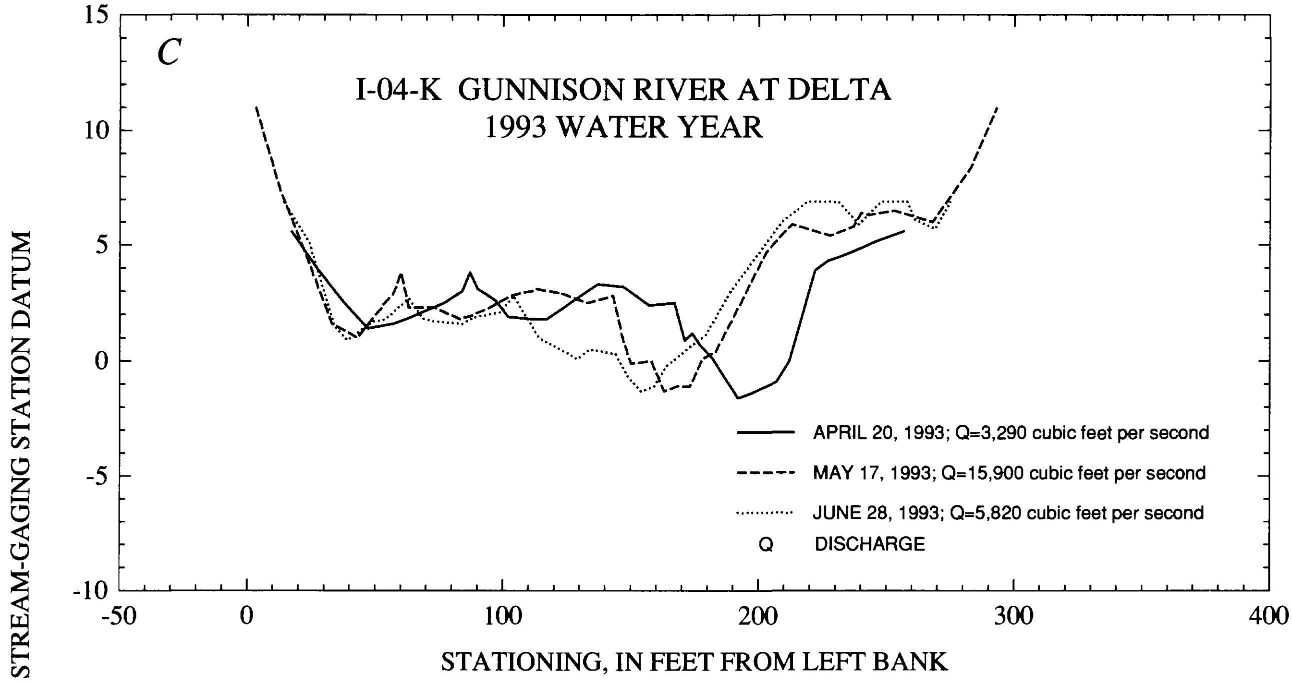
[In pocket at back of report]

Appendix 2—Cross Sections of Scour-Measurement Sites at Various Discharges

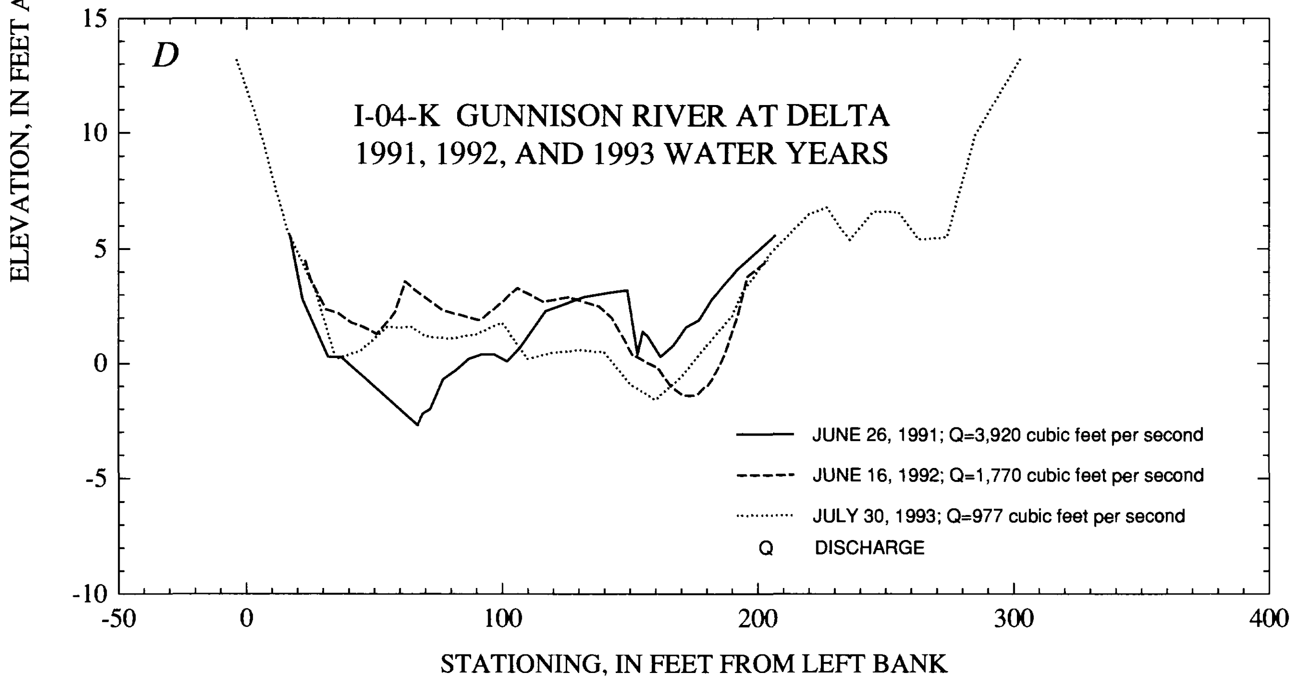
Appendix 2 contains selected stream-channel cross-section plots for the six sites at which scour-measurement data were collected. Figures A–C contain plots for the Gunnison River at Delta for discharges prior to the snowmelt runoff peak, for discharges at or near the peak, and for discharges after the peak for separate water years 1991–93. Figure D is a plot of the cross sections for discharges after the snowmelt runoff peaks in the 1991–93 water years. Figures E–I are plots of cross-section data at various discharges for the remaining five sites. The site North Fork Cache la Poudre River at Livermore (fig. F) is the only site that was not one of the 220 bridge sites analyzed and, therefore, is not listed in table 1 and does not have a corresponding CDOT structure ID number.



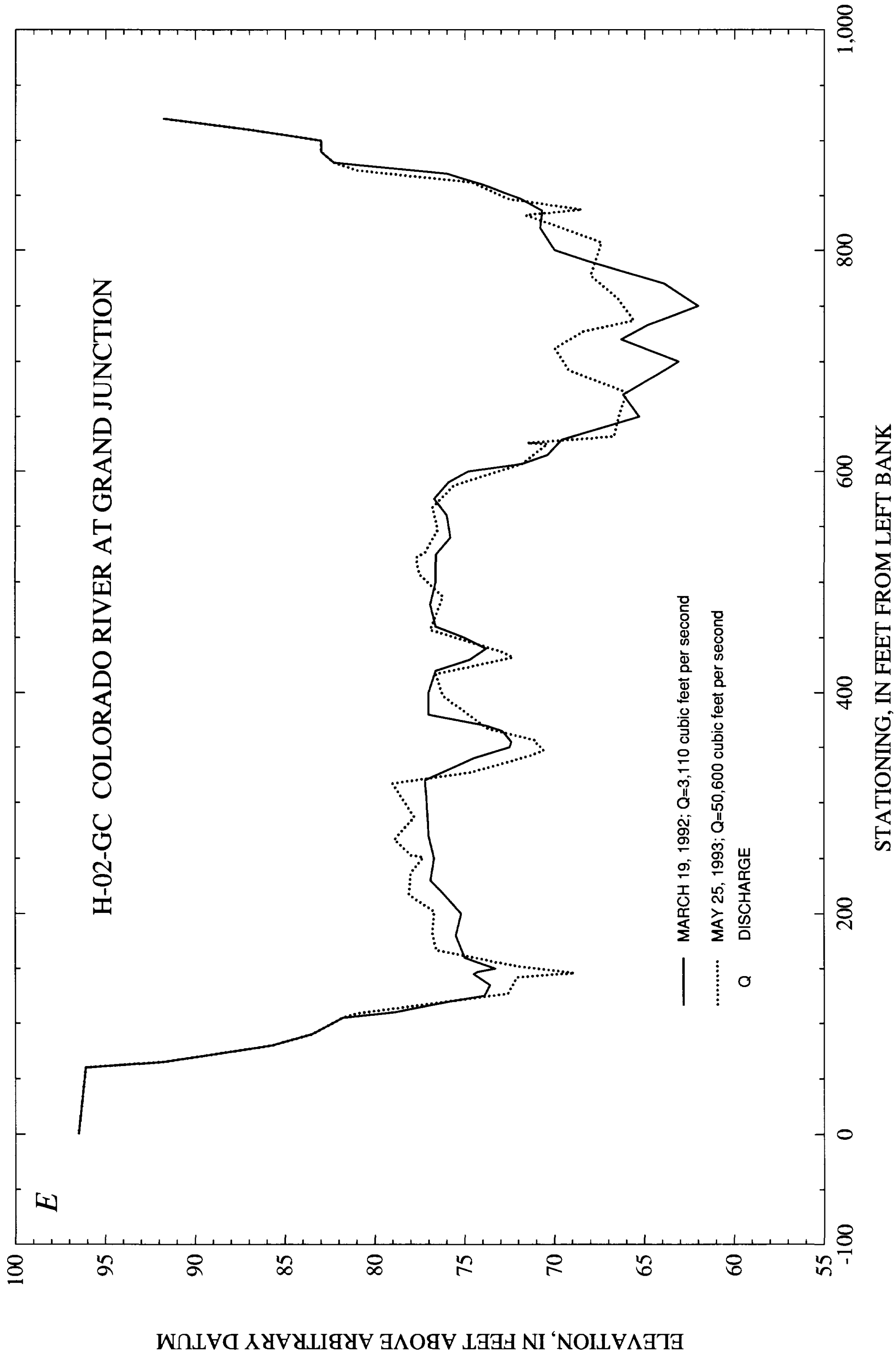
ELEVATION, IN FEET ABOVE STREAM-GAGING STATION DATUM
A
I-04-K GUNNISON RIVER AT DELTA
1991 WATER YEAR
MAY 3, 1991; Q=1,950 cubic feet per second
MAY 23, 1991; Q=5,410 cubic feet per second
JUNE 26, 1991; Q=3,920 cubic feet per second
Q DISCHARGE
STATIONING, IN FEET FROM LEFT BANK
B
I-04-K GUNNISON RIVER AT DELTA
1992 WATER YEAR
MAY 12, 1992; Q=2,430 cubic feet per second
MAY 27, 1992; Q=4,320 cubic feet per second
JUNE 16, 1992; Q=1,770 cubic feet per second
Q DISCHARGE
STATIONING, IN FEET FROM LEFT BANK

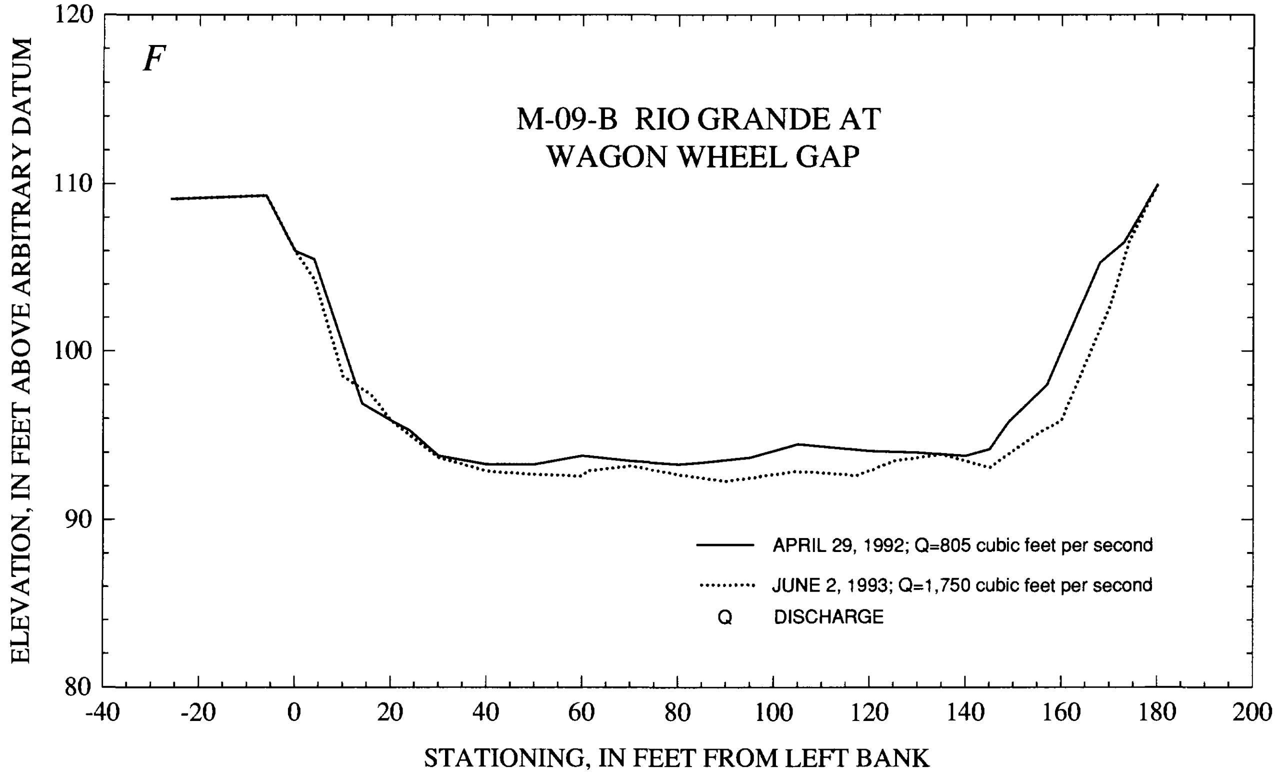


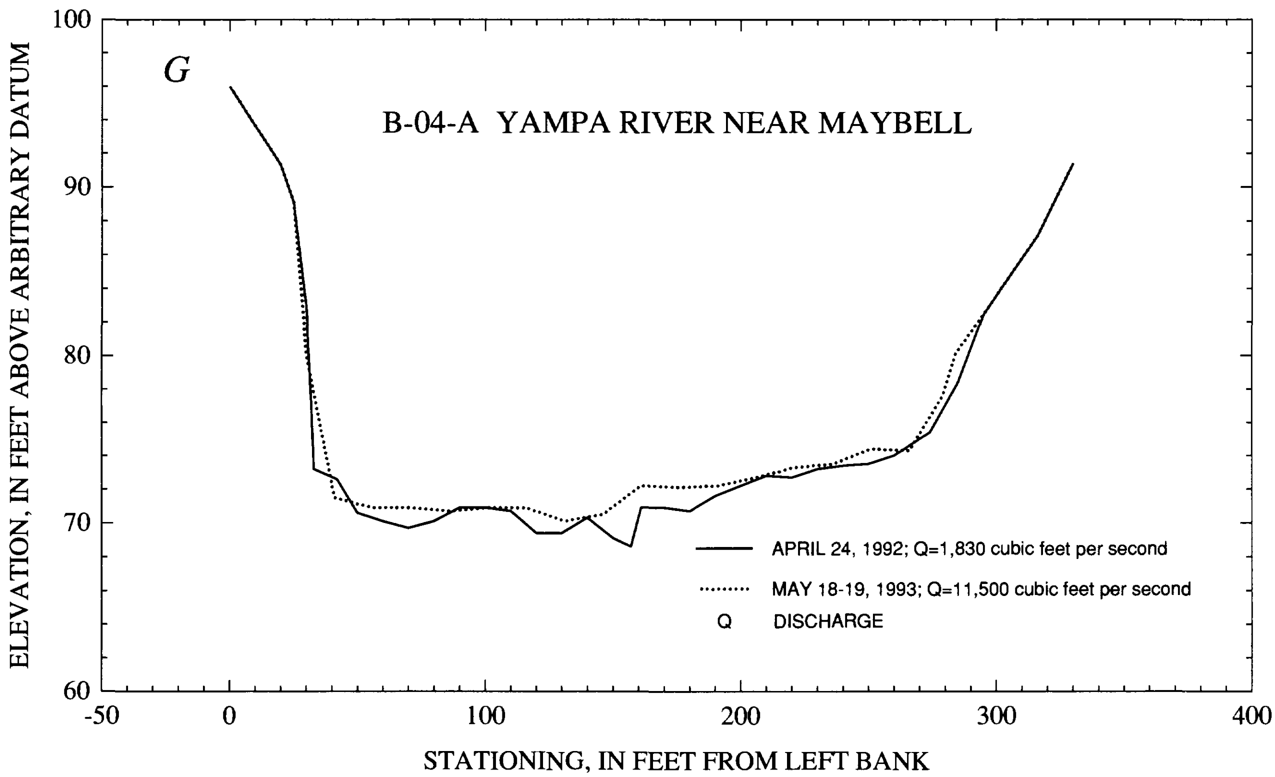
C
I-04-K GUNNISON RIVER AT DELTA
1993 WATER YEAR
ELEVATION, IN FEET ABOVE STREAM-GAGING STATION DATUM
15
10
5
0
-5
-10
-50
0
100
200
300
400
STATIONING, IN FEET FROM LEFT BANK
APRIL 20, 1993; Q=3,290 cubic feet per second
MAY 17, 1993; Q=15,900 cubic feet per second
JUNE 28, 1993; Q=5,820 cubic feet per second
Q DISCHARGE

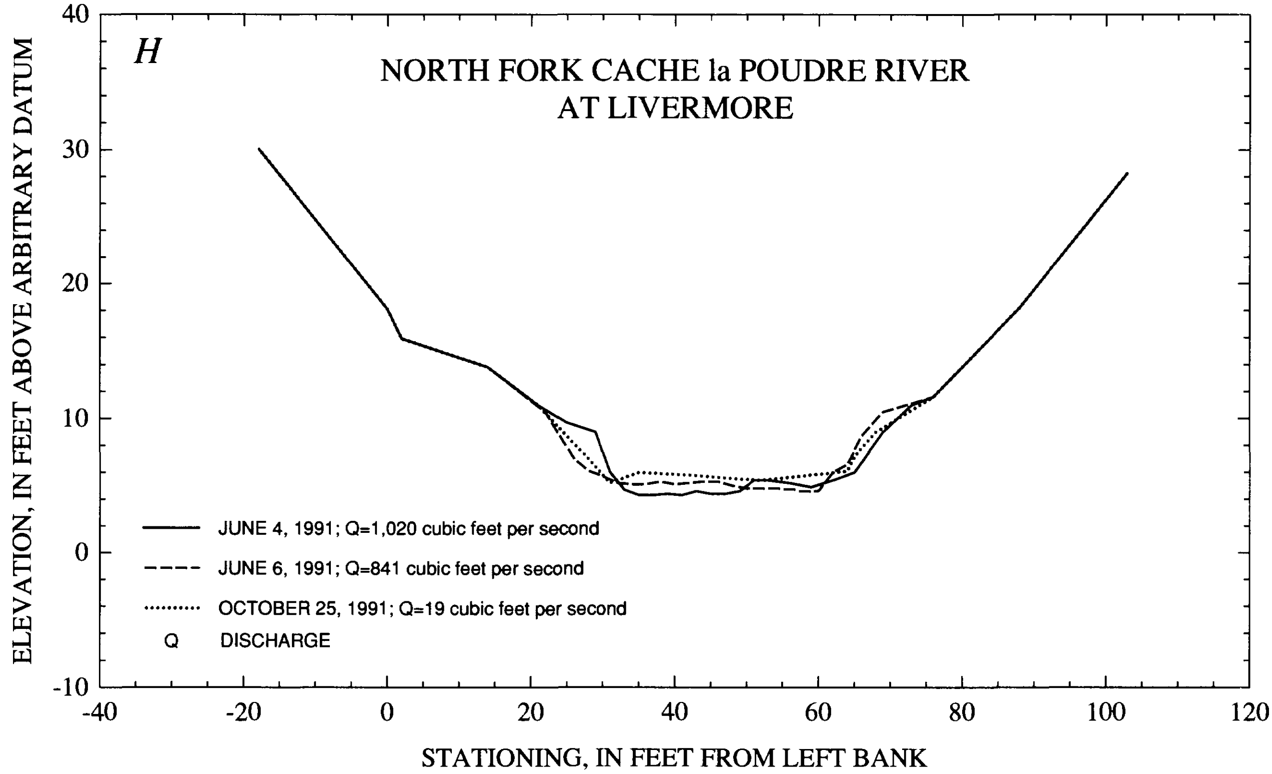


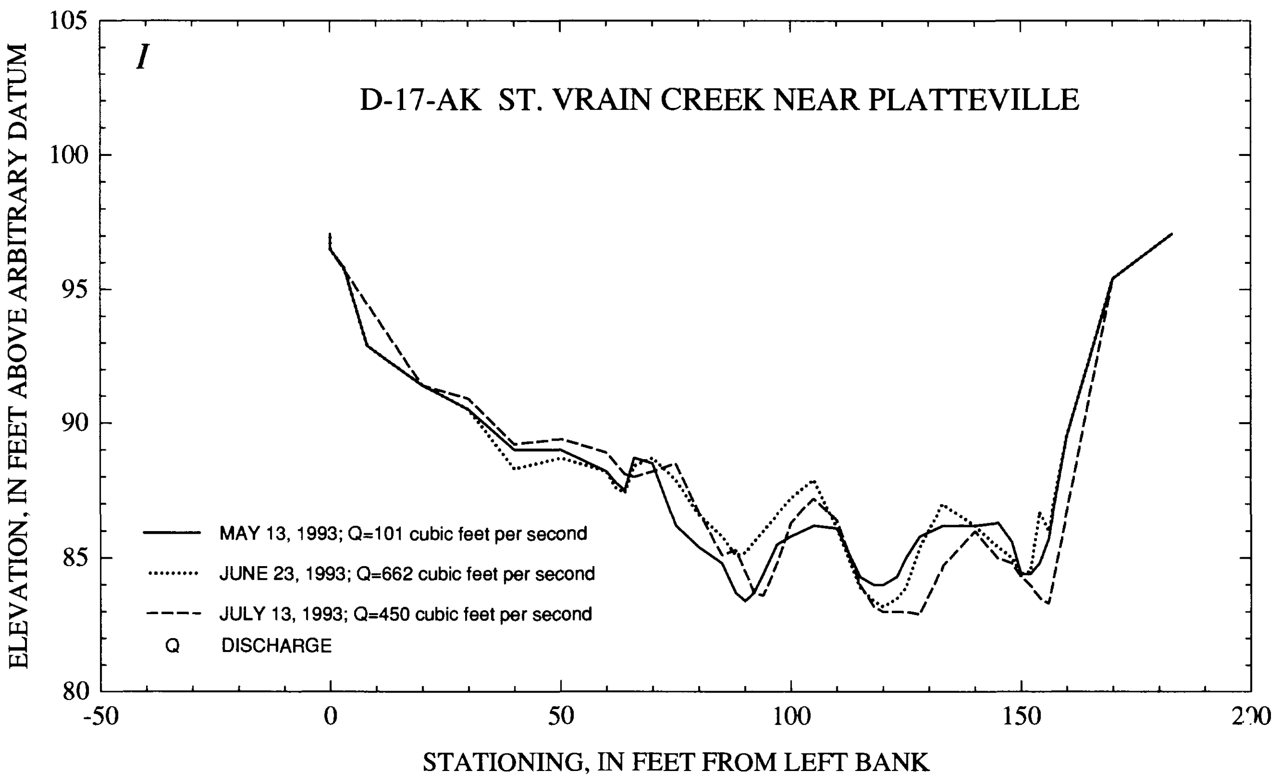
D
I-04-K GUNNISON RIVER AT DELTA
1991, 1992, AND 1993 WATER YEARS
15
10
5
0
-5
-10
-50
0
100
200
300
400
STATIONING, IN FEET FROM LEFT BANK
JUNE 26, 1991; Q=3,920 cubic feet per second
JUNE 16, 1992; Q=1,770 cubic feet per second
JULY 30, 1993; Q=977 cubic feet per second
Q DISCHARGE


E
H-02-GC COLORADO RIVER AT GRAND JUNCTION
MARCH 19, 1992; Q=3,110 cubic feet per second
MAY 25, 1993; Q=50,600 cubic feet per second
Q DISCHARGE
STATIONING, IN FEET FROM LEFT BANK
ELEVATION, IN FEET ABOVE ARBITRARY DATUM
-100
0
200
400
600
800
1,000
55
60
65
70
75
80
85
90
95
100


F
M-09-B RIO GRANDE AT
WAGON WHEEL GAP
ELEVATION, IN FEET ABOVE ARBITRARY DATUM
120
110
100
90
80
-40
-20
0
20
40
60
80
100
120
140
160
180
200
STATIONING, IN FEET FROM LEFT BANK
APRIL 29, 1992; Q=805 cubic feet per second
JUNE 2, 1993; Q=1,750 cubic feet per second
Q DISCHARGE


G
B-04-A YAMPA RIVER NEAR MAYBELL
ELEVATION, IN FEET ABOVE ARBITRARY DATUM
100
90
80
70
60
-50
0
100
200
300
400
STATIONING, IN FEET FROM LEFT BANK
APRIL 24, 1992; Q=1,830 cubic feet per second
MAY 18-19, 1993; Q=11,500 cubic feet per second
Q DISCHARGE


H
NORTH FORK CACHE la POUDRE RIVER
AT LIVERMORE
ELEVATION, IN FEET ABOVE ARBITRARY DATUM
STATIONING, IN FEET FROM LEFT BANK
JUNE 4, 1991; Q=1,020 cubic feet per second
JUNE 6, 1991; Q=841 cubic feet per second
OCTOBER 25, 1991; Q=19 cubic feet per second
Q DISCHARGE
40
30
20
10
0
-10
-40
-20
0
20
40
60
80
100
120


I
D-17-AK ST. VRAIN CREEK NEAR PLATTEVILLE
ELEVATION, IN FEET ABOVE ARBITRARY DATUM
STATIONING, IN FEET FROM LEFT BANK
MAY 13, 1993; Q=101 cubic feet per second
JUNE 23, 1993; Q=662 cubic feet per second
JULY 13, 1993; Q=450 cubic feet per second
Q DISCHARGE
105
100
95
90
85
80
-50
0
50
100
150

Appendix 3—Example of a Bridge Scour Analysis

Appendix 3 is an example of a bridge scour analysis. The example includes (A) a list of the hydraulic variables used in the scour analysis, (B) a hydraulic analysis summary of the variables used in the scour equations, using procedure 2 (see p. 10), (C) a scour computation summary, (D) flood-frequency computations for the 100- and 500-year discharges, (E) WSPRO output with maximum streamtube-depth computations and maximum streamtube velocity noted, (F) the plan view of the site, and (G) the cross-section plots of the site. The plan view and the cross-section plots are examples of computer output from an in-house plotting program enhanced by graphics.

A. List of Variables

Variable	Definition of Variable
Q	Flow for which scour depths were computed.
Y2	Average depth in contracted (bridge) section.
Y1(c)	Average depth in the main channel of the approach section.
Qmc2	Flow in the contracted (bridge) section.
Qmc1	Flow in the main channel of the approach section.
Wc1	Width of the main channel of the approach section.
Wc2	Width of the contracted (bridge) section.
K1(c)	Exponent for ratio of the widths.
Ys(c)	Average depth for contraction scour.
K1(p)	Correction factor in pier-scour equation for pier nose shape.
K2(p)	Correction factor in pier-scour equation for angle of attack of the flow.
V1	90 percent of the maximum streamtube velocity in the contracted (bridge) section.
Fr	Froude number based on V1 and Y1(p).
Y1(p)	Maximum streamtube depth in the contracted (bridge) section.
Ys(p)	Depth of pier scour.
Ae	Flow area of the approach cross section obstructed by the embankment.
Qe	Flow obstructed by the abutment and bridge approach embankment.
Ya	Average depth of flow on the flood plain.
K1(a)	Coefficient for abutment shape.
Theta	Angle of embankment to flow.
K2(a)	Coefficient for angle of embankment to flow.
A'	Length of abutment projected normal to flow.
Ve	Velocity of flow in the flood plain (Qe/Ae).
Fre	Froude number of approach flow upstream of the abutment $(Ve/(GYa)^{1/2})$.
Ys(a)	Depth of abutment scour.
n/a	Not applicable.
ALPH	Velocity head correction factor for nonuniform velocity distribution.
AREA	Flow area of a cross section.
BETA	Momentum correction factor for nonuniform velocity distribution, used in computing expansion loss downstream from bridge.
C	Coefficient of discharge for bridge opening.
CODE	Label used in output headings for record identifiers.
CRWS	Water-surface elevation for critical flow.
EGL	Elevation of the energy-grade line.
ERR	Discrepancy in balancing energy and (or) discharge.
FLEN	The effective flow length computed for the approach reach in the bridge-backwater computations.
FR#	Computed value of Froude number for approximate check for possibility of critical flow.
HF	Friction loss.
HO	Losses other than friction loss.
K	Cross-sectional conveyance.
KQ	Conveyance of the Kq segment of the approach section.
LEW	Left edge of water.
LSEL	Value for low-chord elevation in a bridge used to test for possible pressure flow.

M[G]	Geometric contraction ratio.
M[K]	Flow contraction ratio.
OTEL	Minimum elevation at which road grade could be built without being subjected to overtopping.
P/A	Ratio of pier (pile) area to gross area in the bridge opening.
PPCD	Code to distinguish between piers and piles.
Q	Discharge specified for each profile and velocity and conveyance distribution.
REW	Right edge of water.
SA#	Subarea number in a subdivided cross section.
SRD	Section reference distance.
SRDL	Difference between adjacent SRD's (same as SLEN).
TYPE	Type of bridge opening (same as BRTYPE).
VEL	Flow velocity.
VHD	Velocity head.
WSEL	Computed or assumed water-surface elevation.
XLKQ	Left limit of Kq section.
XRKQ	Right limit of Kq section.
XSID	Column heading for SECID's.
XSTW	Cross-sectional top width.
XSWP	Cross-sectional wetted perimeter.
YMIN	Minimum cross-section elevation.
Q–100	Magnitude of 100-year flood event.
Q–500	Magnitude of 500-year flood event.
D50	Median bed-material particle size.
mm	Millimeters.
HEC–18	Hydraulic Engineering Circular 18.
WS	Water surface.
HO	"Other losses" term from WSPRO output.
US	Upstream.
Wc1	Bottom width of main channel at approach section.
Y1	Mean depth in main channel of the approach section (approach section area divided by Wc1).
Wc2	Width of main channel at the bridge (contracted) section.
Qmc2	Discharge in the bridge (contracted) section.
Qmc1	Discharge in the main channel at the approach section.
R	Hydraulic radius of main channel at the approach section (approach section area divided by the wetted perimeter).
S	Slope of the energy gradeline from the approach section to the bridge section. Computed from the constricted flow WSPRO output as the energy gradeline value (EGL) at the approach section minus the energy gradeline (EGL) value at the bridge section divided by the flow length (FLEN) value in the approach (APPR) section output.
L	Length of pier upstream to downstream.
a	Width of pier obstructing flow.
Flow attack angle	Angle, in degrees, that the centerline of the pier differs from the direction of the flow.
Shape	Shape of the upstream side of the pier.

B. Hydraulic Analysis Summary

Stream name Cottonwood Creek | Structure no. A–26–AY

DISCHARGE

Q_{100} 18,700 | Q_{500} 38,900 | Channel slope 0.0016 ft/ft

HYDRAULIC VARIABLES

Main channel D50 5 mm | Fall velocity, 'w' 1.6 (page 44, HEC–18)

	Q = 500 ft^3/s
Bridge section WS elevation	100.34
Friction losses through bridge (HO)	0.14
Water surface @ US bridge opening	100.48
Approach section area	164
Bottom width, Wc1, at approach section	50
Depth, Y1, subarea area/subarea top width	3.28
Width, Wc2, at bridge (contracted) section	41
Qmc2, contracted flow at bridge section	500
Qmc1, main channel flow at approach section	265
Left bank overflow discharge at approach	135
Right bank overflow discharge at approach	100
Wetted perimeter at approach section	53
Hydraulic radius, R, at approach section	3.09
Energy gradeline slope, S, approach to bridge	0.0047
Shear stress at approach (62.4 x R x S)	0.91
Shear velocity [shear stress/1.94] *0.5	0.68
Shear velocity/fall velocity ratio	0.43

*, indicates 'raised to the power' of the following number.

Pier scour:

Length, L 41 | Width, a 1.0 | Flow attack angle 0 | Shape Pointed

Pier no.	Station		Q = 500 ft^3/s
1	21	Max. velocity	4.77
		90% max. vel.	4.29
		Max. depth	6.56

Velocities used in scour equations are 90 percent of the maximum subsection velocity in the cross section. Depths are computed as the subsection area divided by the subsection width. The maximum depth and 90-percent maximum velocity are used for all piers.

C. Scour Computation Summary

CONTRACTION-SCOUR CALCULATIONS - Main channel

Q	Y2	Y1(c)	Qmc2	Qmc1	Wc1	Wc2	K1(c)	Ys(c)
500	6.35	3.28	500	265	50	41	0.59	3.1

CONTRACTION SCOUR - Overbank, clear-water scour

Q	Y2	Y1	Qob2	D50	Wset	Ys
						n/a

PIER-SCOUR CALCULATIONS - Main channel

Angle	a	K1(p)	K2(p)	Y1(p)	V1	Fr	Ys(p)
0	1.0	0.9	1.0	6.56	4.29	0.30	2.1

PIER-SCOUR CALCULATIONS - Overbank

Angle	a	K1	K2	Y1	V1	Fr	Ys
							n/a

ABUTMENT-SCOUR CALCULATIONS

Left abutment

Q	Ae	Qe	Ya	K1(a)	Theta	K2(a)	a′	Ve	Fr	Ys(a)	
500	121	135	0.92				132	1.12	0.21	2.2	a′/a > 25, use $Ys/ya = 4Fr^{0.33}$

Right abutment

Q	Ae	Qe	Ya	K1	Theta	K2	a′	Ve	Fr	Ys(a)
500	92	100	0.94				98	1.09	0.20	2.2

TOTAL SCOUR

Q	Left abutment	Right abutment	Piers - Main	Piers - Overbank
500	5.3	5.3	5.2	n/a

D. Flood-frequency Computations

[Q100, 100-year flood discharge; Q500, 500-year flood discharge]

Site ID A–26–AY   Site Name Cottonwood Creek   Route 138

Drainage Area 83 mi^2 At Gaging Station No   Gage Nearby No

Flood Region Plains

Flood Computation Reference(s) Tech. Manual No. 1

Equations:

Q100	Q500
$Q100 = 1770(A)^{0.463}Sb^{0.086}$	$Q500 = 5770(A)^{0.432}$
Variables: Drainage area (A) Basin slope (Sb)	Variables: Drainage area (A)

Computations:

Q100	Q500
$Q100 = 1770(83)^{0.463}(36.6)^{0.086}$	$Q500 = 5770(83)^{0.432}$
$= 18{,}700\ ft^3/s$	$= 38{,}900\ ft^3/s$

REMARKS: Sb computed from Colorado Atlas

L = 13.9 mi, 0.1L = 1.39 mi, elev = 3655 ft

0.8L = 11.12 mi, elev = 4035 ft

$$Sb = \frac{4035 - 3655}{11.78 - 1.39} = \frac{380}{10.39} = 36.6\ ft/mi$$

Computed by J.E. Vaill 7–26–93   Checked by D.L. Collins 7–27–93

E. WSPRO Output

```
WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
V060188              MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS
        WSPRO PROFILES --- COTTONWOOD CREEK NEAR SEDGEWICK, CO
          STRUCTURE ID:  A-26-AY
        BRIDGE SCOUR EVALUATION PROJECT
           *** RUN DATE & TIME: 09-30-93  16:29
 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS      Q    WSEL
       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
SYN1 :XS   ******    21.     185.  0.12 *****  100.26   98.25    500.  100.14
        0. ******    93.   12491.  1.05 ***** *******    0.31    2.71
EXIT :XS     100.    21.     185.  0.12  0.16  100.43 *******    500.  100.31
      100.   100.    93.   12565.  1.05  0.00    0.01    0.30    2.70
FULL :FV      40.    21.     186.  0.12  0.06  100.50 *******    500.  100.38
      140.    40.    94.   12614.  1.05  0.00    0.01    0.30    2.69
         <<<<<THE ABOVE RESULTS REFLECT "NORMAL" (UNCONSTRICTED) FLOW>>>>>
APPR :AS      79.    94.     335.  0.04  0.10  100.60 *******    500.  100.56
      219.    79.   362.   15447.  1.12  0.00    0.00    0.25    1.49
         <<<<<THE ABOVE RESULTS REFLECT "NORMAL" (UNCONSTRICTED) FLOW>>>>>
 ===220 FLOW CLASS 1 (4) SOLUTION INDICATES POSSIBLE PRESSURE FLOW.
        WS3,WSIU,WS1,LSEL =   100.34     100.63     100.70     100.39
 ===245 ATTEMPTING FLOW CLASS 2 (5) SOLUTION.
 ===250 INSUFFICIENT HEAD FOR PRESSURE FLOW.
                        YU/Z,WSIU,WS = 1.06     100.62     100.72
 ===270 REJECTED FLOW CLASS 2 (5) SOLUTION.
            <<<<<RESULTS REFLECTING THE CONSTRICTED FLOW FOLLOW>>>>>
 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS      Q    WSEL
       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
BRDG :BR      40.     2.     150.  0.19  0.09  100.52   98.41    500.  100.34
      140.    40.    43.    9550.  1.08  0.01    0.00    0.32    3.32
     TYPE PPCD FLOW       C     P/A    LSEL   BLEN   XLAB   XRAB
       4.   0.   1.  0.963   0.036  100.39 ****** ****** ******
    XSID:CODE     SRD   FLEN    HF   VHD      EGL      ERR       Q    WSEL
   ROAD :RG     160.         <<<<<EMBANKMENT IS NOT OVERTOPPED>>>>>
 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS      Q    WSEL
       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
APPR :AS      38.    88.     376.  0.03  0.07  100.74   98.73    500.  100.71
      219.    47.   368.   18005.  1.10  0.14    0.00    0.21    1.33
       M(G)   M(K)       KQ   XLKQ   XRKQ    OTEL
      0.847  0.492    9121.   224.   265.   100.68
                 <<<<<END OF BRIDGE COMPUTATIONS>>>>>
```

```
WSPRO         FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
V060188            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS
        WSPRO PROFILES --- COTTONWOOD CREEK NEAR SEDGEWICK, CO
          STRUCTURE ID:  A-26-AY
        BRIDGE SCOUR EVALUATION PROJECT
           *** RUN DATE & TIME: 09-30-93  16:29
  FIRST USER DEFINED TABLE.
    XSID:CODE   SRD       Q    WSEL         K      AREA    XSTW    XSWP     YMIN
   SYN1 :XS      0.    500.  100.14    12491.      185.     72.     75.    94.24
   EXIT :XS    100.    500.  100.31    12565.      185.     73.     75.    94.40
   FULL :FV    140.    500.  100.38    12614.      186.     73.     76.    94.47
   BRDG :BR    140.    500.  100.34     9550.      150.     41.     48.    94.20
   ROAD :RG    160.      0.****************************************   102.04
    XSID:CODE  DAVG
   ROAD :RG  ******
   ROAD :RG  ******
    XSID:CODE   SRD       Q    WSEL         K      AREA    XSTW    XSWP     YMIN
   APPR :AS    219.    500.  100.71    18005.      376.    280.    283.    94.20
 SECOND USER DEFINED TABLE.
    XSID:CODE  ALPH  BETA      VEL      FR#  VHD      HF     HO      EGL     CRWS
   SYN1 :XS    1.05  1.02     2.71     0.31  0.12************  100.26    98.25
   EXIT :XS    1.05  1.02     2.70     0.30  0.12   0.16   0.00  100.43********
   FULL :FV    1.05  1.02     2.69     0.30  0.12   0.06   0.00  100.50********
   BRDG :BR    1.08  1.04     3.32     0.32  0.19   0.09   0.01  100.52    98.41
   ROAD :RG  ************     1.00********  0.01************  102.22********
   APPR :AS    1.10  1.03     1.33     0.21  0.03   0.07   0.14  100.74    98.73
```

WSPRO FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY

V060188 MODEL FOR WATER-SURFACE PROFILE COMPUTATIONS

WSPRO PROFILES --- COTTONWOOD CREEK NEAR SEDGEWICK, CO

STRUCTURE ID: A-26-AY

BRIDGE SCOUR EVALUATION PROJECT

*** RUN DATE & TIME: 09-30-93 16:29

CROSS-SECTION PROPERTIES: ISEQ = 6; SECID = APPR ; SRD = 219.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	121.	4851.	132.	132.				656.
	2	164.	9482.	50.	53.				1688.
	3	92.	3719.	98.	98.				502.
100.71		377.	18052.	280.	283.	1.10	88.	368.	2364.

VELOCITY DISTRIBUTION: ISEQ = 6; SECID = APPR ; SRD = 219.

WSEL	LEW	REW	AREA	K	Q	VEL
100.71	88.4	368.3	376.5	18052.	500.	1.33

X STA.	88.4		147.3		162.7		178.3		194.0		211.7
A(I)		36.6		18.6		18.8		19.0		19.7	
V(I)		0.68		1.34		1.33		1.31		1.27	
X STA.	211.7		229.3		233.7		235.6		237.4		239.2
A(I)		26.0		16.6		11.5		11.6		11.7	
V(I)		0.96		1.51		2.18		2.16		2.13	
X STA.	239.2		241.0		242.8		246.2		252.0		259.2
A(I)		11.1		11.1		15.0		17.0		18.6	
V(I)		2.26		2.25		1.67		1.47		1.34	
X STA.	259.2		271.2		285.2		298.7		311.3		368.3
A(I)		23.9		18.2		17.5		17.3		36.7	
V(I)		1.05		1.37		1.43		1.44		0.68	

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WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
V060188                MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS
        WSPRO PROFILES --- COTTONWOOD CREEK NEAR SEDGEWICK, CO
          STRUCTURE ID:  A-26-AY
        BRIDGE SCOUR EVALUATION PROJECT
           *** RUN DATE & TIME: 09-30-93  16:29
    VELOCITY DISTRIBUTION:  ISEQ =  4;  SECID = BRDG ;  SRD =     140.
         WSEL      LEW     REW    AREA        K        Q     VEL
       100.44      2.0    43.0   152.6     6490.     500.   3.28
X STA.       2.0         5.7         8.3        10.1           11.3     12.2≠
 A(I)            11.9        8.2         7.4         6.6          5.9
 V(I)            2.10        3.05        3.40        3.77         4.22
X STA.      12.2        13.2        14.2        15.2        16.4        17.4
 A(I)             5.8         5.8         6.1         6.3         5.8
 V(I)            4.28        4.28        4.07        3.97        4.28
X STA.      17.4        18.4        19.5        20.5        21.6        22.6
 A(I)             5.2         5.8         5.8         5.8         5.8
 V(I)            4.77*        4.33        4.30        4.34        4.29
X STA.      22.6        23.9        25.6        29.2        35.0        43.0
 A(I)             6.2         6.9        10.5        13.3        17.3
 V(I)            4.02        3.62        2.39        1.88        1.44
```

≠ maximum streamtube depth ($\frac{5.9}{12.2-11.3} = 6.56$)

* maximum streamtube velocity

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WSPRO         FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
V060188           MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS
       WSPRO PROFILES --- COTTONWOOD CREEK NEAR SEDGEWICK, CO
         STRUCTURE ID:  A-26-AY
       BRIDGE SCOUR EVALUATION PROJECT
          *** RUN DATE & TIME: 09-30-93  16:29
 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS       Q    WSEL
       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
SYN1 :XS   ******    20.     213.  0.13 *****  100.63   98.44    600.  100.50
        0. ******   113.   14999.  1.10 ***** *******    0.34    2.81
EXIT :XS    100.     20.     215.  0.13  0.16  100.80 *******    600.  100.67
      100.   100.   114.   15090.  1.10  0.00    0.01    0.34    2.80
FULL :FV     40.     20.     215.  0.13  0.06  100.88 *******    600.  100.74
      140.    40.   115.   15163.  1.10  0.00    0.01    0.34    2.78
        <<<<<THE ABOVE RESULTS REFLECT "NORMAL" (UNCONSTRICTED) FLOW>>>>>
 ===135 CONVEYANCE RATIO OUTSIDE OF RECOMMENDED LIMITS.
                                   "APPR "     KRATIO =  1.48
APPR :AS     79.     84.     439.  0.03  0.08  100.96 *******    600.  100.93
      219.    79.   378.   22410.  1.07  0.00    0.00    0.20    1.37
        <<<<<THE ABOVE RESULTS REFLECT "NORMAL" (UNCONSTRICTED) FLOW>>>>>
 ===255 ATTEMPTING FLOW CLASS 3 (6) SOLUTION.
                              WS3N,LSEL =   100.74     100.39
           <<<<<RESULTS REFLECTING THE CONSTRICTED FLOW FOLLOW>>>>>
 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS       Q    WSEL
       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
BRDG :BR     40.      2.     147.  0.26 *****  100.65   98.61    600.  100.39
      140. ******    43.    6490.  1.00 ***** *******    0.38    4.08
     TYPE PPCD FLOW      C    P/A    LSEL   BLEN   XLAB   XRAB
       4.   0.   3.  0.800  0.036  100.39 ****** ****** ******
    XSID:CODE    SRD   FLEN    HF   VHD     EGL     ERR       Q    WSEL
   ROAD :RG     160.        <<<<<EMBANKMENT IS NOT OVERTOPPED>>>>>
 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS       Q    WSEL
       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
APPR :AS     38.     83.     526.  0.02  0.09  101.24   98.99    600.  101.22
      219.    48.   391.   29178.  1.04  0.00    0.00    0.16    1.14
      M(G)   M(K)       KQ   XLKQ   XRKQ    OTEL
     ****** ****** ******** ****** ******   101.20
                      <<<<<END OF BRIDGE COMPUTATIONS>>>>>
```
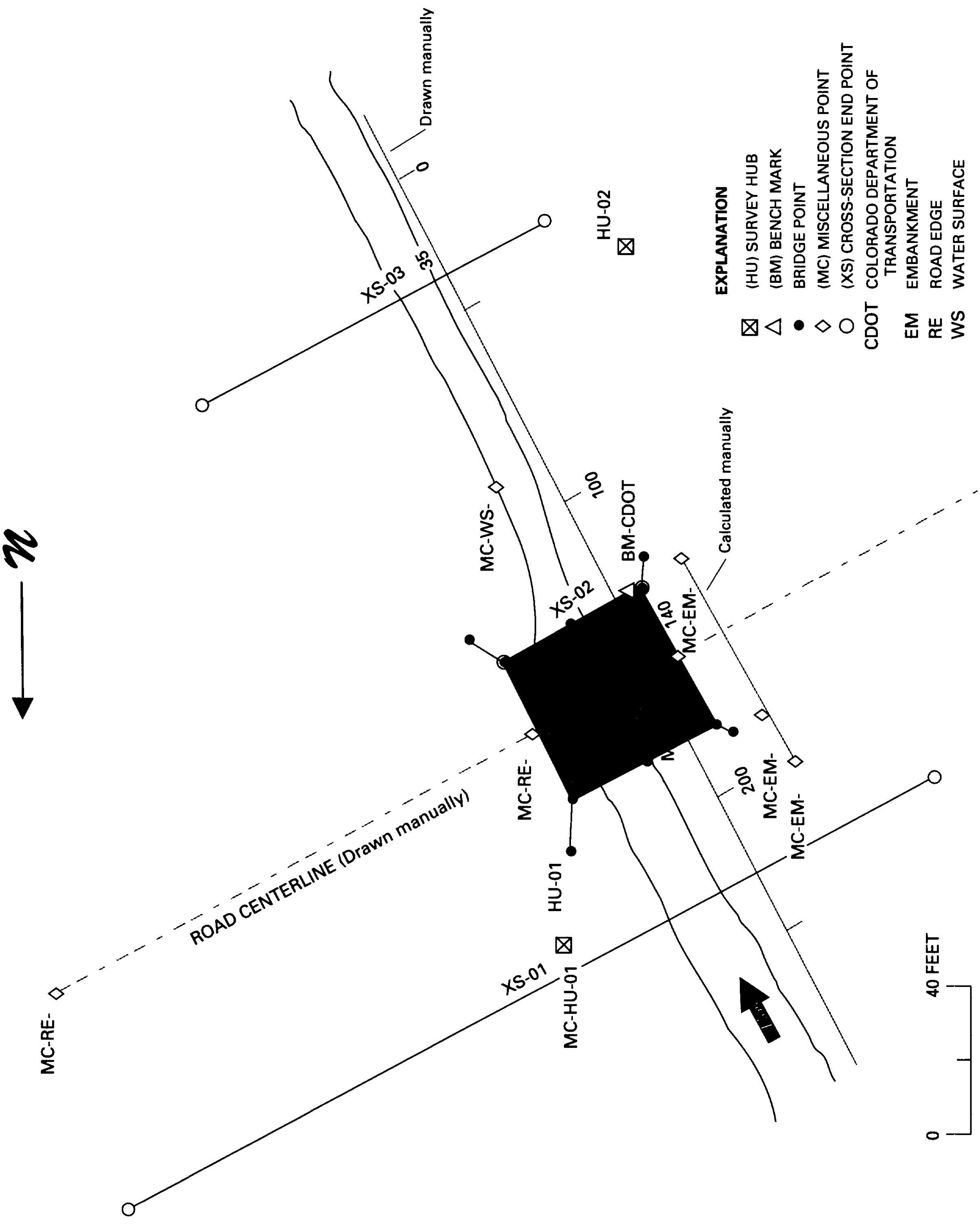
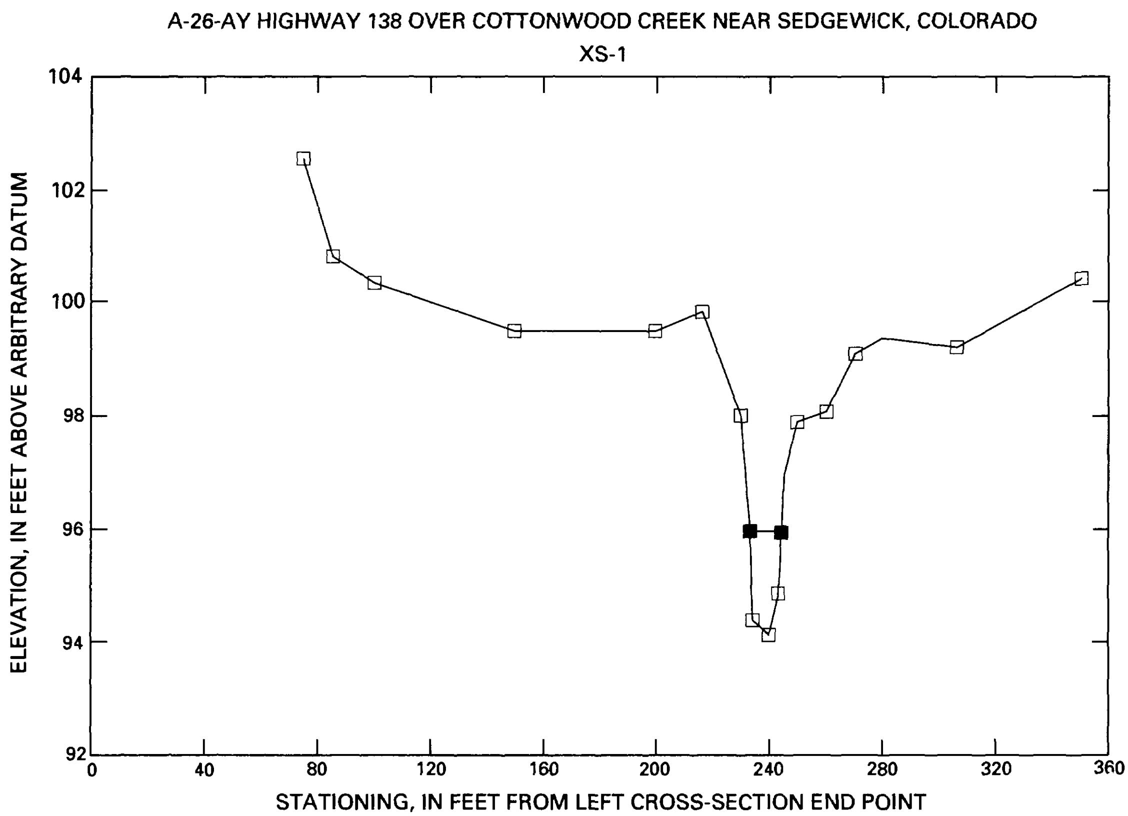
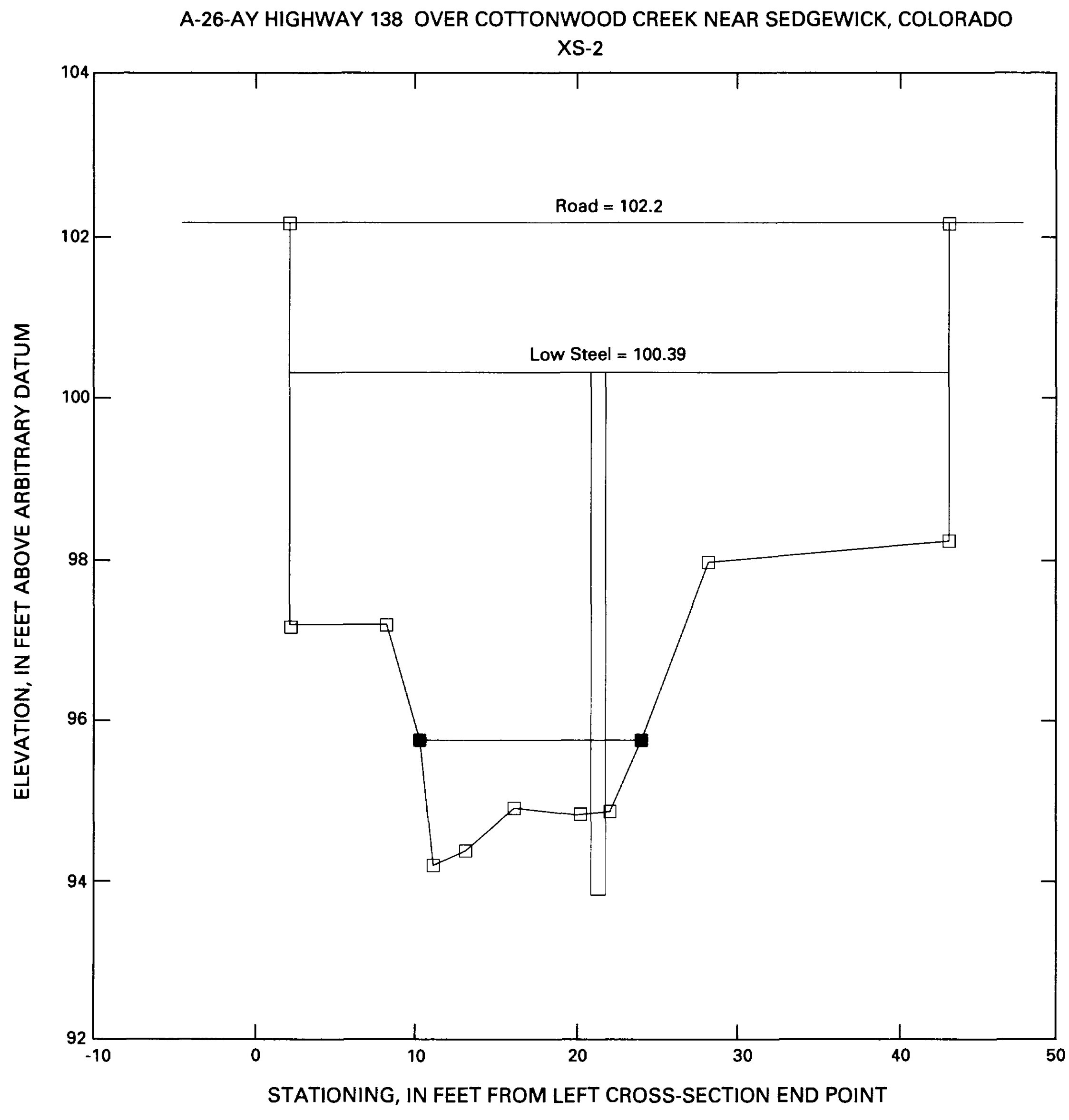



F. Plan View of the Site

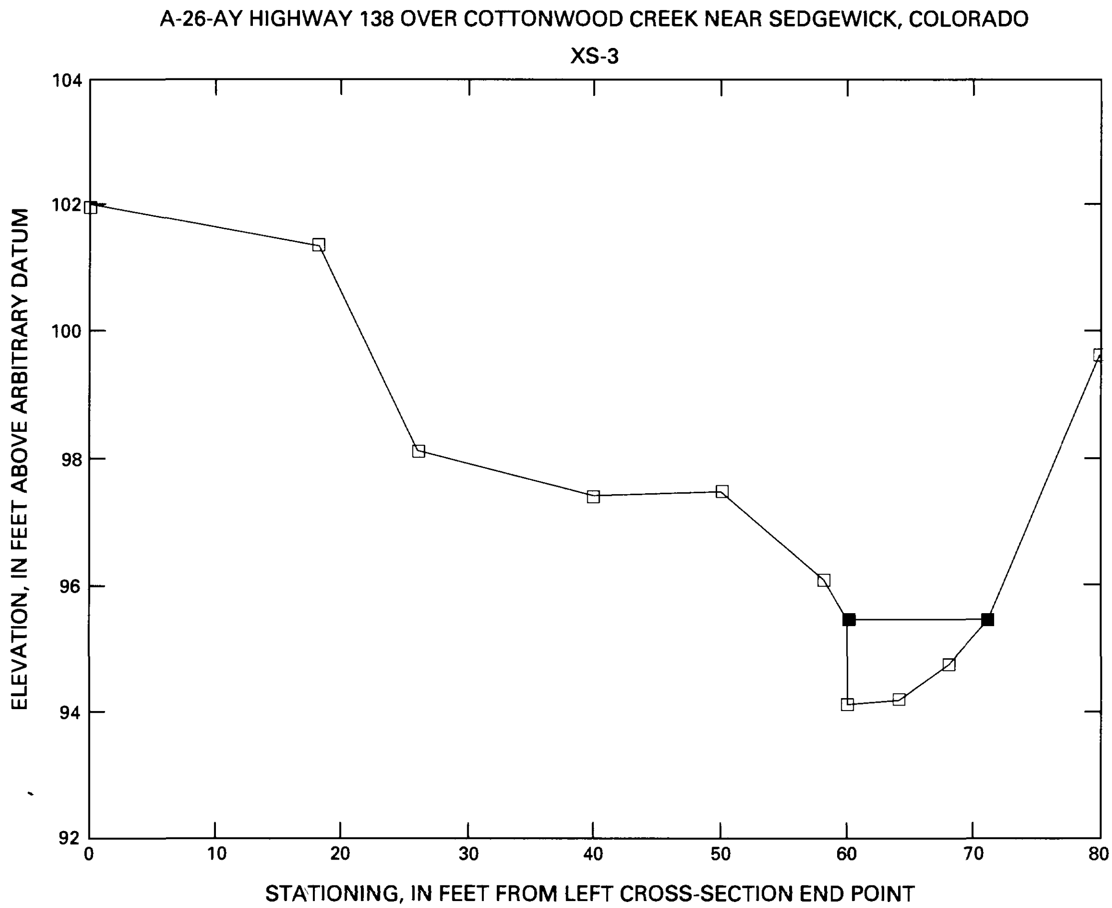
G. Cross-Section Plots of the Site



G. Cross-Section Plots of the Site--Continued



G. Cross-Section Plots of the Site--Continued



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