Channel-Pattern Adjustments and Geomorphic Characteristics of Elkhead Creek, Colorado, 1937–97

By John G. Elliott and Stevan Gyetvai

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot (ft)
kilograms per square meter (kg/m^2)	0.2048	pounds per square foot (lb/ft^2)
newtons per square meter (N/m^2)	0.02088	pounds per square foot (lb/ft^2)
foot (ft)	0.3048	meter (m)
mile	1.609	kilometers (km)
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometers (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
ton, short	0.9072	megagram (Mg)

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.

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Abstract

Onsite channel surveys and sediment measurements made in 1997, aerial photographs taken from 1937 through 1993, and streamflow-gaging-station record from 1954 to 1996 were used to determine the probable cause of accelerated streambed and streambank erosion in the lower reaches of Elkhead Creek, a perennial, meandering tributary of the Yampa River. Concern about the possible effects of Elkhead Reservoir, constructed in 1974, has been expressed by landowners living downstream. Evidence cited as an indication of reservoir-related effects include the trapping of bedload-transported sediment in the reservoir, vertical incision of the streambed, and lateral erosion causing loss of agricultural land. A large deltaic deposit composed of approximately 163 acre-ft of bedload-transported sediment formed in Elkhead Reservoir between 1974 and 1993, the contemporary bankfull stage of Elkhead Creek is several feet below the elevation of a broad terrace that previously was the flood plain, and lateral erosion at meander bends occurs at a higher rate than in previous periods at some locations.

Elkhead Creek meander migration rates were used as a measure of lateral instability in the study reaches. Meander migration rates based on changes in channel centerline position were calculated for three periods from five sets of rectified aerial photographs for reaches upstream and downstream from the reservoir. The creek upstream from Elkhead Reservoir was unaffected by impoundment and was used as the control reach. Mean meander migration rates in the downstream study reach were 1.2 ft/yr from 1938 to 1953, 2.5 ft/yr from 1954 to 1970, and 4.8 ft/yr from 1978 to 1993, compared to rates of 0.5 ft/yr, 1.6 ft/yr, and 6.6 ft/yr for the same periods in the upstream study reach.

Sediment and channel-geometry measurements and estimated hydraulic conditions at eight cross sections indicate that most of the sediment sizes represented in the streambed are mobile at frequently occurring streamflows; those streamflows are less than or equal to the bankfull discharge of approximately 1,800 to 2,200 cubic feet per second. Discharge data from 1954 through 1996 recorded at a site upstream from the reservoir were examined to determine the effect of hydrology on meander migration rates. The discharge data were assumed to be representative of the total streamflow and flood hydrology of both the upstream and downstream reaches because Elkhead Reservoir normally has a full pool. Mean annual streamflow increased 122 percent, and the mean annual flood increased 130 percent from the pre-regulation period (1954 to 1970) to the post-regulation period (1978 to 1993), a possible explanation for much of the increase observed in meander migration rate in both the upstream and downstream reaches in the period after reservoir construction.

Channel instability, quantified by meander migration rates, has increased throughout Elkhead Creek since 1977. The most probable cause is a combination of external factors affecting the

entire watershed, such as changes in annual runoff and flood magnitude and sedimentation in Elkhead Reservoir. Local land-use practices, such as intentional meander cutoff and riparian vegetation removal, also can decrease channel stability, but these factors were not addressed in this study.

INTRODUCTION

The lower portion of Elkhead Creek is a meandering tributary of the Yampa River in northwestern Colorado and flows through a relatively broad, alluvial valley that has been utilized for ranching since the 19th century. Recently, several landowners along Elkhead Creek have expressed concern over the extent and rate of streambank erosion and the loss of productive pasture acreage. Questions have arisen over the potential effects of Elkhead Reservoir, a 13,000-acre-ft impoundment located a short distance upstream from the eroding reaches, on sediment delivery and streamflow fluctuations and, consequently, on channel stability and streambank erosion. A proposal to enlarge the storage capacity of Elkhead Reservoir has been challenged on the basis of concern that downstream erosion rates could increase. Channel instability recently rendered the Smith Ditch irrigation diversion from Elkhead Creek nonfunctional and has compounded efforts to repair it.

Many natural and human factors affect the behavior of a meandering alluvial stream. The hydrology of Elkhead Creek is dominated by snowmelt and is complicated by the effects of reservoir impoundment and numerous irrigation diversions and returns. U.S. Geological Survey (USGS) topographic maps and aerial photographs suggest that channel-pattern shifts and meander-bend avulsions were common in the sinuous, lower 12 miles of Elkhead Creek before Elkhead Reservoir was constructed in 1974. Cattle grazing in the watershed may have affected sediment yield, riparian vegetation growth, and streambank morphology to an unknown extent. Consequently, the degree to which channel instability and bank erosion rates are influenced by Elkhead Reservoir, land-use practices, geology, sediment characteristics, climate variability, and hydrology has not been established. The USGS, in cooperation with the Colorado River Water Conservation District (CRWCD), evaluated these issues, which are important as they relate to the effectiveness of potentially costly erosion-mitigation activities and irrigation diversion repairs. Results of the evaluation also will further the understanding of channel-pattern adjustments and bank-erosion processes.

Purpose and Scope

This report will identify some likely causes of recent streambank erosion in lower Elkhead Creek and will provide information useful in guiding decisions about mitigation activities where appropriate. The following are specific objectives of the investigation:

1. determine the history of channel-pattern adjustments and the rate of meander-bend migration and cutoff before and since reservoir construction;
2. determine the contemporary depth of incision below the flood plain;
3. quantify the sediment characteristics of the streambed and the adjacent flood plain;
4. examine the relation between peak runoff and channel-pattern adjustments resulting in streambank erosion;
5. determine whether these channel adjustments are unique to the reach downstream from Elkhead Reservoir or are common to all meandering reaches of lower Elkhead Creek; and
6. estimate the accumulation of bedload-transported sediment in the Elkhead Reservoir deltaic deposit.

Acknowledgments

The study was made possible with the permission and cooperation of the many landowners and residents along Elkhead Creek. The authors are especially grateful to Jonathan Evans (USGS) for invaluable logistical support and assistance in the field and to Jennifer Sieverling (USGS) for assistance in preparation of aerial photographs for GIS analysis. R.E. Florida and Ed Neilson of the Natural Resources Conservation Service (NRCS) supplied some of the cross-section survey data. Additional field assistance was provided by Ray D. Tenney (CRWCD). Technical reviews of the report were provided by Janet S. Heiny and Paul J. Kinzel (USGS).

STUDY AREA

Geomorphic data were collected from two principal areas in the lower part of the Elkhead Creek watershed. A reach approximately 5 river miles long upstream from Elkhead Reservoir was selected to represent relatively unregulated conditions in the watershed and to identify trends in fluvial geomorphology unrelated to reservoir effects. A reach approximately 9 river miles long downstream from the reservoir was studied to identify any detectable reservoir effects. (A river mile is the in-channel distance measured along a river or stream course.)

Geographic Setting

Elkhead Creek is a large, perennial tributary of the Yampa River in northwestern Colorado (fig. 1). The Elkhead Creek watershed is located southwest of the Elkhead Mountains and has a drainage area of about 250 mi^2. Elevations range between 10,500 and 6,220 ft. The geology of the headwater areas includes the sedimentary Iles Formation, the Williams Fork Formation, and the Lewis Shale of Cretaceous age; the sedimentary Fort Union and Wasatch Formations of Tertiary age; and isolated Tertiary basaltic intrusives. The Elkhead Creek main stem and most of the principal tributaries flow over shales and sandstones of the

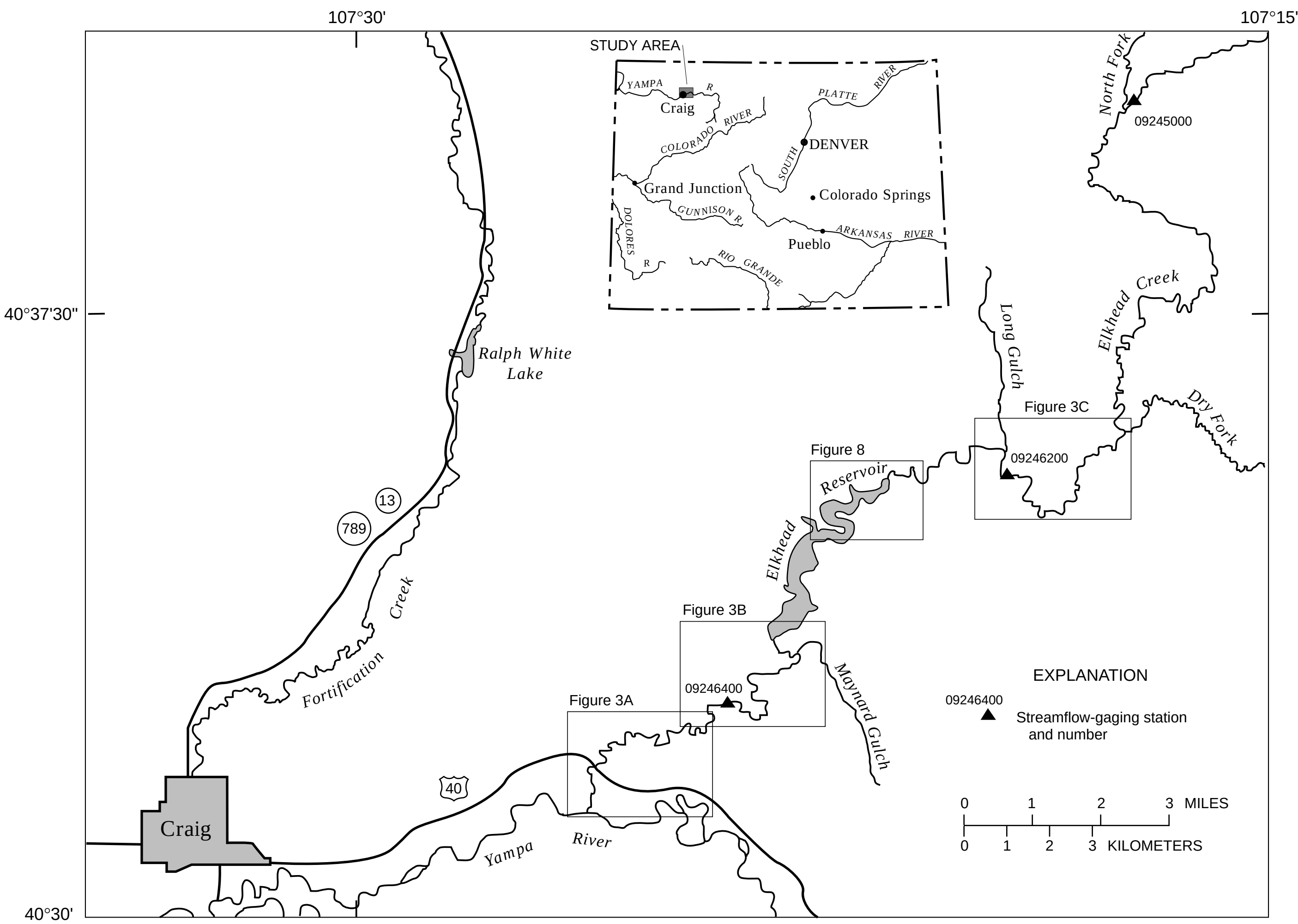


Figure 1. Map of Elkhead Creek showing study area, streamflow-gaging stations, and Elkhead Reservoir.

Upper Cretaceous Lance Formation (Tweto, 1976) and Holocene alluvium. The valley gradient in the lower 16 miles of the watershed ranges from 0.0045 to 0.0022 ft/ft.

Elkhead Creek is a meandering stream in the lower part of the watershed with sinuosity ranging from 1.1 to 2.2 and averaging 1.6. Oxbow ponds, meander scrolls, and arcuate groves of cottonwood trees in the valley of Elkhead Creek are evidence of previous meander development and channel-pattern adjustment typical of meandering stream systems. The streambed is composed predominantly of gravel and cobbles, and sand deposits cover some streambank and point-bar surfaces. Valley-fill material exposed in cutbanks is typical of fining-upward flood-plain sediment; gravel and sand strata are overlain by a thick, loamy deposit.

The valley floor and adjacent hillslopes in the lower watershed have been used for grazing and hay production since the late 19th century (Wes Signs, Colorado River Water Conservation District, oral commun., 1998). The existing riparian vegetation is dominated by cottonwood trees, willows, and other woody shrubs. Elkhead Reservoir was constructed in 1974 and has a normal pool capacity of 13,000 acre-ft. The reservoir is located 9 river miles upstream from the mouth of Elkhead Creek.

Hydrology

Elkhead Creek is a snowmelt-dominated stream with annual discharge peaks usually occurring from late April to late May. The USGS has operated six streamflow-gaging stations at various times on the main stem and on the North Fork, a large tributary of Elkhead Creek. Station 09245000 Elkhead Creek near Elkhead, in the middle part of the watershed, has the longest period of record (1953–96) and is used for hydrologic reference in this study. This gage, which was discontinued after water year 1996, recorded runoff from approximately 27 percent of the watershed.

Two new gaging stations were established in late 1995 to replace the discontinued station 09245000. Station 09246200 Elkhead Creek above Long Gulch is located approximately 10.6 river miles upstream from Elkhead Dam and records most of the inflow to the reservoir (fig. 1). Runoff from approximately 68 percent of the watershed passes the upstream gage at station 09246200. The second new gage, station 09246400 Elkhead Creek below Maynard Gulch, is located approximately 3.3 river miles downstream from the dam and 5.9 river miles upstream from the confluence with the Yampa River. The downstream gage at station 09246400 records runoff from approximately 85 percent of the watershed, which includes outflow from Elkhead Reservoir.

Annual peak discharges vary widely in magnitude and reflect the water content of the preceding winter snowpack and the spring weather patterns. Annual peak discharges recorded at station 09245000 have ranged from 224 ft^3/s in 1992 to 2,850 ft^3/s in 1984 (fig. 2); both extremes occurred subsequent to construction of Elkhead Reservoir in 1974. The mean annual peak discharge at this station was 1,028 ft^3/s. Annual streamflow, the total runoff from the watershed in a year, ranged from 12,010 acre-ft in 1977 to 82,380 acre-ft in 1984. The mean annual streamflow for 1954–96 was 40,200 acre-ft (Crowfoot and others, 1997).

CHANNEL-PATTERN ADJUSTMENTS AND GEOMORPHIC CHARACTERISTICS

A combination of data from the streamflow-gaging stations, aerial-photographic interpretation, and onsite measurements was used to quantify channel-pattern adjustments and describe geomorphic characteristics in two reaches of Elkhead Creek.

Streamflow

Peak flow frequency and the duration of daily mean discharges were calculated by standard USGS procedures (U.S. Interagency Advisory Committee on Water Data, 1982) with the record from station 09245000 Elkhead Creek near Elkhead (fig. 1). The 100-year flood at this location of the watershed was 2,580 ft^3/s and the 10-year flood was about 1,700 ft^3/s (table 1). Based on discharge record analysis, observations made during high streamflow in 1998, and commonly accepted statistical properties for the bankfull discharge, 950 ft^3/s (the 2-year flood) was identified as a reasonable approximation of the bankfull discharge in Elkhead Creek at station 09245000. This discharge, as an instantaneous annual flood peak, was equaled or exceeded in 25 of the 44 years of record

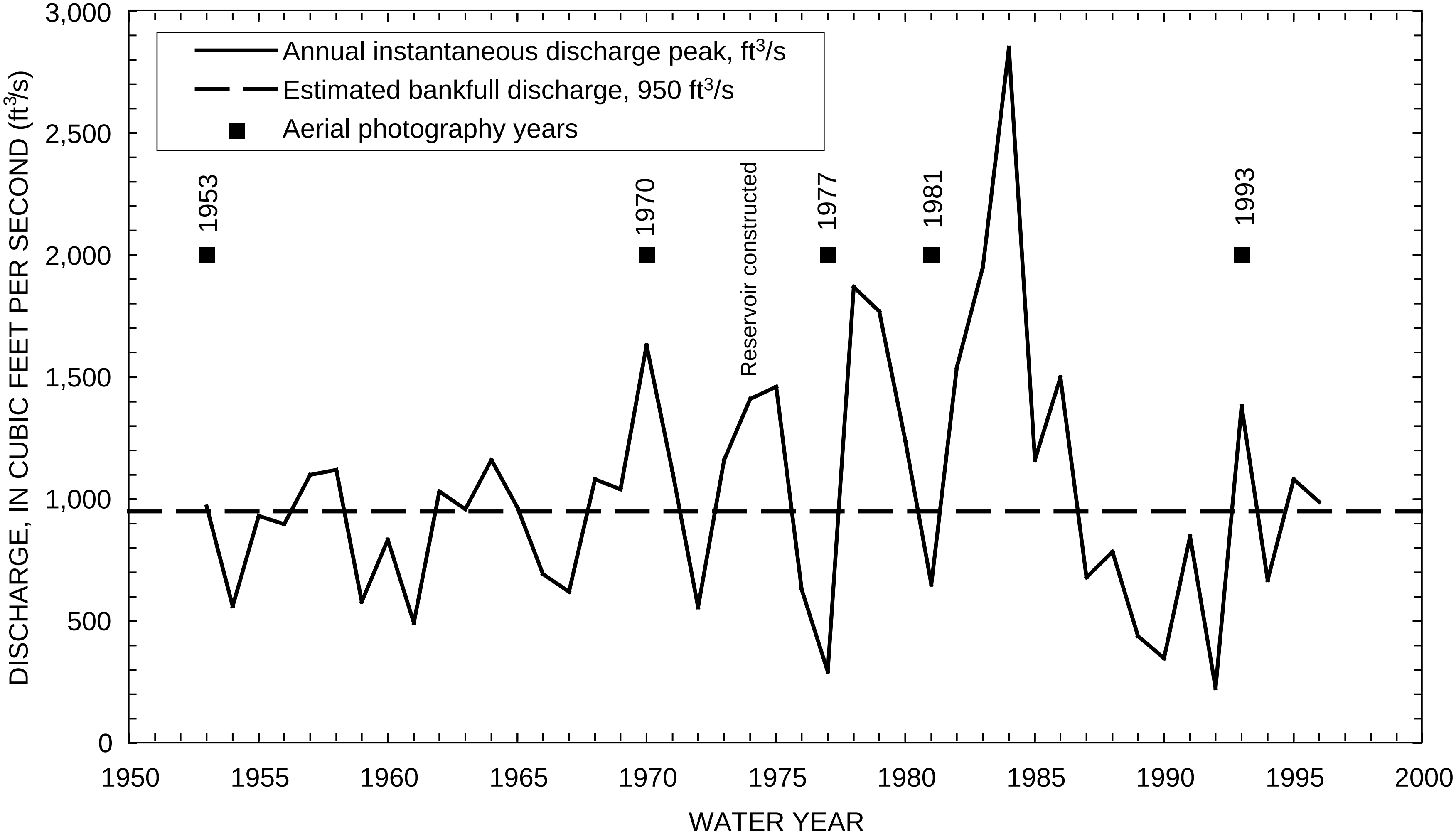


Figure 2. Annual peak discharges and estimated bankfull discharge from streamflow-gaging station 09245000 Elkhead Creek near Elkhead, 1953–96.

Table 1. Streamflow characteristics at streamflow-gaging station 09245000 Elkhead Creek near Elkhead, Colorado, 1954 through 1996

[Recurrence interval in years equals reciprocal of exceedance probability; streamflow duration, in percentage of time specific discharge is equaled or exceeded; ft^3/s, cubic foot per second]

Peak flow frequency		Streamflow duration	
Recurrence interval	Discharge	Percentage of time equaled or exceeded	Discharge (ft^3/s)
1.05	403	95	1.20
1.11	493	90	2.30
1.25	623	85	2.30
2.00	950	80	3.31
5.00	1,402	75	3.71
10.0	1,697	70	4.20
25.0	2,060	65	4.59
50.0	2,324	60	4.98
100	2,580	55	6.00
200	2,832	50	6.94
500	3,160	45	7.92
		40	9.06
		35	11.4
		30	14.2
		25	21.1
		20	37.8
		15	83.3
		10	175
		5	342

(fig. 2). As a daily mean discharge, 950 ft^3/s was equaled or exceeded approximately 0.73 percent of the time on average, or about 3 days per year.

Peak flow frequency and flow duration statistics have not been calculated for the two new gaging stations on Elkhead Creek—09246200 upstream from the reservoir and 09246400 downstream from the reservoir—because of inadequate record lengths. However, an approximate correlation was made between streamflow at the long-term gaging station (09245000) and streamflow at the two new gaging stations based on 1 year of concurrent record. Daily mean discharges during April through September were regressed for the one concurrent year (1996). No traveltime lag was used in the regression, but the time difference between diurnal peaks at the long-term gage and the new gage above Long Gulch was approximately 2–4 hours. The linear regression between data from the long-term gage several miles upstream (09245000) and the new gage above Long Gulch (09246200) resulted in a coefficient of determination (R^2) of 0.92.

The time difference between diurnal peaks at the long-term gage and the new gage below Maynard Gulch (09246400) was approximately 9–12 hours. The regression between data from the long-term gage and the new gage below Maynard Gulch resulted in a coefficient of determination (R^2) of 0.87. A weaker correlation between these station records resulted when data from the entire year were used in the regression analysis. Small, low-elevation tributaries introducing runoff to Elkhead Creek between the long-term gage and the new gages before the annual spring peak may have contributed to the weaker correlation at low discharges.

Some of the effects of Elkhead Reservoir on the hydrology of Elkhead Creek can be seen in the brief streamflow record at the two new gaging stations. Elkhead Reservoir is approximately 3.8 miles long and has a normal pool capacity of 13,000 acre-ft. The reservoir is operated in such a way that it is normally full or nearly full. Spring snowmelt runoff generally flows into and through the reservoir with a short residence time. Station-to-station linear regression between daily mean discharges recorded in April through September 1996 at the gage on Elkhead Creek above Long Gulch (09246200) and the gage below Maynard Gulch (09246400) resulted in an R^2 of 0.98. Although there is a very strong correlation between the stations in daily mean discharge (the streamflow averaged over a 24-hour period), there are notable differences in the diurnal range and volume of streamflow.

Instantaneous diurnal discharge peaks recorded at the Maynard Gulch gage downstream from the reservoir lag the peaks at the Long Gulch gage upstream from the reservoir by about 7 hours. The diurnal range in discharge and the instantaneous daily discharge peaks tend to be less at the downstream Maynard Gulch gage than at the upstream Long Gulch gage; however the daily mean discharge, adjusted for traveltime, tends to be greater at the Maynard Gulch gage downstream from the reservoir. The attenuation of diurnal peaks recorded at the Maynard Gulch gage probably is due to streamflow passing through Elkhead Reservoir. The greater daily mean discharges recorded at the downstream Maynard Gulch gage probably are due to additional runoff contributed by tributaries entering between the two gages. The drainage area of Elkhead Creek increases by 24 percent from the Long Gulch gage to the Maynard Gulch gage, an increase representing 17 percent of the total Elkhead Creek watershed measured at the mouth.

Aerial Photography

Aerial photographs of the Elkhead Creek watershed spanning several years reveal the channel condition and position at discrete times. Year-to-year comparisons of the channel position in photographs rectified to remove optical distortion allows quantification of channel change during the periods between the photograph dates. Meander scrolls, oxbow lakes, and other landforms visible in these photographs also provide a means to interpret geomorphic conditions from a period before the first photographs were taken. Gurnell (1997) described a method for quantifying temporal and spatial river channel changes using aerial photography, onsite cross-section surveys, and a geographical information system (GIS).

Aerial photographs (fig. 3) were used to determine the channel position in 6 specific years and were the basis for calculating meander migration rates and deltaic sedimentation rates. Photographs selected for the Elkhead Creek geomorphic analysis were taken in 1937, 1953, 1970, 1977, 1981, and 1993. Most of the photographs were taken in August or September when seasonal streamflow had receded to low levels. Photographs taken in 1953 and 1970 bracket a period of relatively small flood peaks when only about one-half of the annual flood peaks exceeded the estimated bankfull discharge (fig. 2). Photographs taken in 1977 and 1993 bracket a comparable length of time in which annual flood peaks exceeded the estimated bankfull discharge about the same number of times as in the 1953 through 1970 time period, but with much greater magnitude. The photographs taken in 1977 and thereafter also document the period since construction of Elkhead Reservoir in 1974.

The Elkhead Creek aerial photographs were enlarged to 18 × 18-inch prints having scales of approximately 1:6,000. The enlarged photographs were digitally scanned, and these images were electronically processed to remove optical distortion and photographic parallax common to many aerial photographs. Digital orthophoto quadrangle (DOQ) maps of areas in the Elkhead Creek watershed were created in 1997 by the USGS from 1993 National Aerial Photography Program (NAPP) high-altitude aerial photographs. A DOQ map is a photographic image in which all points have been made planimetric and have been rectified to a standard map-projection coordinate system (latitude/longitude, Universal Transverse Mercator, and so forth). The 1937, 1953, 1970, 1977, and 1981 aerial photographs were registered and rectified to the 1997 DOQ images before geomorphic measurements and analysis were conducted. Digital image processing and geometric correction are described in greater detail by Jensen (1996).

Digital image processing, rectification, and registration to the 1997 DOQ maps were done with ArcView Spatial Analyst software (Environmental Systems Research Institute, 1996). Several semipermanent features such as buildings, road intersections, and trees, visible in all photographs and in the DOQ, were used as rectification control points. These points were at elevations similar to the stream elevation, thereby reducing the potential for rectification error caused by relief displacement (Gurnell, 1997). The original aerial photographs were rectified to the scale and coordinates of the DOQ image with second-order polynomial affine transformation functions fitted to the control points using a least-squares criterion (Jensen, 1996, p.127). Initially, the fit between the rectified image and the DOQ standard was evaluated qualitatively by observing the degree of registration of the control points and other semipermanent geographic features, such as roads and fence lines, on an overlay of the rectified image and the DOQ. In addition, the fit was evaluated quantitatively with root-mean-square error (RMSE) and chi-squared (χ^2) statistics calculated by the ArcView Spatial Analyst extension. The RMSE is an estimate of the standard deviation of the dependent variable, in this case the plotting position of the control points in the rectified image. The RMSE describes the deviation between the control-point locations on the rectified photograph and the control-point coordinates calculated by the transformation function. The χ^2 statistic is a measure of the association between two distributions and, in this analysis, is strongly correlated with RMSE.

The initial photograph-rectification step produced a reasonably good fit to the DOQ, but for some photographs the fit could be improved by eliminating one or more specific control points with large individual RMSE and χ^2. Selected control points were removed iteratively, and the unrectified image was rectified again until the stepwise decrease in total RMSE and χ^2 variables became negligible. Table 2

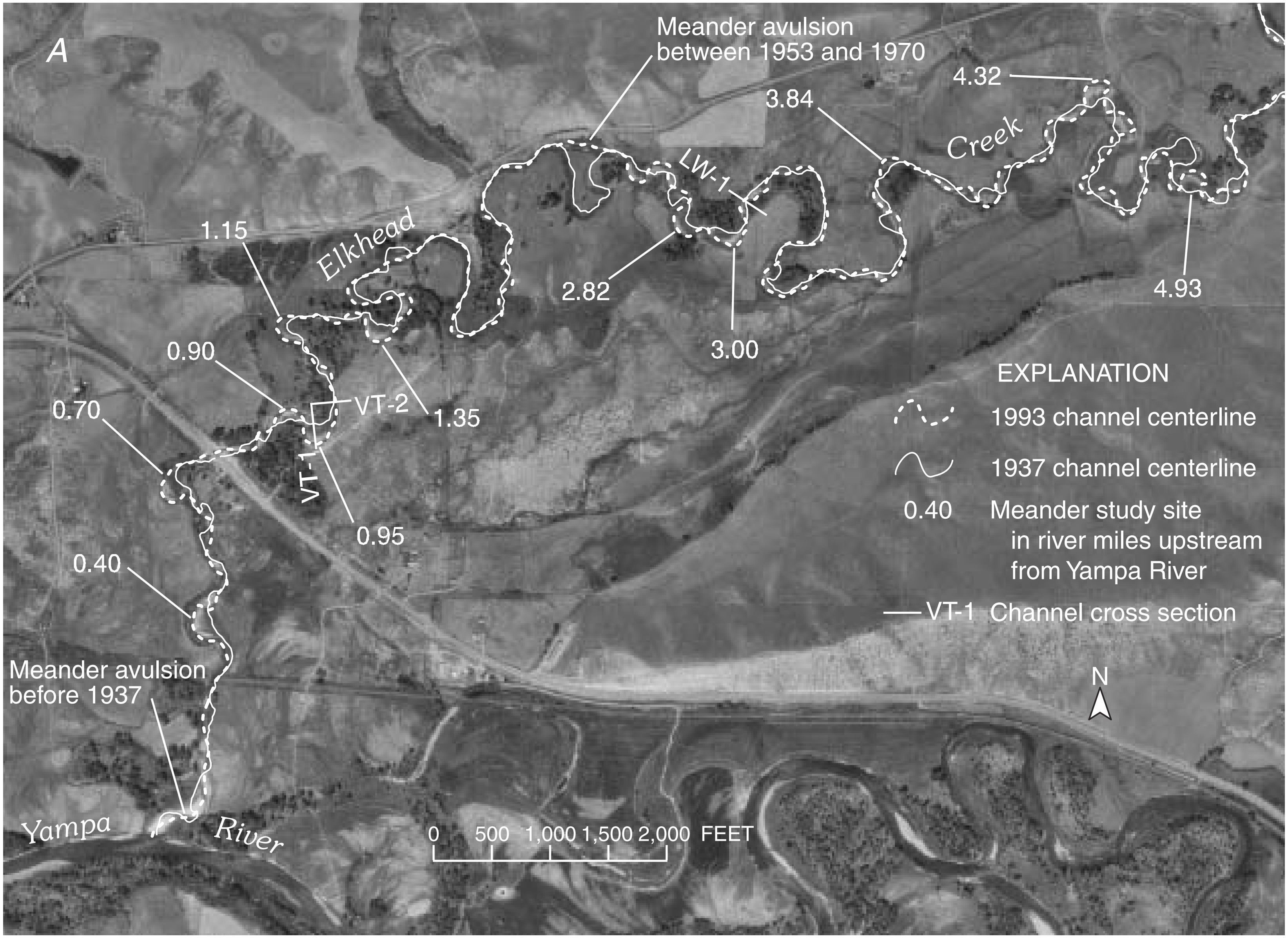
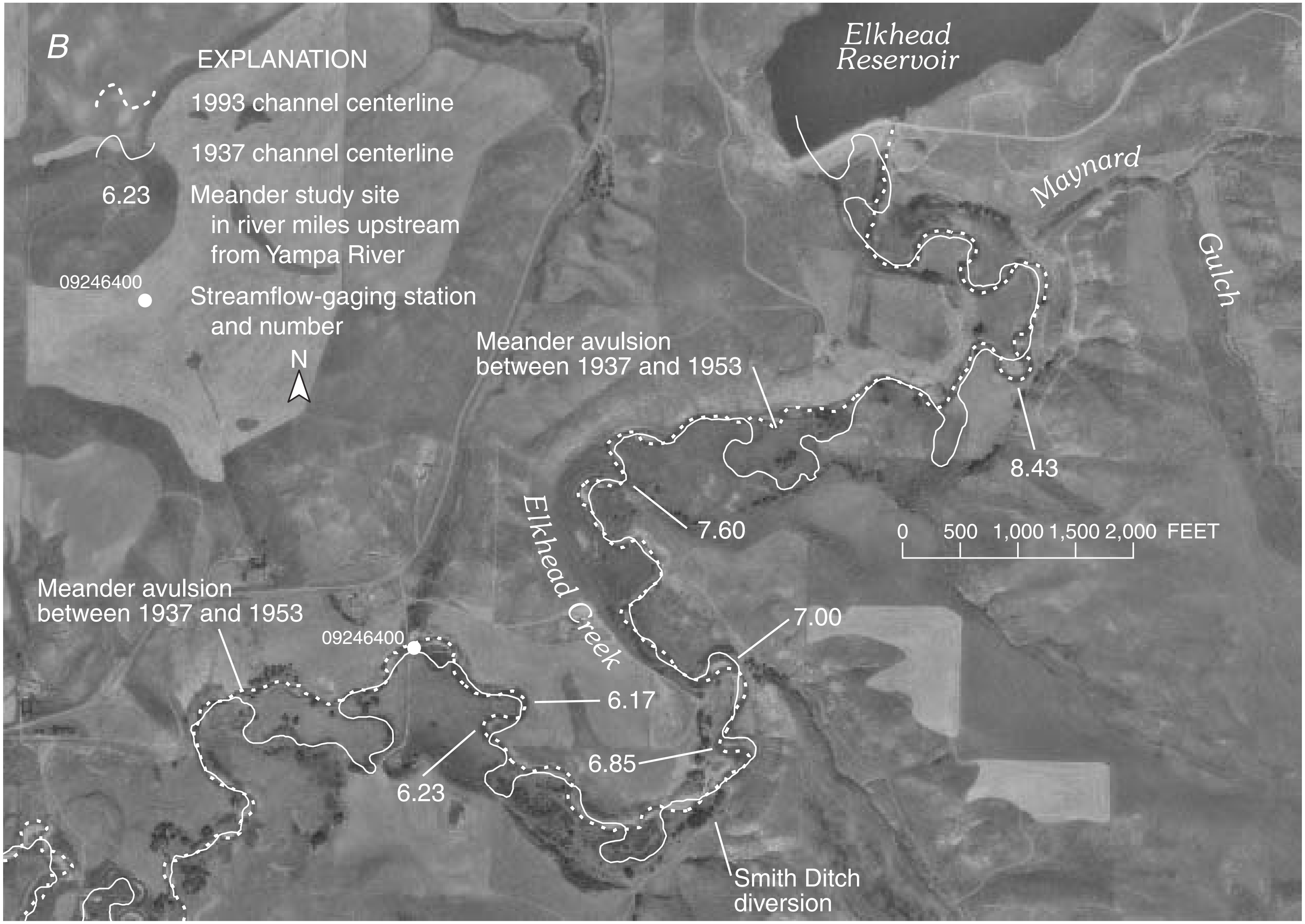


Figure 3. Digital orthophoto quadrangle of Elkhead Creek showing channel positions in 1937 and 1993, meander study sites, and cross-section locations, (*A*) reach upstream from confluence with the Yampa River, (*B*) reach immediately downstream from Elkhead Reservoir, (*C*) reach upstream from Elkhead Reservoir.



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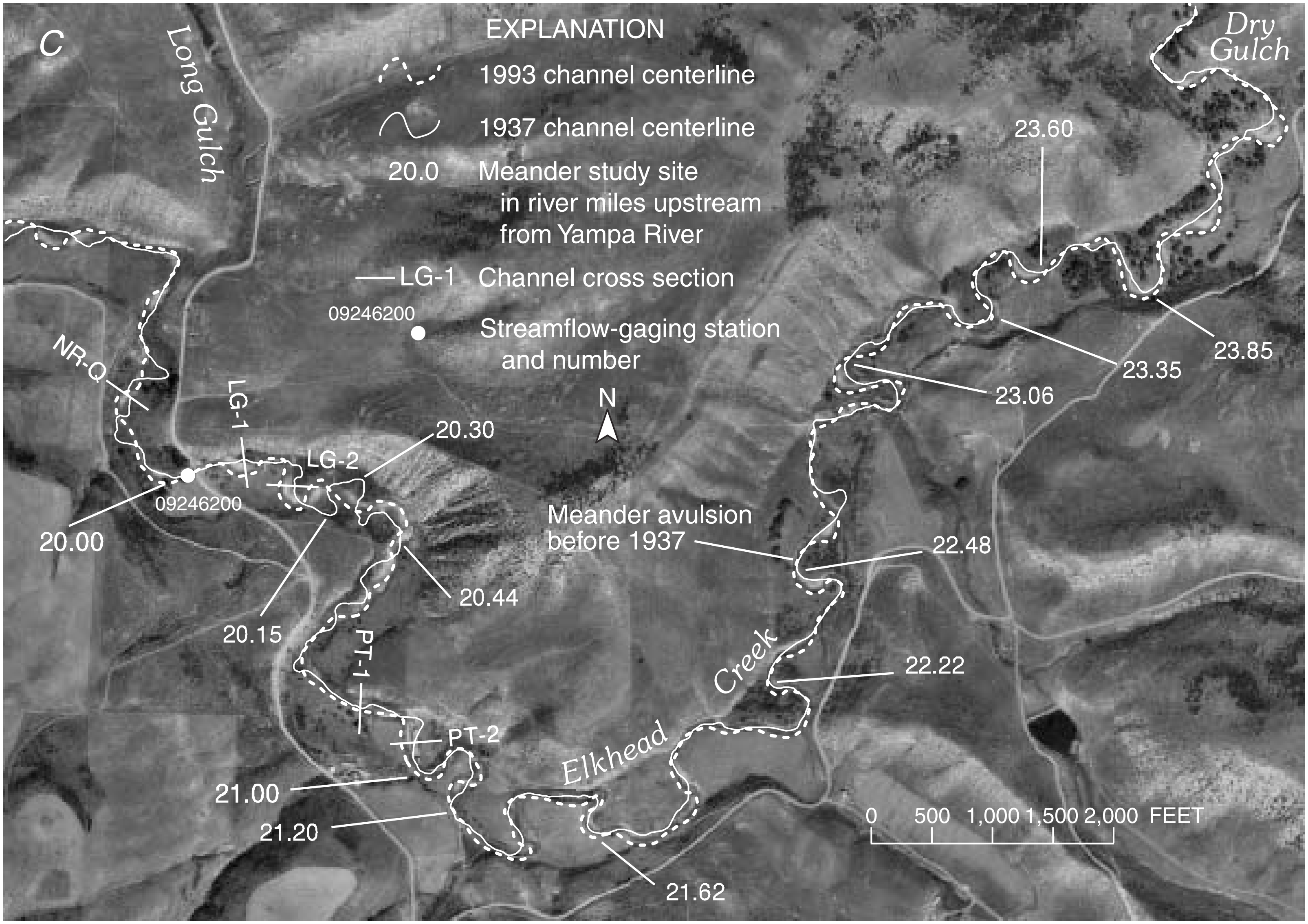

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presents summary statistics from the photograph-rectification procedure.

Use of from 7 to 14 control points near to, and at elevations similar to, the stream, and use of second-order polynomial rectification functions produced reasonably good fits of the rectified photographs to the DOQ (table 2). The range of RMSE (0.360 to 2.613 m) is within the error range noted by Gurnell (1997). Consequently, there was a high degree of confidence that the apparent channel-position change observed during the five photograph-defined periods represented a true change on the land surface. After rectification, channel locations from all 6 years were digitized and plotted on a single map. Changes in the stream channel position were measured with the ArcView Spatial Analyst extension (Environmental Systems Research Institute, Inc., 1996).

Planimetric Geomorphology

Planimetric geomorphic characteristics of Elkhead Creek were determined using 1971 topographic maps and six sets of aerial photographs spanning several decades. Stream-channel and valley gradients over distances of several miles were calculated from USGS 1:24,000-scale quadrangle maps with 20- and 40-ft topographic contours. Valley gradient, calculated with this resolution, was relatively uniform and ranged from 0.0022 to 0.0045 ft/ft. Stream-channel gradient ranged from 0.0010 to 0.0028 ft/ft.

Table 2. Statistics from the digital processing and rectification of aerial photographs to the 1997 digital orthophoto quadrangles

[Photographic images rectified with second-order polynomial affine transformation function; Upper reach, upstream from Elkhead Reservoir; Dam reach, immediately downstream from Elkhead Dam; Lower reach, upstream from confluence with Yampa River; Root mean square error, deviation between control point location on the rectified photograph and the control-point coordinates calculated by the transformation function, calculated for the Easting (x) and Northing (y) directions]

Photograph date and reach	Number of control points	Root mean square error, Easting (meters)	Root mean square error, Northing (meters)	Chi square, Easting	Chi square, Northing
1937 Upper reach	9	1.149	0.519	11.877	2.424
1937 Dam reach	10	0.745	1.579	5.546	34.923
1937 Lower reach	7	1.161	2.613	9.443	47.777
1953 Upper reach	10	2.346	1.759	55.015	30.955
1953 Dam reach	9	1.313	1.148	15.527	11.835
1953 Lower reach	9	0.722	0.811	4.693	5.923
1970 Upper reach	8	0.525	0.559	2.208	2.501
1970 Dam reach	9	0.746	1.833	5.005	30.240
1970 Lower reach	6	0.745	1.578	5.546	24.923
1977 Upper reach	10	1.440	1.809	20.748	32.708
1977 Dam reach	10	0.523	0.808	2.735	6.530
1977 Lower reach	14	1.854	1.616	48.126	56.571
1981 Upper reach	10	0.360	1.097	1.274	12.833
1981 Dam reach	9	1.131	1.109	11.521	11.074
1981 Lower reach	12	0.909	2.025	9.016	49.215

Sinuosity, a descriptor of channel pattern defined as the downstream in-channel distance divided by the down-valley linear distance, is spatially and temporally variable and is influenced by valley gradient, streamflow magnitude, sediment load, and the mechanics of meander development (Schumm, 1977; Schumm and Khan, 1972). Elkhead Creek sinuosity, calculated from the 1971 topographic maps, ranged from 1.08 to 2.57 and averaged 1.57 between Dry Gulch and the confluence with the Yampa River. A stream reach may have a constant average sinuosity, yet within the reach the channel position may change substantially (for example, a meander cutoff in one bend may be offset by meander amplitude increase in another nearby bend).

Channel migration rates are strongly controlled by the unit stream power (essentially a function of discharge and channel gradient), bank erosion resistance (a function of sediment size, cohesiveness, stratigraphic relations, and vegetation characteristics), bank height, meander-bend radius of curvature, channel width, and sediment transport (Hickin and Nanson, 1984). Hickin and Nanson found that the maximum channel migration rates occur where the ratio of meander radius of curvature to channel width, r/w, is between about 2.0 and 3.0 in gravel-bed rivers in western Canada. In straighter reaches (r/w greater than about 3.0), channel migration usually is very slow. In reaches with tight bends (r/w less than about 2.0), channel migration rates decrease because flow breaks down into large eddies that markedly increase flow resistance (Hickin, 1974). Flow resistance in a meander bend can be minimized as the channel gradually changes its cross-section form or bend radius of curvature through bank erosion, or by abruptly changing its position through a meander cutoff, or avulsion. Either process involves erosion and remobilization of sediment that may be a valuable resource, such as a pasture, hay meadow, road, or building site.

Channel adjustments from 1938 through 1993 were studied in individual meander bends to assess trends in erosion rates along Elkhead Creek. Meander migration was measured along the erosional axis of the meander, generally at the apex of the meander, or where the meander bend radius of curvature, r, was a minimum. This is the location where the channel migration rate usually is greatest (Hickin and Nanson, 1984) and, although greater than the overall channel migration rate through the entire valley, it is where increases or decreases in channel migration rates are easiest to detect. Ranchers, landowners, and resource managers are sensitive to losses of productive land and observe the greatest change at these meander locations.

Meander bends included in this study were selected to be representative of other meanders in the valley. Seventeen meanders were selected in the reach downstream from Elkhead Dam (figs. 3*A* and 3*B*), and 13 meanders were selected in the reach upstream from the backwater effects of Elkhead Reservoir (fig. 3*C*). The upstream reach was considered the control reach, unaffected by Elkhead Reservoir (completed in 1974). Meanders selected for study generally were free to migrate through the Elkhead Creek flood plain; however, some meander bends impinged against adjacent valley side slopes from time to time. Valley side-slope impingement usually resulted in a directional change in meander migration, which is typical of meanders throughout the upper reach and in the lower reach immediately downstream from Elkhead Dam where the valley side slopes are closely spaced. The study excluded meanders that had been significantly affected by human activity, such as those fixed in position by bridge works or those meanders intentionally cut off by mechanical means.

Elkhead Creek meander migration rates were calculated using a variation of the method developed by Hickin (1974) and Hickin and Nanson (1984). Hickin (1974) calculated meander migration rates along erosion pathlines, or orthogonals, connecting the point of minimum radius of curvature of time-sequential meander bend locations. The erosional axis of the meander was the orthogonal reflecting the greatest lateral migration rate of the meander on the flood plain. Hickin's (1974) technique was developed using aerial photographs of western Canadian meander bends that had pronounced ridge-and-swale topography accentuated by riparian vegetation. The ridge-and-swale features were formed by the stream as the meander bend migrated laterally, forming a point-bar complex. Meander bend location and morphology from several periods before the photograph date were well preserved in the ridge-and-swale topography visible in Hickin's photographs. As a result, the orthogonals Hickin plotted generally reflected a continuous progression of meander development through time.

The Elkhead Creek meanders occur in a region where riparian vegetation and land-use practices do not accentuate the meander ridge-and-swale topography preserved in point-bar complexes. Consequently, only the active channel position visible in the photograph was used in the Elkhead Creek analysis. Because some of the Elkhead Creek photographs are separated by as much as 16 or 17 years of time, the channel position changes quantified for this analysis reflect average rates for the time interval. The channel center line, rather than the eroding concave bank, was digitized from each rectified aerial photograph. The center line was more easily visible and more objectively determined from the Elkhead Creek photographs than was the concave bank. Also, reversals in channel position (negative migration rates) were easier to detect in the channel center line than along the concave bank. The error in locating the channel center line partly is a function of the aerial photograph-rectification precision (table 2) and the resolution of fluvial features in the photograph. The latter error probably is less than one-half the width of the low-discharge water surface, which ranged from 31 to 50 ft when channel surveys were made in 1997.

Meander bends develop and migrate in different directions and modes. Hickin (1974) noted that cross-valley erosion dominated in early meander development when bends had a low amplitude and large radius of curvature, whereas down-valley erosion dominated in older, higher amplitude meanders. Elkhead Creek meanders included in this study were fully developed meander bends in the 1937 and subsequent photographs. Two predominant meander migration modes were observed in the study areas—amplitude increase and translational shift. Amplitude increase involved lateral migration, usually normal to the down-valley direction, near the point of minimum radius of curvature, and was the most common migration mode observed in Elkhead Creek. The meander amplitude increased, more or less, along an orthogonal that bisected the point bar and was typical of the migration of the Canadian meanders studied by Hickin (1974) (fig. 4). When amplitude increase dominated, the meander-bend limbs upstream and downstream from the point of minimum radius of curvature, or the apex, usually did not change position significantly. Translational shift involved an abrupt change in migration direction at the meander-bend apex, generally changing from cross valley to down valley. Upstream and/or downstream limbs migrated laterally along with the location of minimum radius of curvature when the meander bend underwent a translational shift (fig. 4).

Meander migration rates were determined for five time periods defined by aerial photographs taken in 1937, 1953, 1970, 1977, 1981 and 1993. The aerial photographs were rectified to the 1997 DOQ, which was created from the 1993 photograph (fig. 3). The rectification procedure is described in the preceding section. The periods 1938 through 1953 and 1954 through 1970 are representative of the period before regulation by Elkhead Reservoir. The periods 1978 through 1981 and 1982 through 1993 are representative of the regulated period (downstream from the dam). The period 1971 through 1977 encompasses the construction (1974) and filling of Elkhead Reservoir.

Meander migration rates were calculated for 17 meanders in the reach downstream from Elkhead Dam and for 13 meanders upstream from Elkhead Reservoir (table 3). The migration mode for most of these meanders in all time periods was amplitude increase, although translational shift occurred in a few meanders in one or more periods. None of the meanders included in the migration-rate calculations underwent avulsion. Negative meander migration rates were recorded in some time periods when the channel reversed its lateral movement. An assumption was made that, by assigning negative values to position reversals, the net migration rate was a better reflection of the overall, long-term disruption of the alluvial valley floor. For example, a meander that progressively increased in amplitude by eroding the concave bank would have a significantly greater detrimental effect on nearby land use than would a meander that initially increased in amplitude but subsequently decreased in amplitude (through position reversal) by eroding recently deposited point-bar sediment on the (inner) convex bank rather than undisturbed valley-fill material on the (outer) concave bank.

Meander-bend avulsions, or cutoffs, are another natural mechanism of channel adjustment. An avulsion shortens the distance between two points on a meandering stream, and the immediate effect is to increase the local stream gradient, stream power, and boundary shear stresses that in turn tend to promote additional bed and bank scour. Over time, some of these local effects are mitigated by additional adjustments upstream and downstream from the avulsion in gradient, sinuosity, channel cross section, and roughness. Human-induced, mechanical cutoffs produce similar channel and pattern adjustments over time, although the specific effects may be unpredictable.

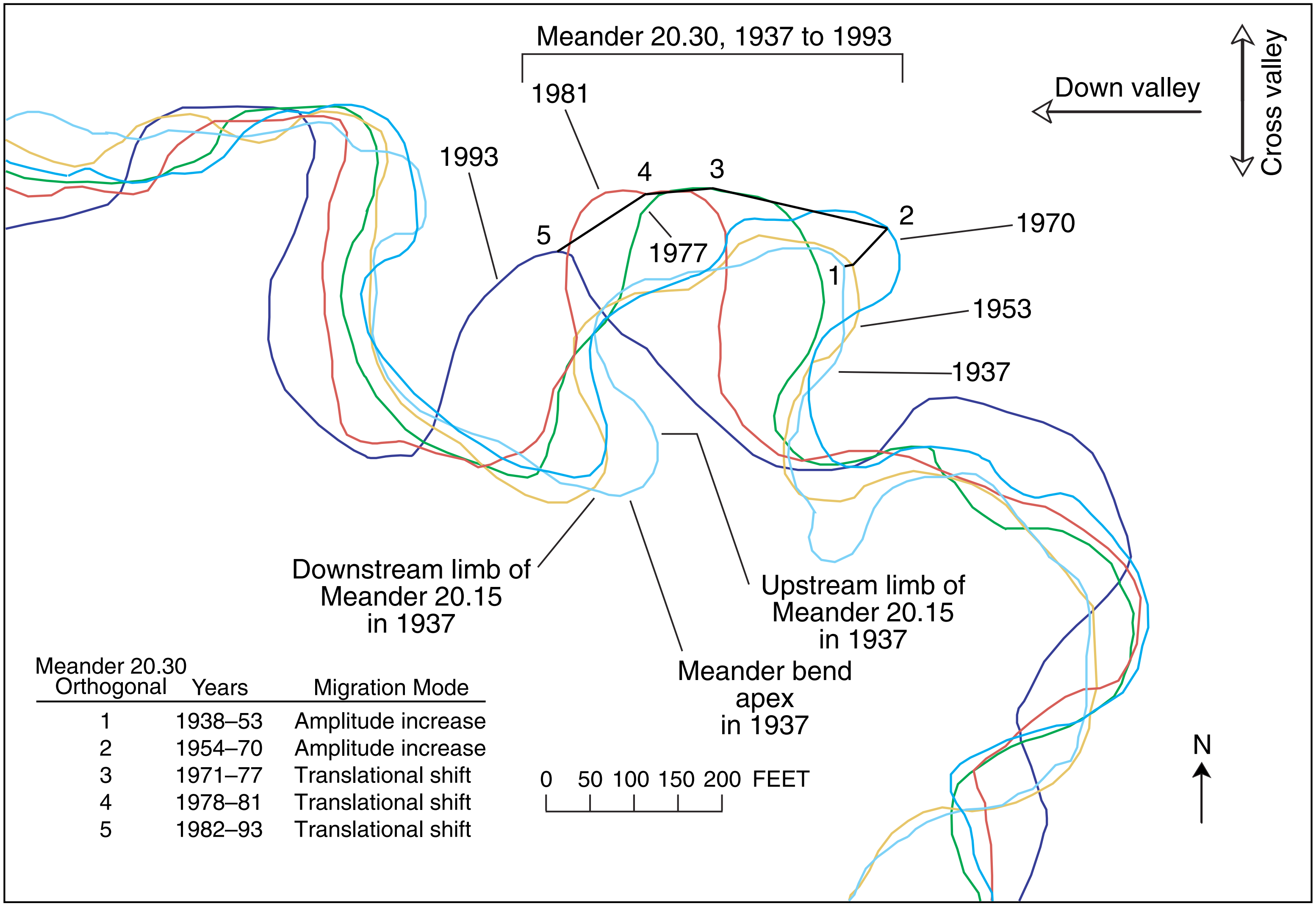


Figure 4. Channel centerline of Elkhead Creek meander 20.30 in 1937, 1953, 1970, 1977, 1981, and 1993 showing amplitude increase during the period 1938 through 1970 and translational shift during the period 1971 through 1993.

Several meander avulsions occurred in Elkhead Creek during the periods defined by the aerial photographs (figs. 3*A* and 3*B*), and two avulsions were observed that occurred since 1993. The remnants of several avulsions that occurred before 1937 also could be seen on terraces and the flood plain (figs. 3*A* and 3*C*). Some avulsions were human induced (Donald Van Tassel, local resident, oral commun., 1997); others probably were the result of progressive channel adjustments. The avulsion rate in the reach downstream from Elkhead Reservoir was 4.6 avulsions per valley mile per century for the 1938 through 1970 period and 2.1 avulsions per valley mile per century for the 1971 through 1997 period. By comparison, the avulsion rate in the reach upstream from Elkhead Reservoir was 2.0 avulsions per valley mile per century for the 1938 through 1970 period and 1.4 avulsions per valley mile per century for the 1971 through 1997 period. Meander avulsion rate is not an accurate indicator of channel-pattern instability for Elkhead Creek because of the intentional cutoff of some meanders. However, because adjustments to either natural or human-induced avulsions tend to propagate to nearby channel segments, a higher incidence of avulsion may correlate with a higher rate of channel migration, bank erosion, or sedimentation in nearby reaches.

Cross-Sectional Geomorphology

Channel-geometry characteristics and the water-surface slope of Elkhead Creek were surveyed at eight cross sections using a total-station laser theodolite in 1997 (fig. 5). Characteristics of sediment in the channel and the stratigraphy of the valley-fill material were determined from onsite inspection during the surveys. Cross sections selected were representative of the channel morphology upstream and downstream from Elkhead Reservoir. All sections except VT-1 were located in relatively straight reaches; cross section VT-1 was located in a meander bend. The surveys allowed determination of bankfull width and depth, the depth of incision below the valley floor or terrace surfaces, and the elevation of alternate bars and point bars. Water-surface slope and cross-sectional characteristics were used to estimate boundary shear stress for selected streamflows.

Bankfull discharge at the new gaging station above Long Gulch (09246200) was estimated to be approximately 1,800 ft^3/s, based on surveyed channel characteristics at cross sections PT-1 (fig. 5*B*) and LG-1 (fig. 5*D*), the 1997 high water marks (peak discharge 2,760 ft^3/s), and water-surface observations in the spring of 1998. This bankfull discharge estimate is applicable to all of the surveyed cross sections in the study reach upstream from Elkhead Reservoir (figs. 5*A*–5*E*). Based on the limited streamflow record at the new gage below Maynard Gulch (09246400), the correlation between streamflow at the Long Gulch and Maynard Gulch gages (described in a previous section) and channel surveys, the estimated bankfull discharge is between 1,800 and 2,200 ft^3/s in the downstream reach. Bankfull width of the eight surveyed cross sections ranged between 67 and 122 ft and averaged 88 ft. The surveys were conducted at low flow, approximately 17 ft^3/s, and the average water-surface width was 41 ft. The bankfull width to depth (W/D) ratio ranged from 12 to 24 and averaged 16.5. Bankfull water-surface slope ranged from 0.0012 to 0.0039 and averaged 0.0023.

Anecdotal evidence from local landowners and residents suggests the channel of Elkhead Creek may have incised in recent decades both upstream and downstream from Elkhead Reservoir (Donald Van Tassel and Leroy Lawton, local residents, oral commun., 1997). A broad terrace surface forms the valley floor along Elkhead Creek in the study reaches. This terrace surface is used for grazing and hay production throughout the valley. If this terrace surface is used as a very crude vertical reference to a former flood-plain surface, an estimation of subsequent vertical incision can be made. The contemporary bankfull surface ranges from 2.5 to 3.8 ft below the terrace surface at cross sections upstream from Elkhead Reservoir (figs. 5*A*–5*E*) and 2.9 to 6.2 ft below the terrace at cross sections downstream from the reservoir (figs. 5*F*–5*H*). Buried, intact tree trunks and dense root masses were observed in the valley-fill material exposed by the cutbank at cross section LW-1 (fig. 5*F*), indicating vertical aggradation of a former flood-plain surface in this reach and subsequent incision to a lower elevation, possibly within the last century. No ages were obtained for the contemporary valley-floor terrace surface or the buried surface on which these trees were rooted; however, one of the partially buried cottonwood trees (*Populus deltoides*) was still living in 1997.

Stratigraphy of the uppermost valley-fill material was recorded from cutbank exposures onsite and is summarized in the cross sections in figure 5. The

Table 3. Elkhead Creek meander migration rates for time intervals determined from aerial photographs

[River mile, channel distance upstream from Yampa River; Orthogonal distance, meander displacement between points of minimum meander bend radius of curvature; T, meander migration mode by translational shift, otherwise by amplitude increase; feet/year, feet per year; MA, mean annual; acre-ft/yr, acre-foot per year; ft^3/s, cubic foot per second; nr, no record]

River mile	1938–53 Orthogonal distance (feet)	1938–53 Meander migration rate (feet/year)	1954–70 Orthogonal distance (feet)	1954–70 Meander migration rate (feet/year)	1971–77 Orthogonal distance (feet)	1971–77 Meander migration rate (feet/year)
Meanders Downstream from Elkhead Reservoir						
0.40	15.8	1.0	90.3	5.3	4.3	0.6
0.70	16.7	1.0	69.4	4.1	36.5	5.2
0.90	39.1	2.4	66.6	3.9	13.0	1.9
0.95	99.3	6.2	17.4	1.0	6.1	0.9
1.15	6.0	0.4	47.8	2.8	7.1	1.0
1.35	57.8	3.6	43.0	2.5	8.0	1.1
2.82	37.3	2.3	19.6	1.2	8.6	1.2
3.00	27.5	1.7	27.1	1.6	20.5	2.9
3.84	–29.7	–1.9	54.9	3.2	7.8	1.1
4.32	51.8	3.2	24.8	1.5	57.5	8.2
4.93	69.8	4.4	36.0	2.1	12.9	1.8
6.17	–18.4	–1.1	11.3	0.7	–23.2	–3.3
6.23	16.2	1.0	43.5	2.6	27.6	3.9
6.85	9.1	0.6	22.5	1.3	84.2	12.0
7.00	7.7	0.5	36.8	2.2	–26.6	–3.8
7.60	–44.3	–2.8	33.7	2.0	27.4	3.9
8.43	–26.2	–1.6	69.3	4.1	62.0	8.9
Mean migration rate		1.2		2.5		2.8
Standard deviation		2.4		1.3		4.0
MA flow, acre-ft/yr		nr		36,062		39,956
MA flood, ft^3/s		nr		923		945
Meanders Upstream from Elkhead Reservoir						
20.00	54.7	3.4	19.0	1.1	14.4	2.1
20.15	T 72.6	4.5	–29.2	–1.7	T 85.4	12.2
20.30	11.2	0.7	62.8	3.7	T 211.6	30.2
20.44	5.6	0.3	67.3	4.0	–24.4	–3.5
21.00	49.1	3.1	–65.1	–3.8	36.4	5.2
21.20	–40.6	–2.5	T 77.3	4.5	59.1	8.4
21.62	T –101.3	–6.3	120.9	7.1	85.6	12.2
22.22	31.5	2.0	–89.3	–5.3	41.5	5.9
22.48	30.4	1.9	–73.0	–4.3	89.7	12.8
23.06	16.9	1.1	0.0	0.0	92.7	13.2
23.35	–31.7	–2.0	54.3	3.2	–52.4	–7.5
23.60	0.5	0.0	95.9	5.6	–45.4	–6.5
23.85	7.1	0.4	118.8	7.0	–55.1	–7.9
Mean migration rate		0.5		1.6		5.9
Standard deviation		2.9		4.3		10.8
MA flow, acre-ft/yr		nr		36,062		39,956
MA flood, ft^3/s		nr		923		945

Table 3. Elkhead Creek meander migration rates for time intervals determined from aerial photographs—Continued

[River mile, channel distance upstream from Yampa River; Orthogonal distance, meander displacement between points of minimum meander bend radius of curvature; T, meander migration mode by translational shift, otherwise by amplitude increase; feet/year, feet per year; MA, mean annual; acre-ft/yr, acre-foot per year; ft^3/s, cubic foot per second; nr, no record]

River mile	1978–81 Orthogonal distance (feet)	1978–81 Meander migration rate (feet/year)	1982–93 Orthogonal distance (feet)	1982–93 Meander migration rate (feet/year)	1938–70 Pre-regulation meander migration rate (feet/year)	1978–93 Post-regulation meander migration rate (feet/year)
Meanders Downstream from Elkhead Reservoir						
0.40	25.4	6.4	47.6	4.0	3.2	4.6
0.70	15.8	3.9	62.0	5.2	2.6	4.9
0.90	13.4	3.3	26.3	2.2	3.2	2.5
0.95	19.6	4.9	31.6	2.6	3.5	3.2
1.15	0.9	0.2	33.1	2.8	1.6	2.1
1.35	15.8	3.9	66.7	5.6	3.1	5.2
2.82	–8.6	–2.1	48.6	4.0	1.7	2.5
3.00	64.0	16.0	21.1	1.8	1.7	5.3
3.84	34.0	8.5	19.2	1.6	0.8	3.3
4.32	14.5	3.6	T 127.8	10.6	2.3	8.9
4.93	4.2	1.1	58.5	4.9	3.2	3.9
6.17	66.3	16.6	–2.6	–0.2	–0.2	4.0
6.23	T 77.3	19.3	48.1	4.0	1.8	7.8
6.85	T 63.6	15.9	49.6	4.1	1.0	7.1
7.00	T 142.0	35.5	–193.6	–16.1	1.3	–3.2
7.60	39.5	9.9	T 154.6	12.9	–0.3	12.1
8.43	78.1	19.5	34.9	2.9	1.3	7.1
Mean migration rate		9.8		3.1	1.9	4.8
Standard deviation		9.6		5.9	1.2	3.3
MA flow, acre-ft/yr		48,460		42,630	nr	44,088
MA flood, ft^3/s		1,383		1,142	nr	1,202
Meanders Upstream from Elkhead Reservoir						
20.00	20.4	5.1	57.2	4.8	2.2	4.8
20.15	T 123.3	30.8	T 79.4	6.6	1.3	12.7
20.30	T 81.1	20.3	T 136.3	11.4	2.2	13.6
20.44	26.9	6.7	T 199.6	16.6	2.2	14.2
21.00	4.1	1.0	57.1	4.8	–0.5	3.8
21.20	44.7	11.2	58.8	4.9	1.1	6.5
21.62	44.4	11.1	5.4	0.4	0.6	3.1
22.22	61.5	15.4	T 74.6	6.2	–1.8	8.5
22.48	41.2	10.3	T 170.8	14.2	–1.3	13.2
23.06	48.8	12.2	25.0	2.1	0.5	4.6
23.35	98.0	24.5	–80.1	–6.7	0.7	1.1
23.60	30.6	7.6	14.4	1.2	2.9	2.8
23.85	–2.8	–0.7	–43.8	–3.6	3.8	–2.9
Mean migration rate		12.0		4.8	1.1	6.6
Standard deviation		9.0		6.6	1.6	5.4
MA flow, acre-ft/yr		48,460		42,630	nr	44,088
MA flood, ft^3/s		1,383		1,142	nr	1,202

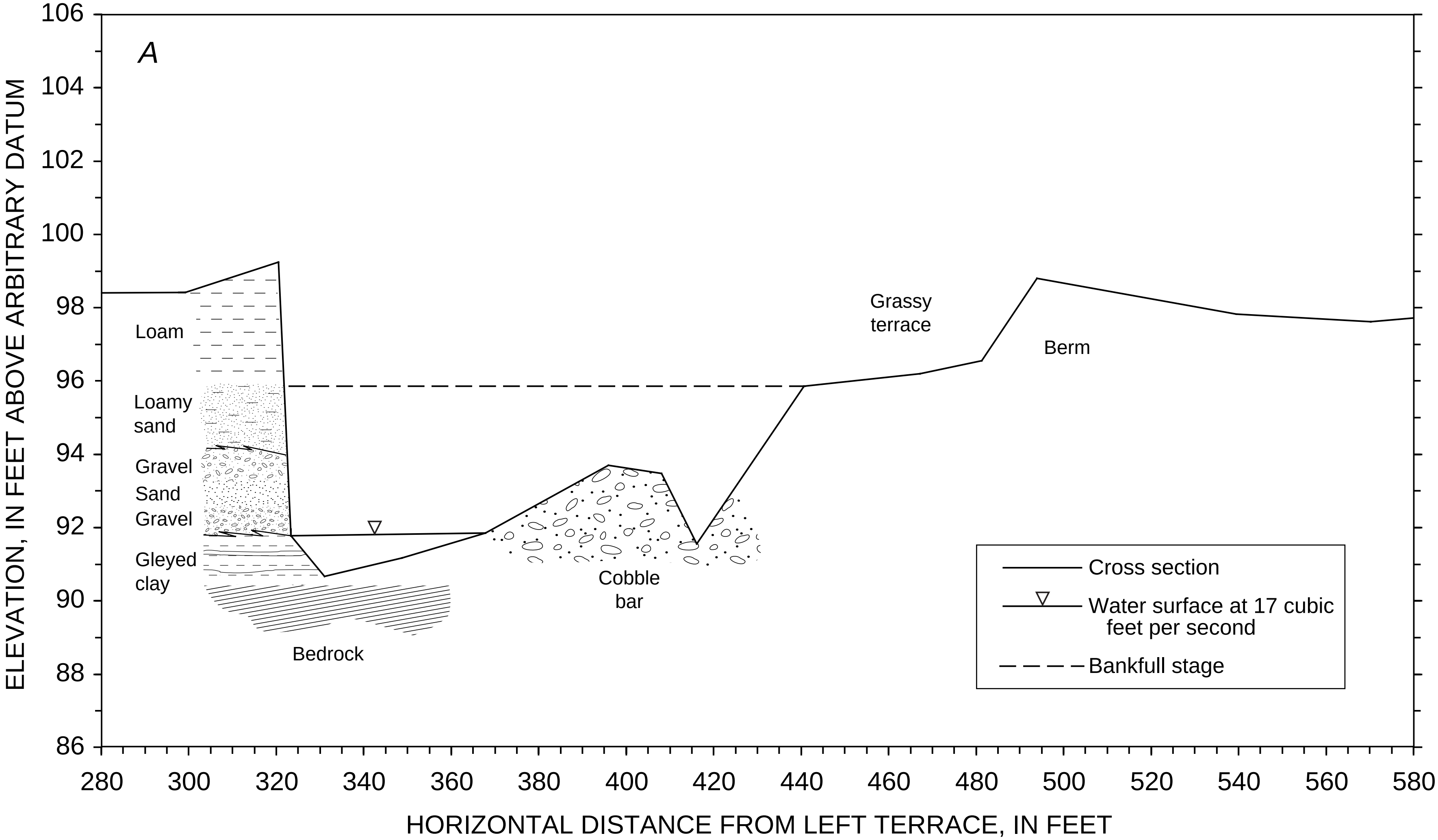
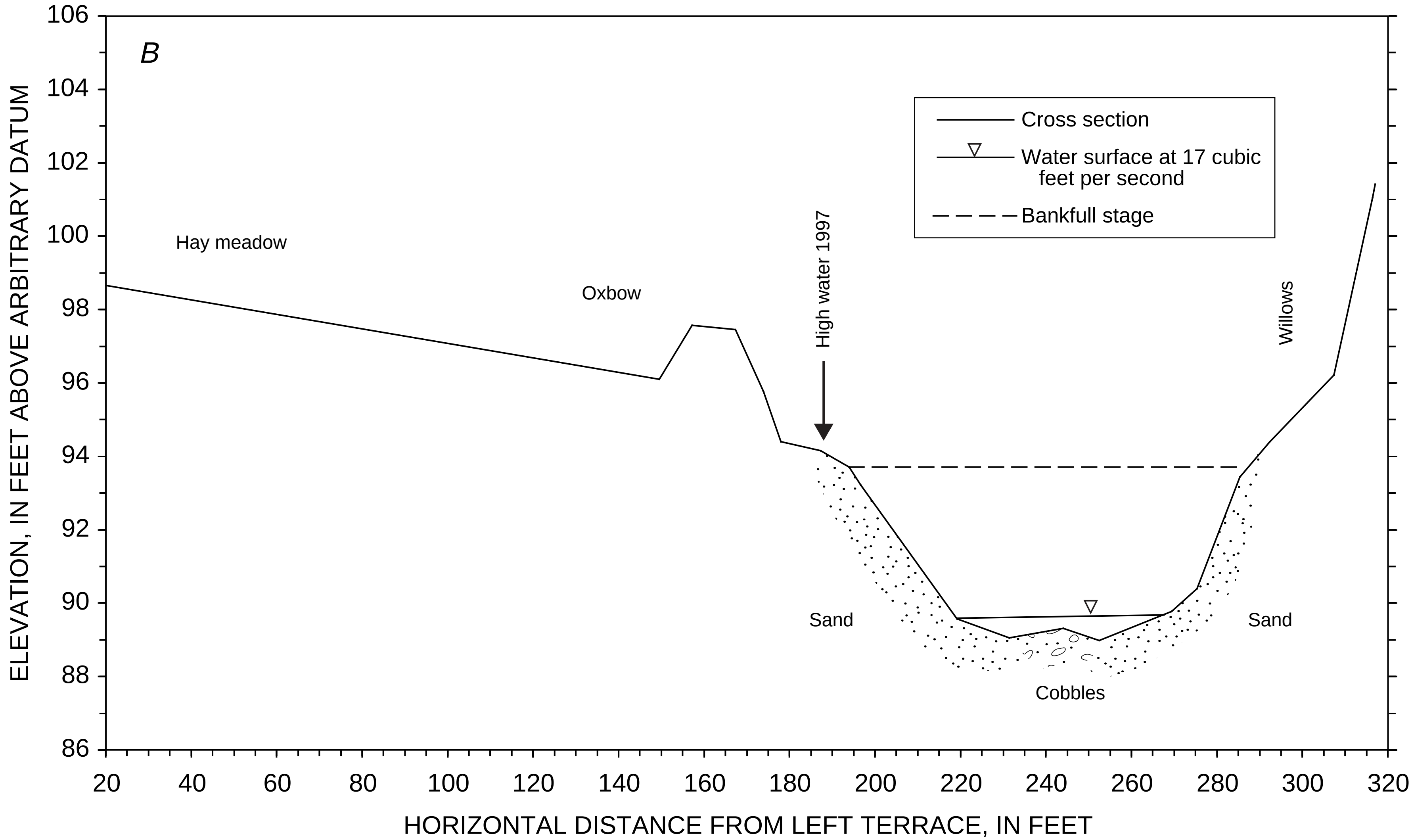


Figure 5. Elkhead Creek cross sections showing geomorphic features, alluvial stratigraphy, and the bankfull stage, (*A*) cross section PT-2, (*B*) cross section PT-1, (*C*) cross section LG-2, (*D*) cross section LG-1, (*E*) cross section NR-Q, (*F*) cross section LW-1, (*G*) cross section VT-2, and (*H*) cross section VT-1. Location of sections shown in figure 3.



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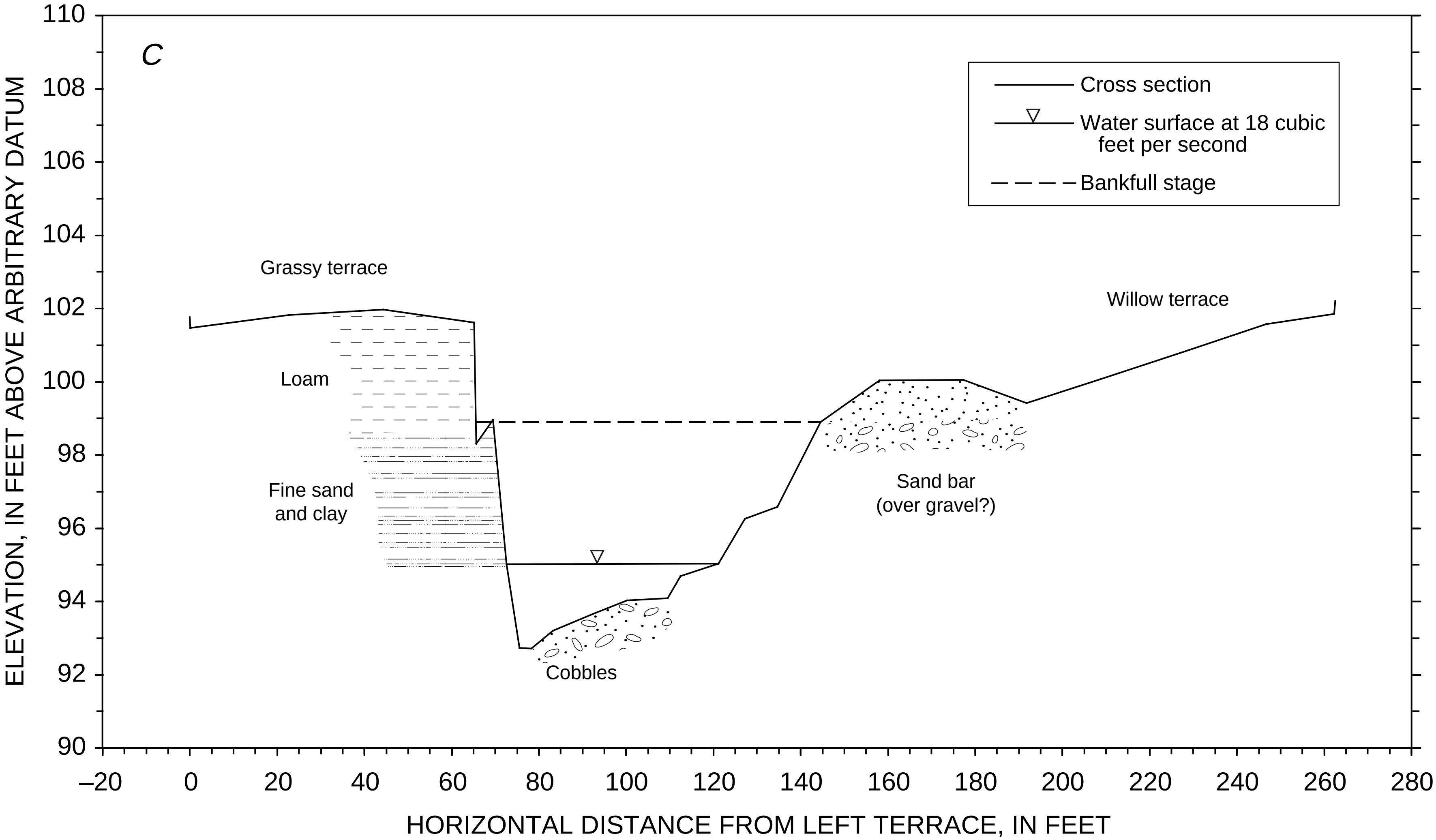

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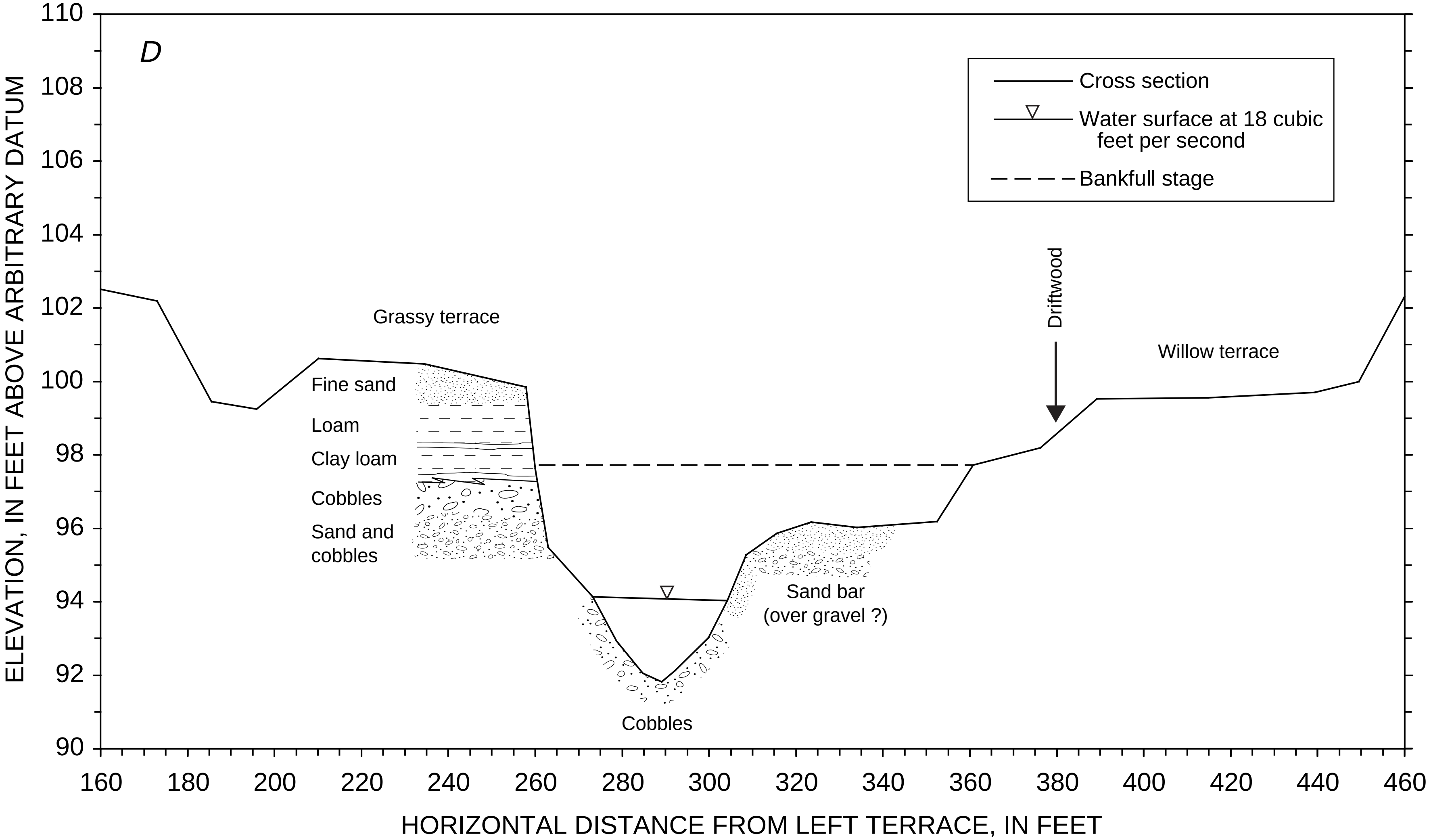

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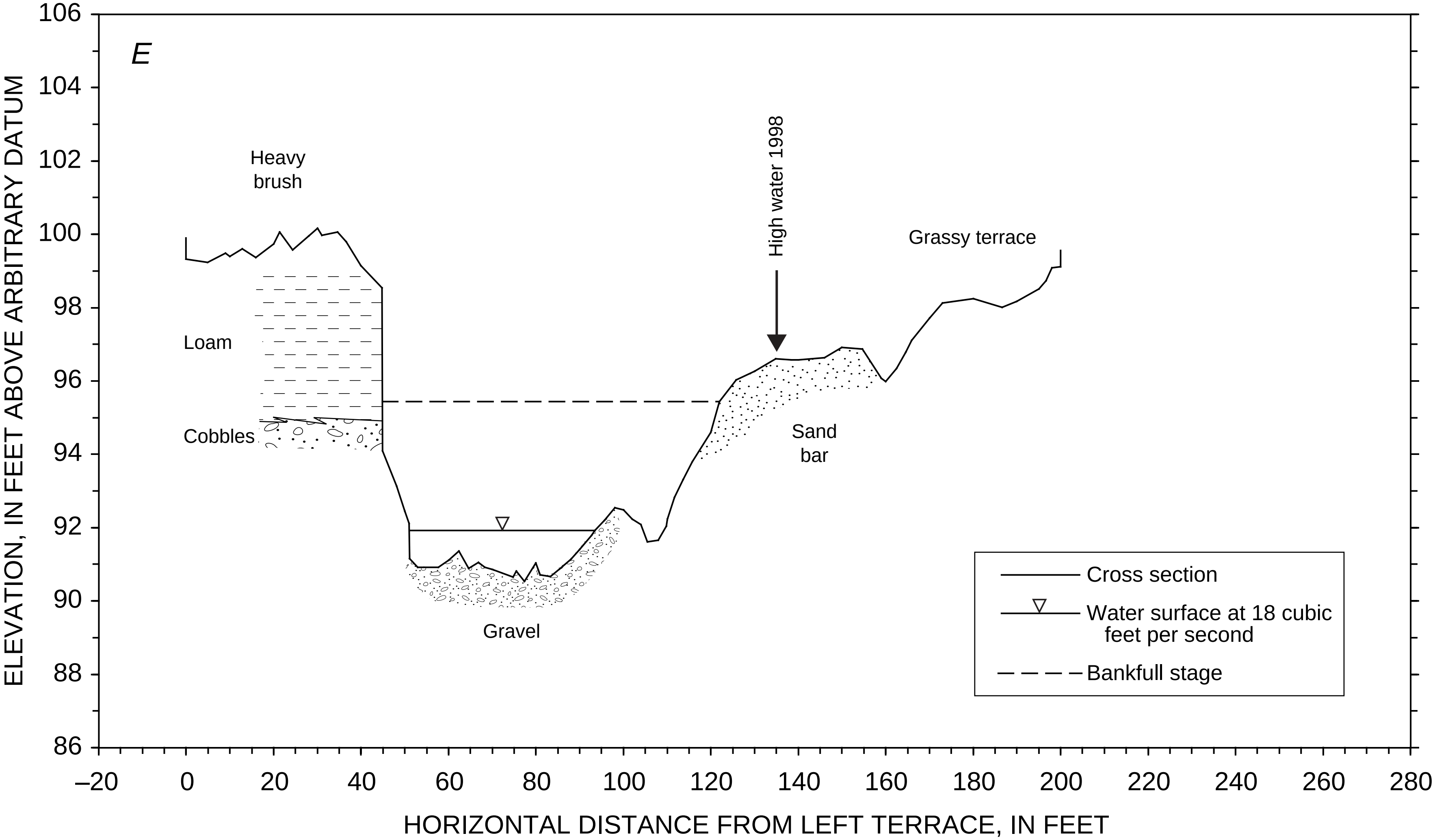

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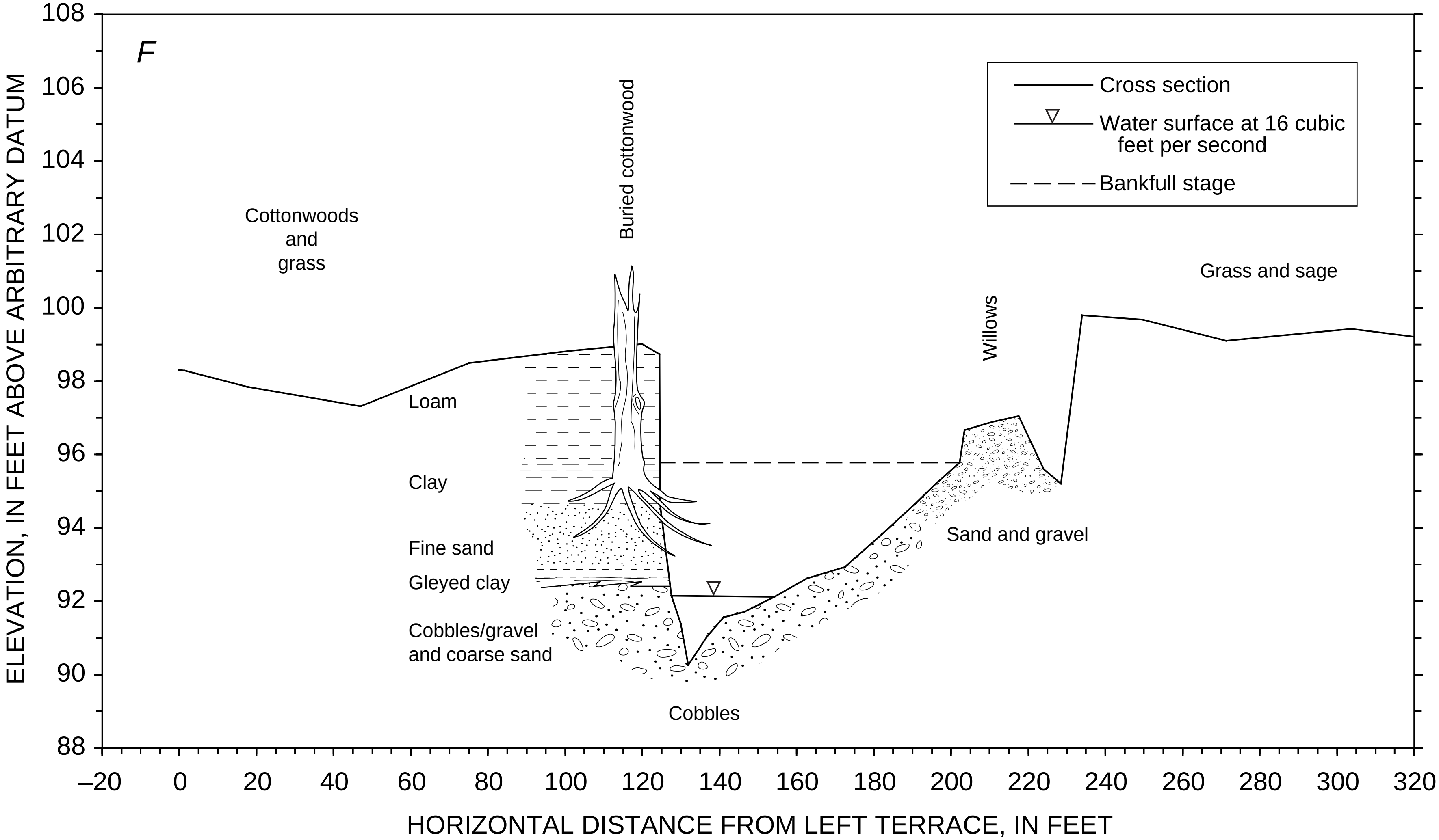

Figure 5. Elkhead Creek cross sections showing geomorphic features, alluvial stratigraphy, and the bankfull stage, (*A*) cross section PT-2, (*B*) cross section PT-1, (*C*) cross section LG-2, (*D*) cross section LG-1, (*E*) cross section NR-Q, (*F*) cross section LW-1, (*G*) cross section VT-2, and (*H*) cross section VT-1. Location of sections shown in figure 3—Continued.

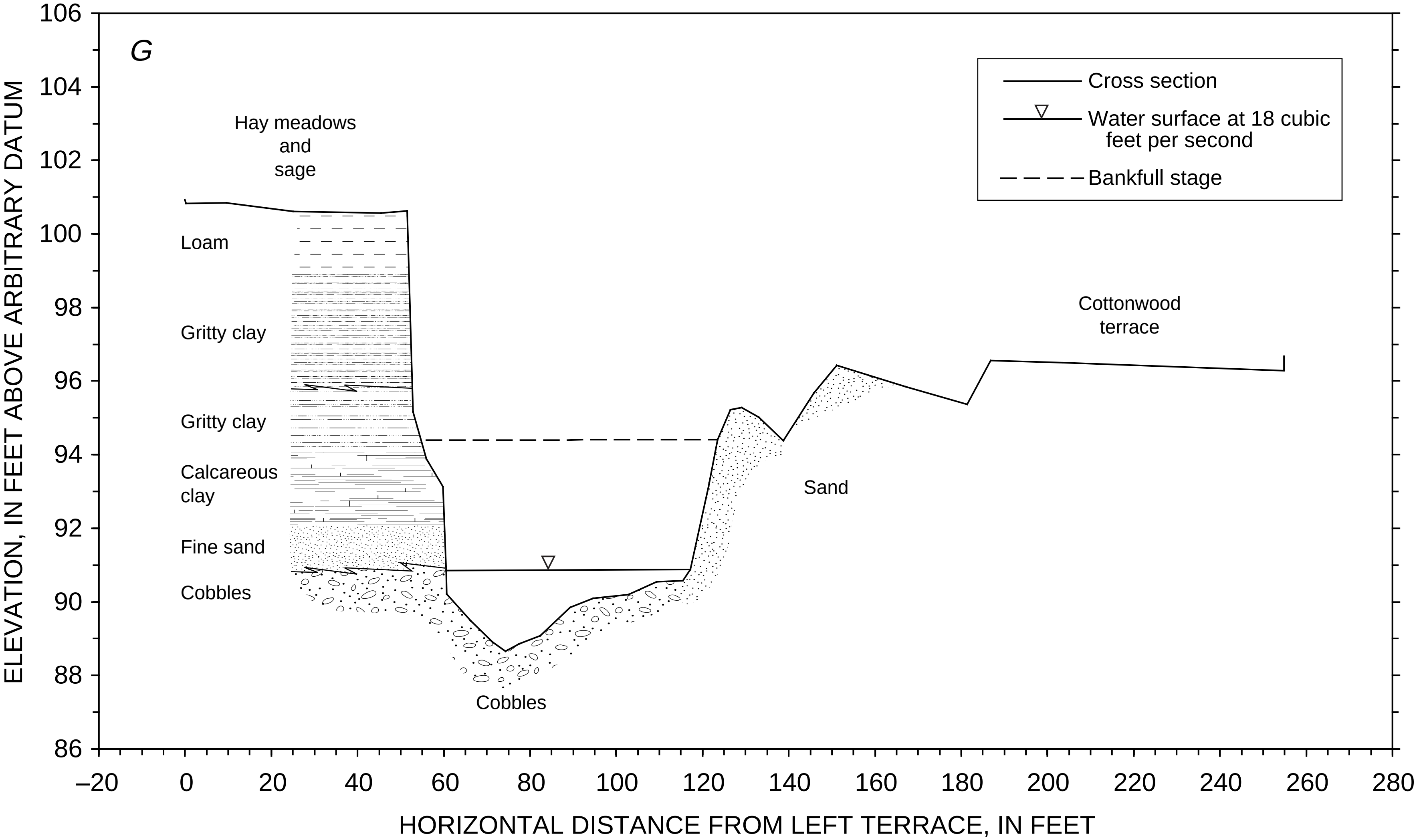

Figure 5. Elkhead Creek cross sections showing geomorphic features, alluvial stratigraphy, and the bankfull stage, (*A*) cross section PT-2, (*B*) cross section PT-1, (*C*) cross section LG-2, (*D*) cross section LG-1, (*E*) cross section NR-Q, (*F*) cross section LW-1, (*G*) cross section VT-2, and (*H*) cross section VT-1. Location of sections shown in figure 3—Continued.

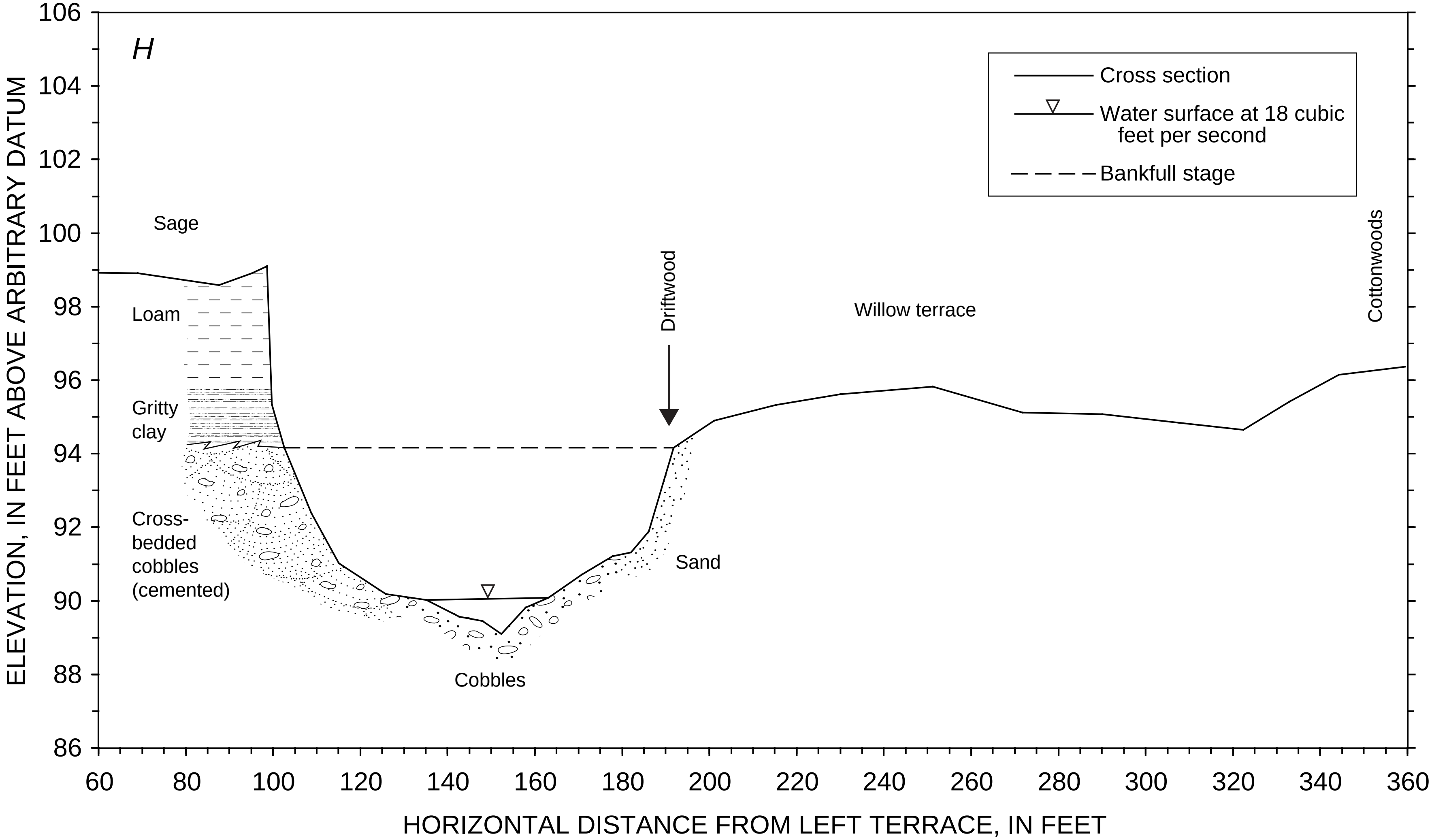

Figure 5. Elkhead Creek cross sections showing geomorphic features, alluvial stratigraphy, and the bankfull stage, (*A*) cross section PT-2, (*B*) cross section PT-1, (*C*) cross section LG-2, (*D*) cross section LG-1, (*E*) cross section NR-Q, (*F*) cross section LW-1, (*G*) cross section VT-2, and (*H*) cross section VT-1. Location of sections shown in figure 3—Continued.

valley-fill material exposed at most Elkhead Creek cross sections consisted of a layer of coarse-grained fluvial sediments overlain by a thick deposit of fine-grained overbank sediments. The uppermost fine-grained overbank sediments consisted of distinctive horizons of fine sand or gritty clay, clay loam, and loam. The upper surface of the lower coarse-grained layer, where present, consisted of sandy gravel and or cobbles and was exposed at depths of about 3.3 to 9.8 ft below the scarp formed by the valley floor. These sediments tended to be noncohesive and easily erodible. The coarse-grained alluvial layer was not observed in the stratigraphy at cross sections PT-1 (fig. 5*B*) and LG-2 (fig. 5*C*). Crossbedded and imbricated gravel and cobbles approximately 4.9 ft below the terrace scarp were well cemented with calcium carbonate at cross section VT-1 (fig. 5*H*). Bedrock was exposed in the streambed at cross section PT-2 (fig. 5*A*), approximately 8 ft below the valley-floor scarp. Both conditions may have had an effect on the vertical incision or channel geometry of these sections.

Riparian vegetation is an important variable in streambank stability that affects sediment resistance to erosion and bank-sediment mass cohesiveness and induces deposition of sediment carried in the streamflow (Thorne, 1990). Scattered stands of trees and shrubs grew along the banks and terraces of Elkhead Creek when onsite cross-section surveys were made in 1997. However, riparian vegetation type and density were difficult to evaluate in the older aerial photographs; consequently, changes in these variables were not examined in this study.

Sediment Size

Sediment from the streambed surface was sampled in 1997 at the Elkhead Creek cross sections using the Wolman method for measuring the sediment-particle intermediate diameter (Wolman, 1954). Size distributions were computed for all cross sections except VT-1, where sediment measurements were not made. Much of the left bank at VT-1 consisted of cemented, crossbedded gravel- and cobble-size sediment. In other respects, the sediment at VT-1 was similar to sediment a short distance upstream at VT-2. The Wolman measurements were made at regularly spaced intervals across the channel in a linear traverse at or very near the surveyed cross section. These measurements were made from bank to bank and included all fluvially deposited material on the channel boundary below the approximate bankfull elevation. The measurements excluded flood-plain sediment exposed in cutbanks and sediment that had slumped into the stream.

Sediment sizes in Elkhead Creek ranged from fine sand to large cobbles (fig. 6). The abrupt inflections of the cumulative size curves at 0.25 mm result from an onsite assessment of all fine sand as having a diameter of 0.25 mm. A greater variation of particle diameters exists within the sand-size range, but the Wolman method is not sensitive to measurements of material finer than about 1 or 2 mm, and no attempt was made to measure the intermediate diameter of this fine sediment. The Elkhead Creek cumulative size distribution curves cluster together in the coarse-gravel and cobble-size regions, indicating that stream-bed sediments from all sampled sites have generally similar characteristics in the coarsest range. However, differences in size distributions are visually apparent in the sand- and gravel-size ranges.

The median grain size, or d_{50}, of the streambed sediment in Elkhead Creek ranged from 2 to 41 mm (table 4), comparable to size categories of very fine gravel to coarse gravel. The largest sediment particles sampled were classified as medium to large cobbles and generally were found in the thalweg, the deepest part of the cross sections (fig. 5). The percentage of sand-size or finer sediment in the streambed ranged from 30 to 50 percent at the cross sections upstream from Elkhead Reservoir (PT-2, PT-1, LG-2, LG-1, and NR-Q). At the two sampled cross sections downstream from the reservoir, the percentage of sand-size or finer sediment was 8 percent (LW-1) and 16 percent (VT-2).

Shear Stress and Sediment Entrainment

Sediment entrainment in stream channels is partly a function of the boundary shear stress acting on sediment particles in the streambed or other inundated alluvial surfaces. Shear stress is proportional to the square of streamflow velocity and is most accurately determined by measurements of velocity vectors in downstream, lateral, and vertical directions. When velocity data are unavailable, mean shear stress in a channel cross section commonly is approximated by the relation between boundary shear stress, flow depth, and energy gradient given by the duBoys equation (Chow, 1959, p. 168):

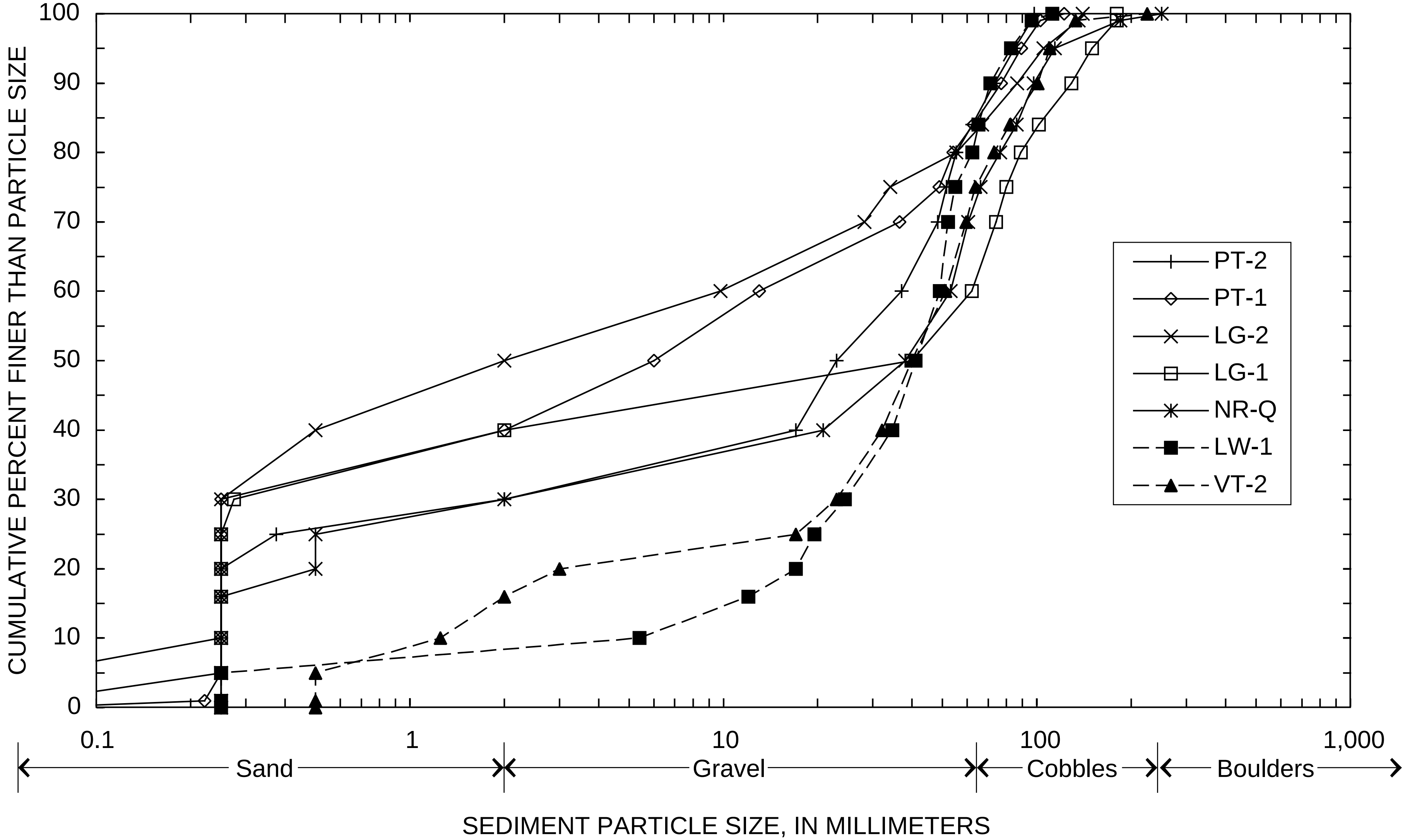

Figure 6. Cumulative size distribution curves for streambed sediment at Elkhead Creek study sites.

Table 4. Streambed sediment-size characteristics from Elkhead Creek study sites

[Percentile, percentage of the sediment sample finer than the indicated particle size; Sorting index = [$(d_{84}/d_{50})+(d_{50}/d_{16})/2)$]; Critical shear stress for d_{50} calculated with equation 2; mm, millimeter; lb/ft^2, pounds per square foot. Size category lower limit: "boulder" = 256 mm, "cobble" = 64 mm, "gravel" = 2 mm, "very coarse sand" = 1.0 mm, "coarse sand" = 0.50 mm, "medium sand" = 0.25 mm, fine sand = 0.125 mm, "very fine sand" = 0.062 mm]

Cross section	Percent sand size	16th percentile (d_{16}) (mm)	25th percentile (d_{25}) (mm)	50th percentile (d_{50}) (mm)	75th percentile (d_{75}) (mm)	84th percentile (d_{84}) (mm)	95th percentile (d_{95}) (mm)	Maximum size (mm)	d_{84}/ d_{50} ratio	d_{84}/ d_{16} ratio	d_{50}/ d_{16} ratio	Sorting index	Critical shear stress for d_{50} (lb/ft^2)
PT-2	30	0.25	0.38	23	52	62	85	98	2.7	248.0	92.0	47.3	0.23
PT-1	40	0.25	0.25	6	49	63	89	122	10.5	252.0	24.0	17.3	0.06
LG-2	50	0.25	0.25	2	34	67	105	140	33.5	268.0	8.0	20.8	0.02
LG-1	40	0.25	0.25	40	80	101	150	180	2.5	404.0	160.0	81.3	0.41
NR-Q	30	0.25	0.50	38	66	86	114	250	2.3	344.0	152.0	77.1	0.39
LW-1	8	12	20	41	55	65	83	112	1.6	5.4	3.4	2.5	0.42
VT-2	16	2	17	40	64	82	110	225	2.1	41.0	20.0	11.0	0.41

$$\tau_o = \gamma D S \qquad (1)$$

where

τ_o is the mean boundary shear stress (in pounds per square foot),

γ is the specific weight of water (62.4 lb/ft^3),

D is the mean flow depth (in feet), and

S is the energy gradient (foot per foot) for a given discharge.

Assumptions for using equation 1 are: (1) the channel cross section has a regular, or trapezoidal, shape and width is at least 10 times greater than depth, (2) streamflow is steady (there is a continuity of discharge within the reach), and (3) streamflow is uniform (velocity is constant in both magnitude and direction through the reach). Application of equation 1 is inappropriate in channel sections where there is a strong lateral variation in acceleration or where abrupt, local changes in streambed gradient occur. Cross sections in this study were not trapezoidal, although all had single-thread channels and all had width at least 10 times mean flow depth.

Most natural streams do not completely satisfy the assumptions for equation 1, and the boundary shear stress associated with any specific discharge is nonuniformly distributed across the channel. Lateral and downstream variations in cross-section morphology and variations in energy gradient with discharge result in a wide range of boundary shear stresses and, consequently, produce variable conditions for sediment entrainment, sorting, and deposition. Streamflow depths at points along each cross section were substituted for the cross-section mean flow depth in equation 1 to illustrate the spatially variable nature of shear stress in the Elkhead Creek cross sections. Shear stresses associated with three reference discharges were calculated for the surveyed Elkhead Creek cross sections to illustrate the effect of varying flow depths and water-surface slopes on sediment entrainment potential. The reference discharges are representative of low-flow conditions (an average of approximately 17 ft^3/s), bankfull conditions (1,800 to 2,200 ft^3/s), and a flood discharge that fills the existing channel to the approximate elevation of the valley floor and former flood-plain surface (discharge unknown).

Figure 7 illustrates the cross-channel shear-stress variation at the three reference discharges for cross section LG-1. Cross section LG-1 has geomorphic features typical of other Elkhead Creek channel sections (figs. 5*A* through 5*H*) including a well-defined, single-thread, low-discharge channel, an alluvial bar in or adjacent to the low-discharge channel that is inundated by the bankfull discharge, a low-elevation terrace inundated by moderate flood discharges slightly greater than the bankfull discharge, and a high-elevation terrace inundated by infrequent floods. Cobble- and gravel-size material is exposed in the deepest part of the channel at most cross sections surveyed. The alluvial bars at most cross sections are composed of sand and gravel. Low-elevation terraces have a similar sediment composition as the alluvial bars but tend to be more densely vegetated. The boundary shear stress calculated with equation 1 is

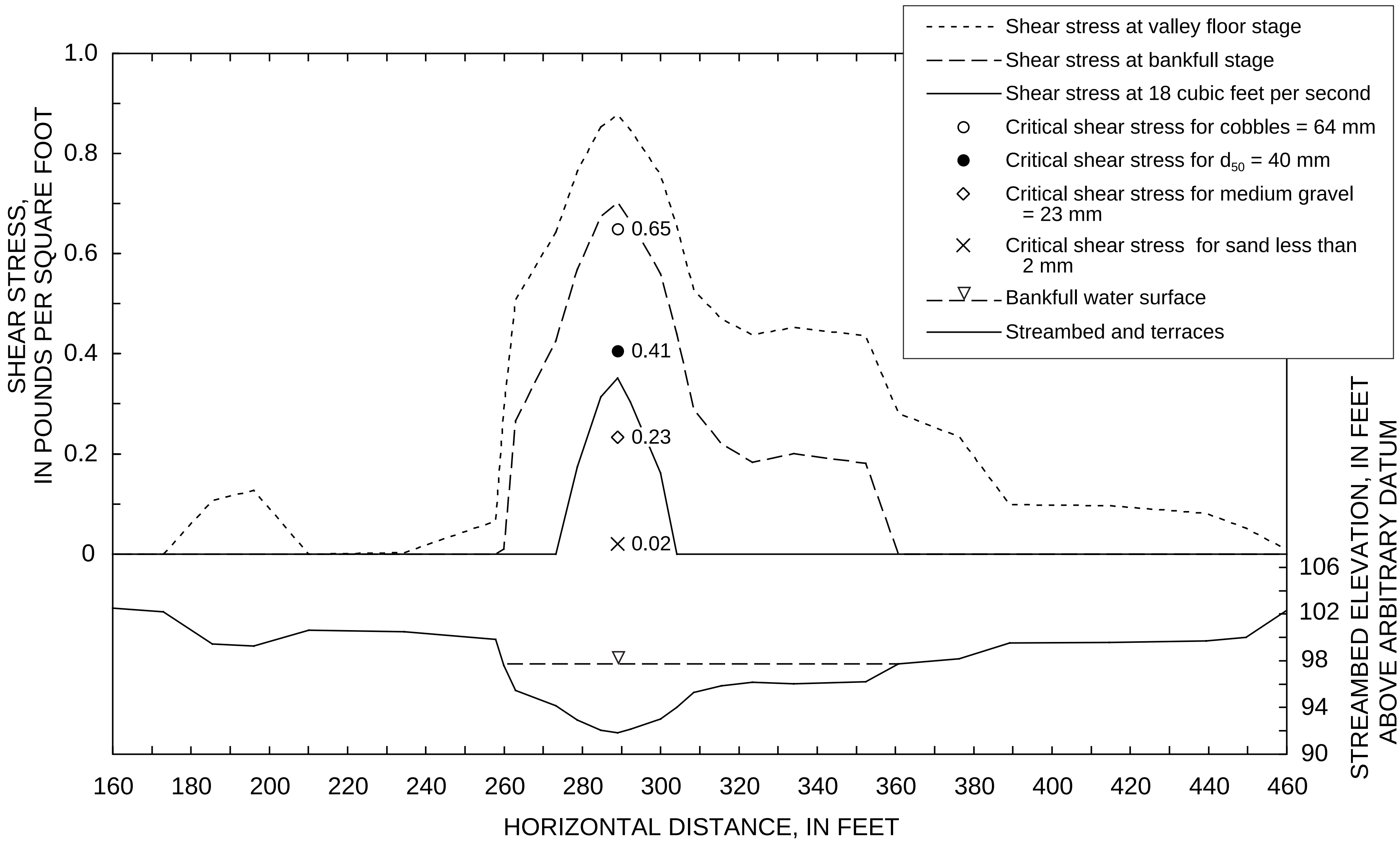

Figure 7. Cross-channel distribution of boundary shear stress for three discharges and the critical shear stress for entrainment of various sediment sizes at a typical Elkhead Creek site, cross section LG-1.

proportional to flow depth. Consequently, the shear stress generated over the higher surfaces is less than that generated over more deeply inundated surfaces, for a given discharge (fig. 7). Shear stress generally increased with discharge because flow depths also increased. However, water-surface slope decreased with increasing discharge at some cross sections. At those cross sections, the rate of shear-stress increase was less than at other cross sections where water-surface slope remained relatively constant or increased with discharge.

The critical shear stress (τ_c), the shear stress at which general movement of sediment begins, has been related to sediment size characteristics (Shields, 1936; Lane, 1955; Komar, 1987; Wilcock, 1992). Critical shear stress for entrainment of the sediment median particle size can be estimated using the Shields (1936) equation:

$$\tau_c = \tau^*_c \, (\gamma_s - \gamma) \, d_{50} \qquad (2)$$

where

- τ_c is the critical shear stress (in newtons per square meter);
- τ^*_c is the dimensionless critical shear stress or the Shields parameter;
- γ_s is the specific weight of sediment (assumed to be 25,990 N/m^3);
- γ is the specific weight of water (9,807 N/m^3); and
- d_{50} is the median sediment size (in meters).

Critical shear stress in equation 2 (newtons per square meter) is converted to English units (pounds per square foot) by multiplying by 0.02088.

Neill (1968) recommended a Shields parameter, τ^*_c, of 0.030 for streambeds composed of coarse materials; however, other investigators have demonstrated a variable τ^*_c in channels with mixed-size sediments (Komar, 1987) and in channels where the bed-surface particle size is significantly larger than the subsurface particle size (Parker and others, 1982; Andrews, 1983). The Shields parameter could not be precisely determined in this study as in some flume and instrumented field studies; therefore, based on published research and the particle-size ranges measured at the Elkhead Creek study sites, critical shear stresses for each sediment measurement were calculated with Shields τ^*_c values of 0.030.

Once τ_c was identified for a specific deposit, the critical discharge (the minimum streamflow required to entrain sediment d_{50}) was estimated by equating τ_o with τ_c and using the relation between shear stress and the reference discharges at a specific cross-section location. Wilcock (1992, p. 297) states that equation 2 and d_{50} can be used to provide a minimum estimate of the shear stress necessary to initiate general movement of a mixed-size sediment based on experiments using sediments with d_{50} up to about 20 mm. Lane's (1955) data indicate that the Shields equation is applicable for sediments with a 75th percentile (d_{75}) up to about 100 mm. Elliott and Parker (1997) and Elliott and Hammack (2000) used the Shields (1936) equation to estimate the critical shear stress for entrainment of sediment d_{50} in the Gunnison River of Colorado. The critical shear stress associated with sediment entrainment (equation 2) is, at best, a minimum estimate of the critical discharge because only a small area of the entire surface or a few particles of the d_{50} size may be entrained by the critical discharge (Lisle and others, 1993; Milhous, 1982). Wilcock and McArdell (1993) observed that complete mobilization of a size fraction, such as d_{50}, occurred at about twice the shear stress necessary for incipient motion of individual particles in that size fraction.

It is possible to evaluate the sediment entrainment potential of each reference discharge with respect to a particular geomorphic surface or location on a cross section when the boundary shear stress, τ_o, is compared with the critical shear stress, τ_c, for the sediment at various locations on the cross sections (fig. 7 and table 4). At cross section LG-1 and at most Elkhead Creek cross sections, sand-size (up to 2-mm diameter) and medium gravel-size (up to 23-mm diameter) sediment theoretically is entrainable from the deepest part of the channel by discharges as low as 16–18 ft^3/s. This is supported by observation of the streambed at low flow, which reveals a dominant streambed particle size (coarse gravel and cobbles) that is greater than the theoretically entrainable particle sizes (sand- and medium-size gravel). At the bankfull reference discharge, the alluvial bar adjacent to the low-discharge channel at LG-1 is inundated. The shear stress generated over this inundated surface theoretically is sufficient to entrain sand and fine gravel, and the shear stress generated over the deepest part of the streambed should be able to entrain all gravel sizes and some sediment as coarse as cobble size (64-mm diameter) or larger. Because this entrainable size range includes the d_{50} at cross section LG-1

(40 mm), it can be stated that the streambed at LG-1 is mobile at the bankfull discharge.

Sedimentation in Elkhead Reservoir

Elkhead Dam impounded a 3.8-mile-long reservoir in 1974, inundating the former Elkhead Creek flood plain and trapping all of the bedload and a large amount of suspended sediment previously transported through this reach of the Elkhead Creek valley. Since impoundment, much of the bedload transported into the reservoir has been deposited in a delta at the northeastern (upstream) end of the reservoir. The mass of sediment deposited in the delta provides some indication of the natural bedload transport rate in this reach of Elkhead Creek and can be considered an approximate surrogate for long-term bedload measurements.

Delta area was digitized for two time periods bracketed by the aerial photographs from 1977, 1981, and 1993. These photographs were taken in September of each year and, as such, reflect the condition of the delta at the end of the runoff season. The distal margins of the deltaic deposits in 1977, 1981, and 1993 are shown in figure 8. After 3 years of impoundment, the deltaic deposits were barely visible and the vestigial channel of the inundated Elkhead Creek still was identifiable in 1977 (fig. 8). Sedimentation during this period probably was relatively low because two of the three annual flood peaks were relatively insignificant. The 1975 flood peak was 1,460 ft^3/s (recurrence interval of 5.5 years), but the 1976 and 1977 flood peaks were considerably smaller than the approximate bankfull discharge.

By 1981, the distal margin of the Elkhead Creek delta had prograded approximately 1,180 ft downvalley from the 1977 limit of flood-plain inundation, and the total surface area of the delta was 17.1 acres (fig. 8). Delta area, in these calculations, includes the distributary channel area as well as the subaerially exposed sediment, but not subaqueous sediment deposited in the reservoir beyond the distal margin, which could not be seen in some of the aerial photographs. During 7 years of sediment deposition from 1975 (the first runoff season following completion of Elkhead Reservoir) through 1981, the delta advanced at a rate of approximately 168 ft per year and added approximately 2.4 acres per year of exposed sediment in the upper end of Elkhead Reservoir (table 5). The amount of subaqueous deposition in the reservoir is not known nor is the amount of suspended sediment that passed through the reservoir. By 1993, the delta had prograded approximately another 1,560 ft beyond the 1981 margin, and the delta area increased by 27.1 acres, a rate of approximately 2.3 acres per year, in the 12-year period from 1982 through 1993.

The Elkhead Creek delta volume was estimated using a contour map created by Ayres Associates (1995) from a topographic survey made when Elkhead Reservoir was drawn down to a low level. The delta surface has relatively low relief and was assumed to be horizontal with an average surface elevation of 6,365 ft, approximately equal to the normal reservoir pool elevation. Surveyed points on the former flood plain immediately downstream from the delta distal margin and approximately 3,700 ft downstream from the proximal (upstream) margin had an average elevation of 6,355 ft. It was assumed that the former valley floor sloped uniformly downstream beneath the new delta; therefore, the delta thickness increased uniformly from zero to 10 ft over a 3,700-ft length. Delta thickness at the distal margins in 1981 and 1993 was calculated as proportional to the distance between the proximal margin and a point 3,700 ft downstream where the depth to the former flood plain was approximately 10 ft. Because of the assumed wedge-shaped longitudinal cross section (horizontal upper surface and sloping lower surface), the average delta thickness was one-half the thickness at the distal margin. Based on valley-side topography and subaqueous delta-front conditions observed in 1997, the lateral and distal boundaries of the deltaic deposit are known to slope steeply but, for the purpose of these volumetric calculations, were assumed to be vertical. By 1981, the delta had an estimated volume of approximately 27.3 acre-ft, which had accumulated at a rate of approximately 3.9 acre-ft per year. By 1993, the delta had a volume of approximately 163.4 acre-ft and, since 1981, accumulated at a rate of approximately 11.3 acre-ft per year (table 5).

The delta mass was estimated from the previously calculated delta volume and an assumed sediment density for the deltaic deposits. The density of sediment deposits in a reservoir is dependent on several variables such as the sediment-size distribution (the percentage of sand-, silt-, and clay-size particles), sediment compaction, and the relative amount of time the sediment is submerged or exposed to the air (Lara and Pemberton, 1965). Prolonged submersion has little effect on the density or unit weight of sand-size sediment, whereas prolonged submersion tends to significantly decrease the unit weight of clay-size sedi-

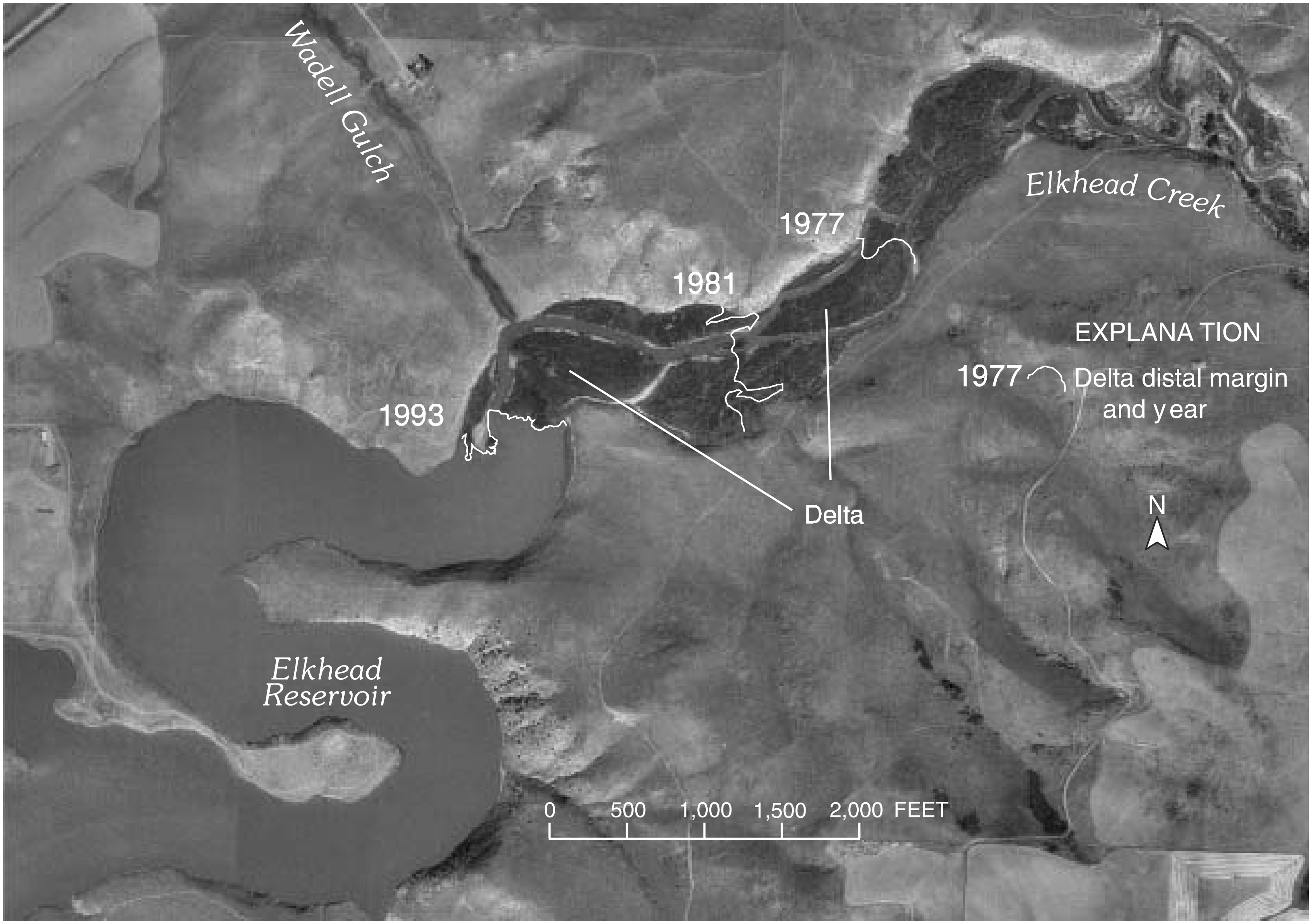

Figure 8. Aerial photograph showing deltaic sedimentation in Elkhead Reservoir and the location of the delta distal margin in 1977, 1981, and 1993.

Table 5. Elkhead Creek delta progradation rates, estimated sediment volume, and extrapolated bedload-transport rates, 1975 through 1993

[ft/yr, feet per year; acre-ft, acre-foot; tons/yr, tons per year; progradation distance and delta surface area digitized from aerial photographs; delta thickness estimated from predeposition topography and an assumed uniform postdepositional surface topography; delta mass assumed a density of 97 pounds per cubic foot; ranked floods from gage 09245000 Elkhead Creek near Elkhead, 1954–96, with number 1 the largest flood discharge, number 2 the second largest, and so forth]

Period	Delta total length (feet)	Progradation rate in period (ft/yr)	Delta total surface area (acres)	Estimated mean delta thickness (feet)	Estimated delta total volume (acre-ft)	Estimated delta total mass (tons)	Sediment deposition rate in period (tons/yr)	Ranked floods in period
1975–81	1,177	168	17.1	1.6	27.3	57,698	8,243	8, 3, 4, 11
1982–93	2,740	130	44.2	3.7	163.4	345,192	23,958	6, 2, 1, 14, 7, 10
1975–93	2,740	144	44.2	3.7	163.4	345,192	18,168	

ment and slightly increase the unit weight of silt-size sediment. Elkhead Reservoir has a relatively constant pool elevation and, consequently, deltaic sediments up to the elevation of the pool surface probably are saturated most of the time. The sediment-size distribution of Elkhead Creek deltaic sediments was not determined; however, onsite examination of sediment deposited on the delta in 1997 indicated a predominance of sand-size material. Based on an assumption that silt- and clay-size particles constituted a very small part of the Elkhead Creek delta and based on the calculations of Lara and Pemberton (1965), a density of 97 pounds per cubic foot was adopted for the delta mass estimation. The delta, in 1981, contained approximately 57,700 tons of sediment and, in 1993, contained approximately 345,000 tons of sediment (table 5).

The mass of deltaic sediment was used to assess the long-term bedload transport rate in Elkhead Creek. Although the streambed at the seven study cross sections was composed of varying amounts of mobile gravel-size material (figs. 5 and 6, table 4), the large percentage of sand in bed-material samples upstream from the Elkhead Reservoir (table 4) and observed in the delta indicates that a significant quantity of the transported bedload was in the sand-size category. The bedload transport of sand, estimated from the delta mass estimates, was approximately 8,240 tons per year from 1975 through 1981 and approximately 24,000 tons per year from 1982 through 1993 (table 5). Because of the sediment-trapping efficiency of Elkhead Reservoir, the bedload transport rate immediately downstream from Elkhead Dam presumably was much lower than these estimates.

FACTORS AFFECTING CHANNEL-PATTERN ADJUSTMENTS

Several variables affect channel instability in Elkhead Creek, and an emphasis of this study has been to distinguish reservoir effects from external variables and natural meandering processes. The presence of Elkhead Reservoir probably has both mitigating and exacerbating effects on channel erosion downstream (Williams and Wolman, 1984). The brief streamflow record at gages 09246200 (upstream) and 09246400 (downstream) illustrates that Elkhead Reservoir reduces the range of diurnal discharge fluctuations and attenuates the daily discharge peak downstream (R^2 = 0.98 for daily mean discharges April–September 1996). A decrease in stage during the annual flood period would generally be accompanied by a decrease in flow depth, boundary shear stress, and erosion potential. Elkhead Reservoir also is very efficient at trapping bedload-transported sediment, as illustrated by the growth of the delta (fig. 8). It is reasonable to presume that sediment stored in the delta is sediment that eventually would have been transported through the lower reaches had the reservoir not been constructed. Streambed sediment upstream from the reservoir generally has a higher sand content than streambed sediment downstream from the reservoir, although only two reaches downstream were sampled (table 4). Clear-water, bedload-deficient releases from Elkhead Reservoir may partly explain the increase in meander migration rates at several meanders immediately downstream from Elkhead Dam in the 1978–93 period (fig. 9*A*). Some downstream effects of a reservoir may continue to develop and propagate for years, as Williams and Wolman (1984) demonstrated.

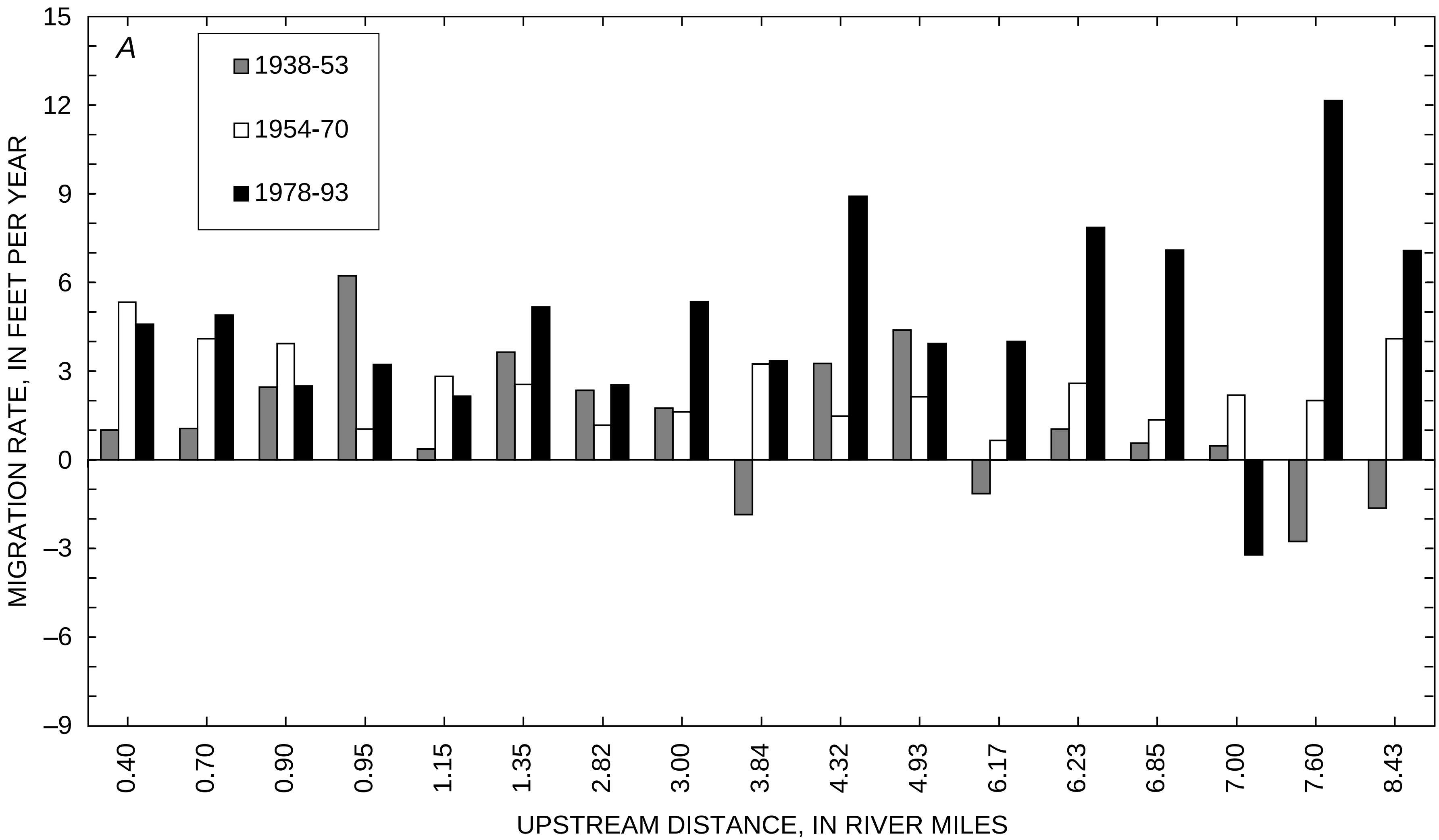

Figure 9. Elkhead Creek meander migration rates for time intervals of equal duration: (*A*) reach downstream from Elkhead Reservoir, and (*B*) reach upstream from Elkhead Reservoir.

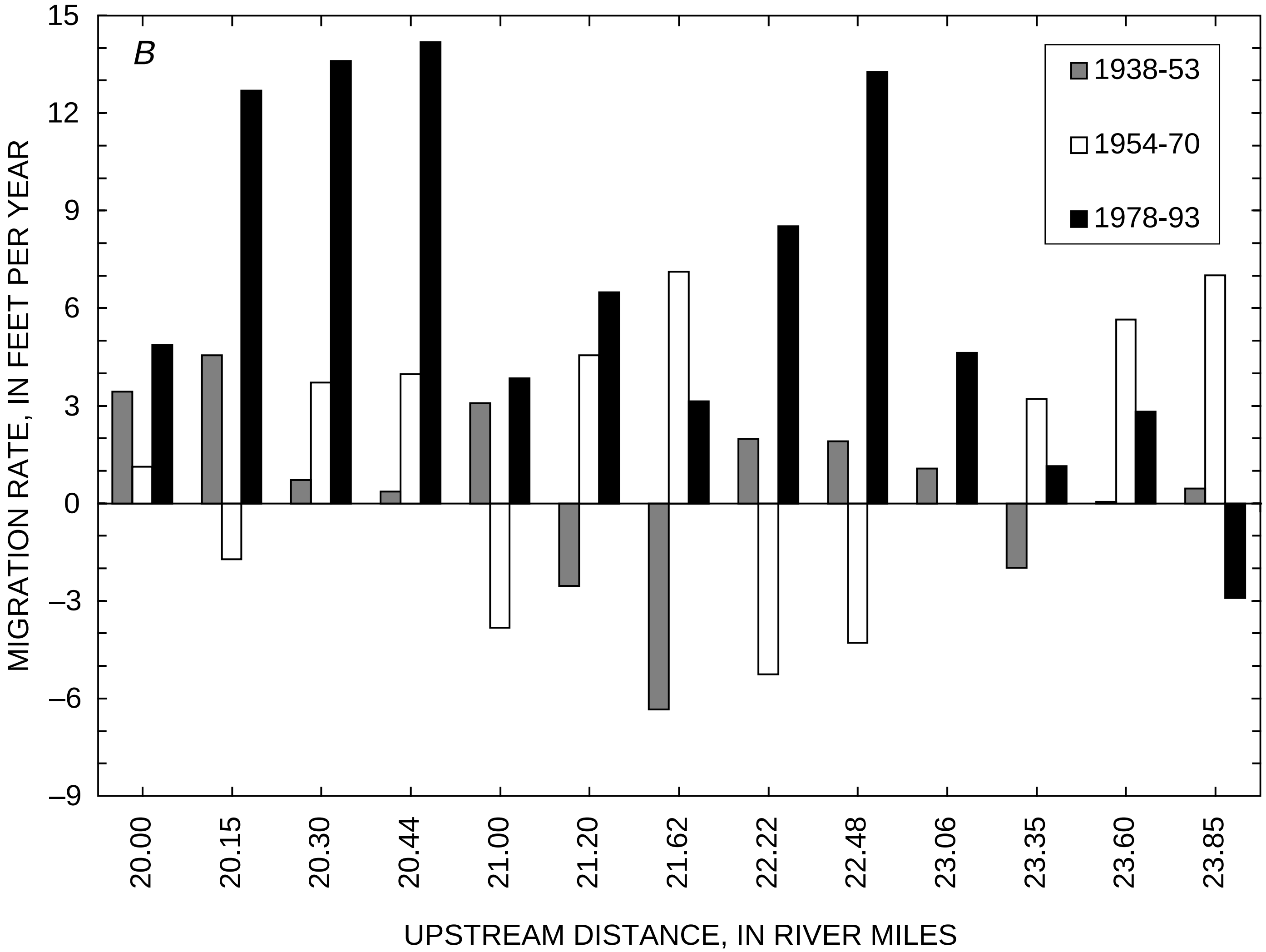

Figure 9. Elkhead Creek meander migration rates for time intervals of equal duration: (*A*) reach downstream from Elkhead Reservoir, and (*B*) reach upstream from Elkhead Reservoir—Continued.

The preexisting characteristics of the flood-plain and channel sediments and the natural variability of climate and streamflow also affect channel behavior. The influence of these variables can be seen both upstream and downstream from Elkhead Reservoir. A large proportion of the streambed sediment in Elkhead Creek is sand and fine gravel that can be transported by relatively low discharges. The cross-channel shear-stress distributions and critical shear-stress values for various sediments in the channel at cross section LG-1 (fig. 7) and the other surveyed cross sections indicate that sand is entrainable at almost any discharge. Medium gravel (up to 23 mm) can be entrainable from the deeper parts of the channel at low discharges and from nearly all channel boundary locations when discharge is approximately bankfull (approximately 1,800–2,200 ft^3/s). Larger or more frequent floods would be more effective at transporting sediment in Elkhead Creek.

The valley-fill stratigraphy exposed at several cross sections provides evidence of the past behavior of Elkhead Creek and the possible mechanisms of future channel adjustments. The buried and subsequently exhumed *Populus deltoides* tree trunks near cross section LW-1 (fig. 5*F*) became established on a sandy surface that may have been an earlier stream-bank or flood-plain surface. The root crown of the tree at cross section LW-1 is buried by clay and loam, typical of overbank sediments, and is approximately 2 to 4 ft below the surface of the adjacent valley floor, indicating a period of vertical aggradation after the tree became established. The age of the tree is unknown but may be on the order of about a century (Wes Signs, Colorado River Water Conservation District, oral commun., 1998). The elevation difference between the contemporary valley-floor terrace surface and the contemporary bankfull surface (2.5 to 6.2 ft) is an indication of vertical incision during the time since the valley floor functioned as the flood plain. Anecdotal evidence indicates that this incision has occurred in recent decades (Donald Van Tassel and Leroy Lawton, local residents, oral commun., 1997).

The physical properties of the valley-fill material exposed in cutbanks along the study reaches affect the processes of channel adjustment in Elkhead Creek. The sandy gravel and cobble layer of the valley-fill sediment exposed near stream level in many reaches of Elkhead Creek (fig. 5) is easily erodible when inundated and, when removed, leaves the overlying loamy sediment unsupported and prone to collapse. Bank failure adds sediment having a variety of sizes to the bedload, much of it transportable, but the larger particles may form a lag-type pavement or armor that resists further degradation except by very large floods (Milhous, 1982). The presence of a pavement or armor, or the presence of nonentrainable surfaces such as the bedrock exposed in the streambed at cross section PT-2 (fig. 5*A*) and the cemented cobbles at cross section VT-1 (fig. 5*H*), could make lateral erosion a more common channel adjustment than streambed scour.

Meander migration rates were calculated for three periods of generally comparable length 1938–53, 1954–70, and 1978–93, inclusive (fig. 9). The 1978–93 period represents the post-reservoir period; streamflow in the earlier two periods was not affected by Elkhead Reservoir. Only the second and third periods span the time for which continuous streamflow record is available and, because bank erosion and meander migration are partly dependent on streamflow, only the latter two periods are discussed here.

Meander migration rates in the reach downstream from Elkhead Reservoir (fig. 9*A* and table 3) had a mean of 2.5 ft/yr and a standard deviation of 1.3 in the 1954–70 period, compared to a mean of 4.8 ft/yr and a standard deviation of 3.3 in the 1978–93 period, following reservoir construction (F-test p=0.0004; t-test p=0.0150; table 3). Based on these statistics alone, one might conclude that Elkhead Reservoir had a substantial effect on hydrology and sediment transport leading to the doubled mean meander-migration rate. However, a similar trend in meander migration rates was observed in the study reach upstream from Elkhead Reservoir (fig. 9*B* and table 3). The mean migration rate in the upstream study reach was 1.6 ft/yr and the standard deviation was 4.3 in the 1954–70 period, whereas the mean was 6.6 ft/yr and standard deviation was 5.4 in the 1978–93 period (F-test p=0.4352; t-test p=0.0156). The fourfold increase in the mean meander-migration rate in the reach unaffected by Elkhead Reservoir requires consideration of other variables that influenced the entire Elkhead Creek watershed.

Channel instability throughout the Elkhead Creek valley may have been influenced by changes in land use, climate, or runoff. Mean annual streamflow at the 09245000 gage increased from 36,062 acre-ft/yr to 44,088 acre-ft/yr between the 1954–70 and 1978–93 periods, and the mean annual flood increased from 923 ft^3/s to 1,202 ft^3/s between the same periods. Sediment-transport rates estimated from the delta volume and mass calculations have potential inaccuracies because the actual thickness of the delta is not known nor is the sediment-size composition and the density of deltaic deposits. However, assuming that these estimates are reasonable, one explanation for the 190-percent increase in sediment transport rate from the 1975–81 period to the 1982–93 period is based on the magnitude of seasonal floods in the two periods. Floods greater than the approximate bankfull discharge, about 950 ft^3/s, occurred, on average, about every other year in both periods; however, the 1982–93 period included the flood of record (1984) and five consecutive years (1982–86) when flood peaks exceeded the bankfull discharge (fig. 2). It is possible that the large floods of the early and middle 1980's initiated a period of increased bank erosion and sediment remobilization from the flood plain and adjacent terraces, both upstream and downstream from Elkhead Reservoir.

The larger volume of runoff and the larger flood peaks after the late 1970's may have resulted in more erosive conditions in Elkhead Creek, all else assumed constant. A cause-and-effect relationship between these hydrologic changes and an increase in upstream-reach meander migration rates seems probable. A case for a similar, though more subtle, causal relationship with downstream meander migration rates also can be made because of the operational characteristics of Elkhead Reservoir. Maintenance of a relatively stable, full pool and spillway passage of excess inflow attenuates but does not eliminate flood events downstream, as indicated by streamflow analysis of discharge data from the concurrently operated streamflow-gaging stations upstream (09246200) and downstream (09246400) from the reservoir. Periods of large floods and increased meander migration in the upstream reach probably were concurrent with periods of large floods and increased meander migration in the reach downstream from Elkhead Reservoir.

SUMMARY AND CONCLUSIONS

The effect of Elkhead Reservoir on downstream channel instability has become an issue in the Elkhead Creek watershed. A study was conducted to identify the likely causes of streambank erosion in lower Elkhead Creek and to distinguish the relative effects of natural or independent variables from the effects of regulated streamflow and sediment entrapment. These issues were addressed by evaluating the channel patterns preserved in aerial photographs in the pre- and post-reservoir periods and by comparing the reaches upstream from and downstream from the reservoir. In addition, 44 years of streamflow record, channel cross-section characteristics, and sediment entrainment potential were examined.

A meandering channel pattern is part of a continuum of planimetric channel configurations that reflect discharge, valley gradient, sediment load, bank strength, and other factors. The process of meandering involves a constant adjustment of the channel cross section and pattern around average conditions. These adjustments can involve bank erosion, point bar development, pattern adjustment (meander-bend amplitude increase, avulsion), streambed scour, and aggradation. All of these adjustments can be considered normal in a "stable channel" that maintains an average channel geometry (width, depth, gradient) and pattern (sinuosity) over time. Meander migration rates, sediment transport rates, and delta progradation rates probably are highly variable from year to year but, averaged over time, show some correlation with discharge, with and without the effects of Elkhead Reservoir.

The principal conclusions of the study are:

1. Bankfull discharge is approximately 1,800 ft^3/s in the study reach upstream from Elkhead Reservoir and approximately 1,800–2,200 ft^3/s in the study reach downstream from Elkhead Reservoir. The bankfull width of eight surveyed cross sections ranged from 67 to 122 ft and averaged 88 ft. The bankfull width-to-depth ratio ranged from 12 to 24 and averaged 16.5. Bankfull water-surface slope ranged from 0.0012 to 0.0039 and averaged 0.0023.
2. Buried tree trunks at cross section LW-1 indicate that vertical flood-plain aggradation has occurred in some reaches of Elkhead Creek, possibly within the last century. The contemporary bankfull elevation at the eight cross sections is several feet below the broad, valley-floor terrace that may have been a former flood plain. The elevation difference between the valley-floor terrace and the contemporary bankfull elevation is an indication of more recent incision, possibly within the last few decades. The elevation difference between the valley-floor terrace and the contemporary bankfull stage ranges from 2.5 to 3.8 ft at cross sections in the reach upstream from

Elkhead Reservoir and 2.9 to 6.2 ft at cross sections in the reach downstream from Elkhead Reservoir.

3. The streambed of Elkhead Creek upstream and downstream from Elkhead Reservoir is composed largely of sediment particle sizes entrainable by commonly occurring discharges (up to the bankfull stage). The median grain size ranged from 2 to 41 mm (very fine gravel to coarse gravel), and the largest particle sizes ranged from 98 to 250 mm (medium to large cobbles). The percentage of sand-size or finer sediment in the streambed ranged from 30 to 50 percent at the cross sections upstream from Elkhead Reservoir, whereas at the two sampled cross sections downstream from the reservoir, the percentage of sand-size or finer sediment was 8 percent and 16 percent.
4. Elkhead Reservoir decreases the range of diurnal discharge fluctuations and attenuates but does not eliminate flood peaks downstream. The reservoir is very efficient at trapping bedload-transported sediment. A delta containing approximately 163 acre-ft of sediment in 1993 has developed since Elkhead Reservoir was constructed in 1974. Some lateral erosion of Elkhead Creek immediately downstream from Elkhead Reservoir may be related to bedload-deficient releases from the reservoir.
5. Mean meander migration rates increased in the 1978–93 period relative to earlier periods of comparable length in reaches both upstream and downstream from Elkhead Reservoir. Meander migration rates in the reach downstream from Elkhead Reservoir had a mean of 2.5 ft/yr in the 1954–70 period compared to a mean of 4.8 ft/yr in the 1978–93 period, following reservoir construction. A similar trend in meander migration rates was observed in the study reach upstream from Elkhead Reservoir. The mean migration rate in the upstream study reach was 1.6 ft/yr in the 1954–70 period, whereas the mean was 6.6 ft/yr in the 1978–93 period. The fourfold increase in the mean meander migration rate in the reach unaffected by Elkhead Reservoir requires consideration of other variables that influenced the entire Elkhead Creek watershed.
6. Mean annual streamflow and annual flood magnitudes affecting both reaches also increased in the 1978–93 period. Mean annual streamflow at the 09245000 gage increased from 36,062 acre-ft/yr to 44,088 acre-ft/yr between the 1954–70 and 1978–93 periods, and the mean annual flood increased from 923 ft^3/s to 1,202 ft^3/s over the same periods.
7. Channel instability, represented by meander migration rates, has increased since 1977 due to a combination of external factors affecting the entire watershed, such as annual runoff and flood magnitude, as well as local factors, such as reservoir sedimentation. Land-use practices that potentially affect channel instability, such as intentional meander cutoff and vegetation removal, were not addressed in this study.

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