Prepared in cooperation with the Colorado River Water Conservation District

Channel-Pattern and Cross-Section Changes in Selected Reaches of Elkhead Creek, Northwestern Colorado, 1938–2009

Scientific Investigations 2011–5201

U.S. Department of the Interior
U.S. Geological Survey

COVER: Elkhead Creek at cross section LW-2, looking downstream. Streamflow is 13 cubic feet per second.

Photograph by John G. Elliott, U.S. Geological Survey, taken July 23, 2009.

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Suggested citation:
Elliott, J.G., and Char, S.J., 2012, Channel-pattern and cross-section changes in selected reaches of Elkhead Creek, northwestern Colorado, 1938–2009: U.S. Geological Survey Scientific Investigations Report 2011–5201, 21 p.

Contents

Abstract 1
Introduction 1
Purpose and Scope 2
Previous Studies 3
Elkhead Creek Study Area 3
Geographic Setting 4
Hydrology 4
Methods 6
Aerial Photography 6
Planimetric Geomorphology 7
Cross-Sectional Geomorphology and Streambed Sediment 9
Channel-Pattern Changes, 1938–2009 10
Cross-Section Changes, 1997–2009 14
Factors Affecting Channel Changes 16
Summary and Conclusions 19
Acknowledgments 20
References Cited 20

Figures

1. Map of Elkhead Creek showing study area, locations of streamflow-gaging stations, and Elkhead Dam and Reservoir, northwestern Colorado 2
2. Plot showing annual peak discharges and estimated bankfull discharges for streamflow-gaging stations in the study area and aerial photography dates 5
3. Aerial photographs of Elkhead Creek in 2009 with plots of the channel centerline in 1937, 1970, 1977, and 2009 7
4. Graphs showing Elkhead Creek meander migration rates for time intervals of equal duration 12
5. Photographs of Elkhead Creek above Long Gulch reach at cross sections LG-1.o and LG-1.n showing lateral erosion and channel migration, view is upstream 15
6. Elkhead Creek channel cross sections surveyed in 1997 and 2009 16

Tables

1. Elkhead Creek meander migration rates 13
2. Comparison of meander migration rates by reach within period 14
3. Comparison of meander migration rates by period within downstream or upstream reach 14
4. Changes in Elkhead Creek cross-section and bed-material properties, 1997 to 2009 18

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
	Pressure	
pound per square foot (lb/ft^2)	47.88	newton per square meter (N/m^2)
	Density	
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Channel-Pattern and Cross-Section Changes in Selected Reaches of Elkhead Creek, Northwestern Colorado, 1938–2009

By John G. Elliott and Steven J. Char

Abstract

Elkhead Creek near Craig, Colorado, is a sinuous, meandering stream whose lower 9 river miles have been regulated by Elkhead Reservoir and Dam since 1974. The U.S. Geological Survey, in cooperation with the Colorado River Water Conservation District, conducted a study from 2009 to 2010 that evaluated channel-pattern and cross-section changes and identified possible causes of streambank erosion in Elkhead Creek that could have been affected by Elkhead Dam and Reservoir. Aerial photographs taken from 1937 through 2009, streamflow records from water years 1953 through 2009, and channel surveys and sediment measurements made in 1997 and 2009 were used to analyze streambed and streambank erosion both downstream and upstream from the reservoir. Erosional trends were evaluated by calculating meander migration rates determined from analyses of georectified aerial photographs and from replicate channel surveys at monumented cross sections established in a previous study. The aerial photography dates defined four periods of roughly equal lengths for which mean meander migration rates were determined. Two periods were prior to and two periods were after Elkhead Reservoir was constructed.

Meander migration rates in the reach downstream from Elkhead Reservoir ranged from –3.2 to 12.1ft/yr, and ranged from –6.3 to 14.2 ft/yr in the reach upstream from the reservoir from 1938–2009. Mean meander migration rates in the reach downstream from Elkhead Reservoir were statistically indistinguishable from upstream means in all periods, indicating that the presence of Elkhead Reservoir has had no apparent long-term effect on channel pattern changes. Meander migration rates in period 3 (1978–93) had the greatest mean and variance in meander migration rates in both the downstream and upstream reaches. A possible explanation for the statistically greater mean meander migration rates in period 3 could be the large annual peak discharges in Elkhead Creek between 1978 and 1993—a period when four of the largest annual peak discharges occurred.

Lateral-erosion rates, calculated from the replicated channel cross-section surveys over the 12-year period from 1997 to 2009, ranged from 0.1 to 1.3 ft/yr downstream from the reservoir, and from –0.3 to 2.5 ft/yr upstream from the reservoir. Lateral-erosion rates measured at cross sections in both reaches were within the ranges of meander migration rates determined from aerial photographs for the period 1994–2009.

The presence and operational characteristics of Elkhead Reservoir probably have had both mitigating and exacerbating effects on channel erosion downstream. However, reservoir effects on meander migration rates, if any, were not detectable in periods 3 (1978–93) and 4 (1994–2009). Other factors, such as characteristics of the flood-plain and channel sediments, the variability of climate and streamflow, land-use practices, and intentional manipulation of the channel also affect channel stability and meander migration rates.

Introduction

Elkhead Creek is a sinuous, meandering tributary of the Yampa River in northwestern Colorado (fig. 1) that flows through a relatively broad, alluvial valley that has been utilized for ranching since the 19th century. As is characteristic of most meandering streams, Elkhead Creek has eroded its banks, and meander bends have migrated across the valley for centuries. U.S. Geological Survey (USGS) topographic maps and aerial photographs indicate that channel-pattern shifts and meander-bend avulsions (or cutoffs) have been common in Elkhead Creek (Elliott and Gyetvai, 1999).

Many natural and manmade factors affect the rate of channel adjustment in a meandering alluvial stream. The hydrology of Elkhead Creek is dominated by snowmelt and is complicated by the effects of numerous irrigation diversions and returns (Kuhn and others, 2003). Streamflow in the lower 9 river miles of Elkhead Creek has been regulated by Elkhead Reservoir since Elkhead Dam was constructed in 1974. (A river mile is the in-channel distance measured along a river or stream course.) Cattle grazing in the watershed may have affected sediment yield, riparian vegetation growth, and streambank morphology to an unknown extent (Elliott and Gyetvai, 1999).

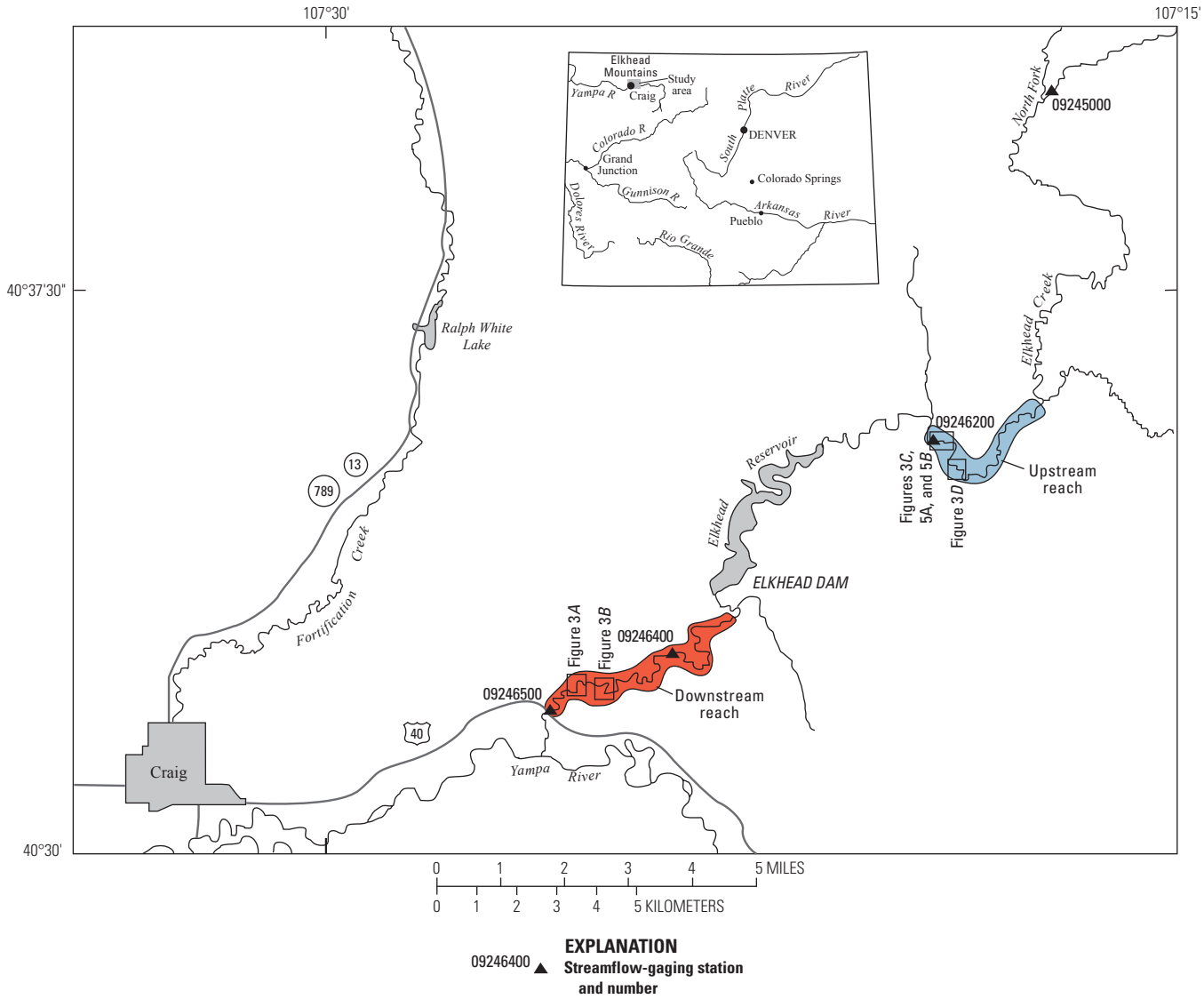

Figure 1. Map of Elkhead Creek showing study area, locations of streamflow-gaging stations, and Elkhead Dam and Reservoir, northwestern Colorado. From Ellliott and Gyetvai (1999).

The elevation of Elkhead Dam was raised by 25 ft during 2005–06, increasing the reservoir capacity from 13,800 to 25,550 acre-ft (*http://www.crwcd.org/page_28*, accessed February 23, 2010). Since then, concern has been expressed by downstream landowners about the potential effects of the enlarged reservoir on sediment delivery and streamflow fluctuations and, consequently, on channel stability, streambank erosion, and the loss of productive pasture acreage. The degree to which channel instability and bank erosion rates are influenced by the enlarged Elkhead Reservoir, climate variability, and hydrology had not been established prior to this study.

The USGS, in cooperation with the Colorado River Water Conservation District, conducted a study from 2009 to 2010 to evaluate channel-pattern and cross-section changes and identify possible causes of streambank erosion in Elkhead Creek that could have been affected by the 2005–06 enlargement of Elkhead Dam and Reservoir. The approach was similar to, and this study was a continuation of, a previous USGS study that evaluated the effects of the original Elkhead Reservoir on the hydrology, sediment-transport potential, and channel stability of Elkhead Creek for the period 1938 through 1993 (Elliott and Gyetvai, 1999).

Purpose and Scope

This report describes channel pattern changes during 1938–2009 and channel cross-section changes between 1997 and 2009 in selected reaches of Elkhead Creek in northwestern Colorado. The report includes information from the period during and following the enlargement of Elkhead Dam in 2005–06 along with results from a previous study of Elkhead Creek (Elliott and Gyetvai, 1999).

More specifically, the report describes the history of channel-pattern changes and the rate of meander-bend migration and cutoff from 1938 through 2009; the relation between hydrology and channel-pattern changes resulting in streambank erosion; and whether these channel changes are unique to the reach downstream from Elkhead Reservoir or are common to all meandering reaches of Elkhead Creek. This report also identifies possible factors affecting channel changes.

Previous Studies

Onsite channel surveys and sediment measurements made in 1997, aerial photographs taken from 1937 through 1993, and streamflow-gaging-station records from 1954 to 1996 were used to analyze streambed and streambank erosion beginning in the year 1938 in the lower reaches of Elkhead Creek in a previous USGS study (Elliott and Gyetvai, 1999). Prior to that study, concern about the possible effects of Elkhead Reservoir, constructed in 1974, had been expressed by landowners living downstream from the reservoir who observed lateral streambank erosion and loss of agricultural land.

Elkhead Creek meander migration rates were used as a measure of lateral channel instability and were calculated from aerial photographs for three periods of approximately equal length in reaches upstream and downstream from the reservoir (Elliott and Gyetvai, 1999). The channel upstream from Elkhead Reservoir was unaffected by impoundment and was used as the control reach for investigating downstream reservoir effects. Channel instability, quantified by meander migration rates, increased noticeably in both the upstream and downstream study reaches from 1978 to 1993.

The aerial photographic prints used to evaluate the Elkhead Creek channel during 1938–93 in the previous study were digitally scanned, and these images were electronically processed to remove optical distortion and photographic parallax common to many aerial photographs. The 1937, 1953, 1970, 1977, and 1981 aerial photographs were registered and rectified to 1997 digital orthophoto quadrangle (DOQ) images (developed from 1993 photographs) before geomorphic measurements and analysis were conducted (Elliott and Gyetvai, 1999, p. 7–11). Digital image processing, rectification, and registration to the 1997 DOQ maps were done with ArcView Spatial Analyst software (Environmental Systems Research Institute, Inc., 1996). Digital image processing and geometric correction are described in greater detail by Jensen (1996).

Use of from 7 to 14 control points near 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 . The range of the root-mean-square error (RMSE) (0.360 to 2.613 m) was within the error range noted by Gurnell (1997). 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).

Sediment characteristics, sediment entrainment potential, and estimated hydraulic conditions in Elkhead Creek established that most of the sediment represented in the streambed was mobile at frequently occurring discharges. Therefore, the channel was susceptible to erosion and lateral migration at frequently occurring discharges.

Streamflow data from water years 1953 through 1996 were examined to determine the effect of hydrology on meander migration rates. (A water year runs from October 1 through September 30.) Mean annual flood (average of the maximum instantaneous discharge, or peak discharge, in a water year, for the period) increased by 30 percent from the pre-regulation period (water years 1953 to 1970) to the post-regulation period (water years 1978 to 1993). Mean annual streamflow (average of the annual total of streamflow at a location, for the period) increased by 22 percent from the pre-regulation period (water years 1954 to 1970) to the post-regulation period (water years 1978 to 1993). (Note: Collection of streamflow data at this gage began in April 1953, after the beginning of the water year but before the 1953 instantaneous peak discharge. Therefore, the period of annual streamflow begins with water year 1954; whereas, the period of annual floods begins in water year 1953). The most probable cause for the observed channel instability and the increase in meander migration rates in both the upstream and downstream reaches was a combination of external factors affecting the entire watershed, such as increases in annual streamflow and peak flood magnitude, rather than the operation of Elkhead Reservoir. Local land-use practices, such as intentional meander cutoff and riparian vegetation removal, also may have decreased channel stability (Elliott and Gyetvai, 1999).

Other recent studies of Elkhead Creek include a comprehensive evaluation of the hydrology from multiple locations within the Elkhead Creek watershed and by different time periods (Kuhn and others, 2003). Ruddy (2010) evaluated the discharge gain and loss characteristics of Elkhead Creek between Elkhead Reservoir and its confluence with the Yampa River, and noted the effects of reservoir operation strategies and constraints on the magnitude and duration of peak flows.

Elkhead Creek 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 studied to represent relatively unregulated conditions in the watershed and to identify trends in fluvial geomorphology unrelated to Elkhead Reservoir effects. A reach approximately 9 river miles long downstream from Elkhead Reservoir was studied to identify any detectable reservoir effects (fig. 1).

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 223 mi^2 (U.S. Geological Survey, 2010). Elevations range between 6,220 and 10,500 ft. The geology of the headwater areas includes the sedimentary Iles Formation, Williams Fork Formation, and 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 Upper Cretaceous Lance Formation and Holocene alluvium (Tweto, 1976). The valley gradient in the lower 16 mi of the watershed ranges from 0.0045 to 0.0022 ft/ft (U.S. Geological Survey 7½ minute quadrangle maps Rock Spring Gulch, Colorado, 1971 and Ralph White Lake, Colorado, 1971).

Elkhead Creek is a meandering stream in the lower part of the watershed with sinuosity ranging from 1.1 (relatively straight) to 2.2 (highly sinuous) 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 (Elliott and Gyetvai, 1999).

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 riparian vegetation is dominated by cottonwood trees, willows, and other woody shrubs. Elkhead Reservoir is located 9 river miles upstream from the mouth of Elkhead Creek. Elkhead Dam was constructed in 1974 and had a normal pool capacity of 13,800 acre-ft. The dam elevation was increased by 25 ft during 2005–06, increasing the reservoir normal pool capacity from 13,800 to 25,550 acre-ft (*http://www.crwcd.org/page_28*, accessed February 23, 2010).

Hydrology

Elkhead Creek is a snowmelt-dominated stream with annual discharge peaks usually occurring from late April to late May. The USGS has operated several streamflow-gaging stations at various times in the watershed of Elkhead Creek (fig. 1). Station 09245000 Elkhead Creek near Elkhead, located in the middle part of the watershed, has the longest period of record (water years 1953–96), recorded streamflow from approximately 30 percent (68 mi^2) of the watershed, and is used for hydrologic reference in this study. This gage was discontinued in October 1996.

Two additional gaging stations, one upstream and one downstream from Elkhead Reservoir, were established in August 1995 to replace the discontinued station 09245000. Station 09246200 Elkhead Creek above Long Gulch is approximately 10.6 river miles upstream from Elkhead Dam and records most of the inflow to the reservoir (fig. 1). Streamflow from approximately 77 percent (171 mi^2) of the watershed passes the upstream gage at station 09246200.

The second gage, station 09246400 Elkhead Creek below Maynard Gulch (fig. 1), is approximately 3.3 river miles downstream from the dam and 5.9 river miles upstream from the confluence with the Yampa River and recorded streamflow until July 2008 when it was discontinued. The downstream gage at station 09246400 recorded streamflow from approximately 95 percent (212 mi^2) of the watershed and included outflow from Elkhead Reservoir. A new streamflow-gaging station was established approximately 5.1 mi downstream from station 09246400 in July 2008 and given a station identification of 09246500 Elkhead Creek near Craig; this new gage records streamflow from approximately 100 percent (222 mi^2) of the watershed.

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 ranged from 224 ft^3/s in water year 1992 to 2,850 ft^3/s in water year 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 ranged from 12,010 acre-ft in 1977 to 82,380 acre-ft in 1984 with a mean annual streamflow of 40,200 acre-ft (Crowfoot and others, 1997).

The hydrology of the lower Elkhead Creek watershed is affected by Elkhead Reservoir, constructed in 1974 and enlarged during 2005–06. The reservoir volume is kept near maximum capacity, and for most of the year, the reservoir outflow is kept similar to the inflow recorded at streamflow-gaging station 09246200 Elkhead Creek above Long Gulch where discharge can exceed 1,000 ft^3/s for several days. Reservoir operations during spring runoff can be varied to make optimal use of the outlet works, which are screened to prevent escape of non-native game fish from the reservoir and can pass about 590 ft^3/s (Ruddy, 2010). During any time of the year, but mostly during the low-flow period from July through October, downstream owners of Elkhead Reservoir water may request the release of their water. After these requested releases, subsequent releases may be less than the upstream inflow in order to refill the reservoir.

Discharge data were collected concurrently at streamflow-gaging stations 09245000, 09246200, and 09246400 for only one water year, 1996; however, some inferences can be made from this short period for the similarity of hydrologic characteristics at all three sites (Elliott and Gyetvai, 1999). During most of water year 1996, daily mean discharge downstream from Elkhead Reservoir (station 09246400) was similar to daily mean discharge upstream from the reservoir (station 09246200), indicating that, when Elkhead Reservoir is full, inflow to the

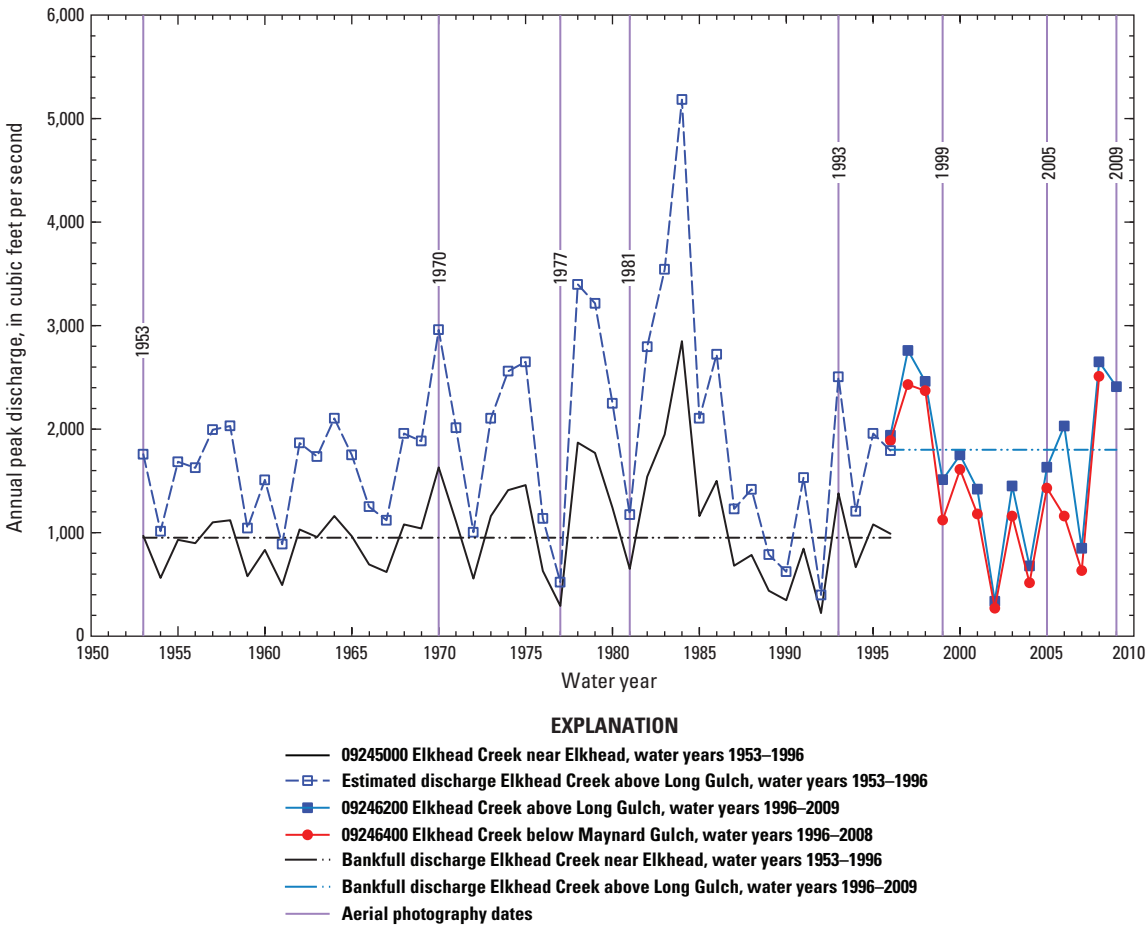

Figure 2. Plot showing annual peak discharges and estimated bankfull discharges for streamflow-gaging stations in the study area and aerial photography dates.

reservoir is about equal to outflow from the reservoir. Instantaneous diurnal discharge peaks at the downstream station lagged the upstream station by about 7 hours in 1996.

Flow duration curves of daily mean discharge for water years 1996–2001 at stations 09246200 and 09246400 were nearly identical for discharges greater than 10 ft^3/s, and the shape of the flow duration curve for water years 1954–1996 at station 09245000 was similar to those of the two, newer downstream gaging stations indicating that hydrologic characteristics were similar at all three stations (Kuhn and others, 2003, their fig. 3).

In water year 1996, the year all three gaging stations were operating concurrently, the peak discharges at stations 09246200 and 09246400 were about two times larger than the peak discharge at station 09245000, but whether this is representative of the long-term ratio is not known. Although daily mean discharges at station 09246400 are not affected substantially by Elkhead Reservoir, the instantaneous peak discharges at station 09246400, below the reservoir, are attenuated in comparison to peak discharges at station 09246200 upstream from the reservoir (Elliott and Gyetvai, 1999, p. 6; Kuhn and others, 2003, their figs. 2 and 3).

A continuous discharge record at a fixed location in the Elkhead Creek watershed does not exist for the period of this study. Therefore, discharge at streamflow-gaging station 09246200 for the period before 1996, when that station was established, was estimated by using the relation between discharge at stations 09246200 and 09245000 during the peak-discharge months of May and June in the year of their concurrent operation, 1996 (U.S.Geological Survey, National Water Information System, *http://waterdata.usgs.gov/co/nwis/*, accessed December 28, 2011). A linear regression analysis resulted in the equation:

$$Q_2 = 1.8224\,(Q_1) - 10.356, \qquad (1)$$

where,

Q_2 is the daily mean discharge at station 09246200 Elkhead Creek above Long Gulch, in cubic feet per second,

and

Q_1 is the daily mean discharge at station 09245000 Elkhead Creek at Elkhead, in cubic feet per second.

Equation 1 has a coefficient of determination (r^2) of 0.9864, indicating a strong relation between discharge during the peak flow months at the two stations. Consequently, an assumption was made that the relation between the daily mean discharges could be used to estimate the instantaneous peak discharge at station 09246200 from the recorded instantaneous discharge peaks at station 09245000. The estimated peak discharges at station 09246200 for 1953 through 1996 are shown in figure 2.

Elliott and Gyetvai (1999) examined instantaneous peak discharges for different time intervals determined by the dates of aerial photography and found that the mean annual flood at station 09245000 was 30 percent greater in the period water years 1978–93 (1,202 ft^3/s), a period after reservoir construction, than in the period water years 1953–70 (923 ft^3/s), a period of similar length before reservoir construction. Because this gaging station was discontinued at the end of water year 1996, no comparison to the more recent period from water years 1994–2009 could be made.

Annual streamflow (total streamflow from a watershed in a year) at station 09245000 was evaluated for the period of record (water years 1954–96) to detect trends in the periods before and after construction of Elkhead Reservoir. Kuhn and others (2003) found that although there was no statistical difference in the mean annual streamflow of the pre-reservoir period (37,970 acre-ft) and post-reservoir period (42,320 acre-ft), the variance in annual streamflow statistically was significantly greater in the post-reservoir period, water years 1975–96 (standard deviation 19,980 acre-ft), than in the pre-reservoir period, water years 1954–74 (standard deviation 11,960 acre-ft).

Methods

Data from several sources were used to evaluate channel-pattern and cross-section changes in Elkhead Creek. The three principal methods are described in the following sections.

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 taken in 1937, 1953, 1970, 1977, 1981, and 1993 were used to determine the channel position and to calculate meander migration rates in a previous USGS study (Elliott and Gyetvai, 1999, their fig. 3 and table 3). Aerial photographs taken in 1993, 1999, 2005, and 2009 were used to determine channel position and to calculate meander migration rates in this study, for the period subsequent to the previous study. Most of the photographs were taken in August or September, after the annual peak discharge for that year, when seasonal streamflow had receded to low levels, exposing the streambanks and alluvial bars (figs. 3*A* through 3*D*). Because the aerial photographs were taken after the date of the peak discharge in any given year, subsequent discharge-related channel changes were assumed to have occurred no sooner than in the first year following the photograph date. Consequently, the evaluation period began the year following the aerial photograph date and ended in the year of the subsequent aerial photograph.

Photographs taken in 1937 and 1953 bracket a period (period 1, 1938–53) prior to the establishment of a streamflow-gaging station on Elkhead Creek. Photographs taken in 1953 and 1970 bracket a period (period 2, 1954–70) of relatively small flood peaks when only about one-half of the annual flood peaks exceeded the estimated bankfull discharge at streamflow-gaging station 09245000 (fig. 2). Photographs taken in 1977 and 1993 bracket a comparable length of time (period 3, 1978–93) in which annual flood peaks exceeded the estimated bankfull discharge at 09245000 about the same number of times as in period 2, but with much greater magnitude. The photographs taken in 1977 and thereafter document the period since construction of Elkhead Reservoir in 1974.

Photographs taken in 1993 and 2009 bracket a period (period 4, 1994–2009) in which the 09245000 streamflow gage was discontinued (October 1996) and replaced farther downstream by the 09246200 and 09246400 gages (established August 1995). Annual flood peaks in period 4 exceeded the estimated bankfull discharges at the respective gages about one-half of those years, and the year-to-year variability was large (fig. 2). The 2009 photographs document the channel condition following the enlargement of Elkhead Dam and Reservoir during 2005–06.

The aerial-photographic analysis of the Elkhead Creek channel in period 4, a subject of this study, is a continuation of the aerial-photographic analysis of the channel in periods 1, 2, and 3 (Elliott and Gyetvai, 1999). The method of aerial-photographic analyses for periods 1, 2, and 3 is described in the Previous Studies section of this report and results from Elliott and Gyetvai (1999) are reproduced in this report to facilitate comparison to the analysis of Elkhead Creek in period 4.

Imagery of the Elkhead Creek channel for analysis in the present study was obtained in digital format for the years 1993, 1999, 2005, and 2009. The 1993 data were obtained from the USGS as digital orthophoto quarter quadrangles that were provided in orthorectified format. The 1999 data were obtained from the Aerial Photography Field Office of the U.S. Department of Agriculture Farm Service Agency as unrectified imagery scanned from National Aerial Photography Program film (*http://eros.usgs.gov/#/Guides/napp*). In a methodology similar to Elliott and Gyetvai (1999), by identifying

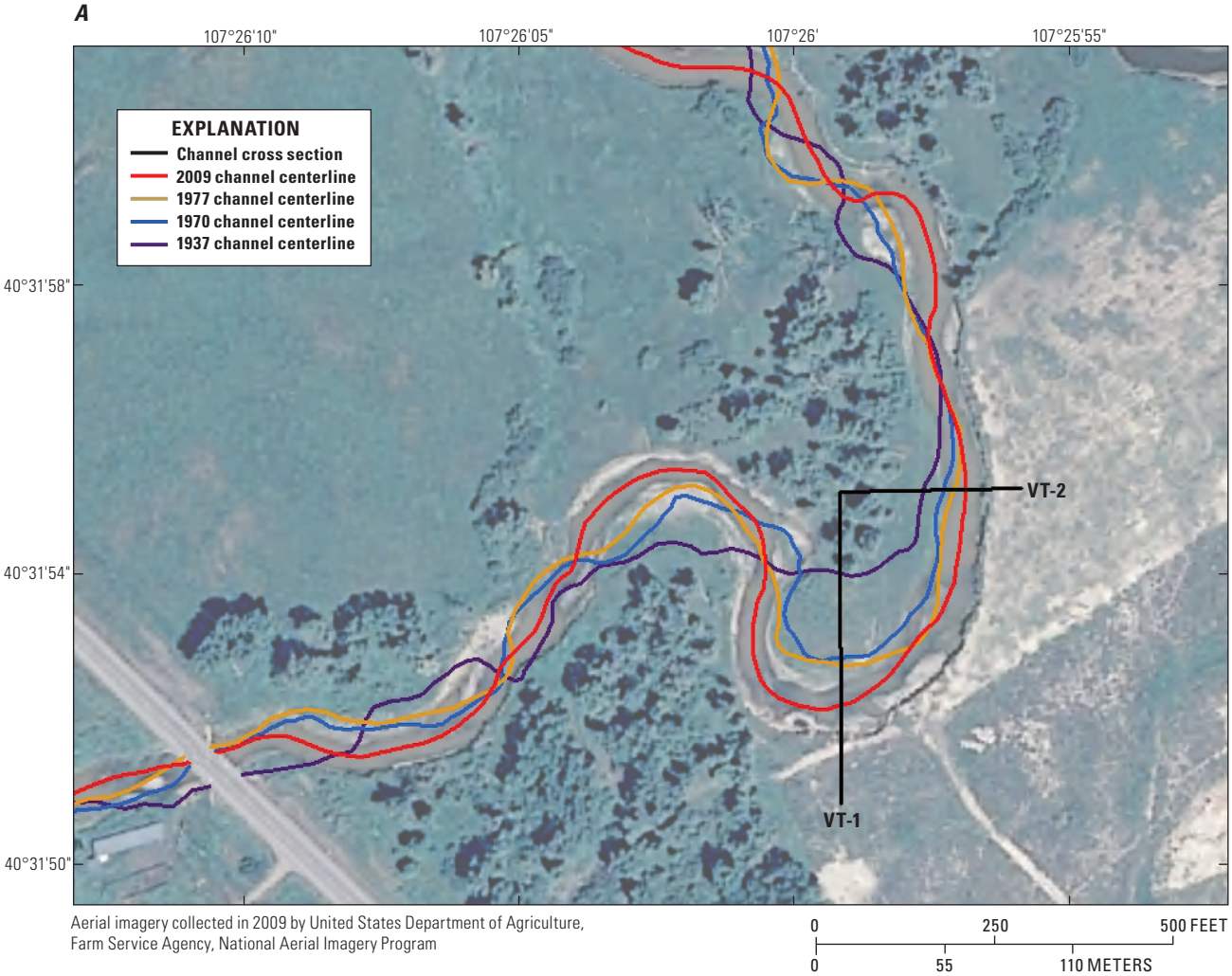

Figure 3. Aerial photographs of Elkhead Creek in 2009 with plots of the channel centerline in 1937, 1970, 1977, and 2009, (*A*) Cross sections VT-1 and VT-2 downstream from Elkhead Reservoir.

semipermanent features in both 1999 and 1993 aerial photographs, the 1999 imagery was rectified to the 1993 imagery using a second-order polynomial transformation in the Georeferencing Toolbar of ESRI ArcGIS ArcMap, version 9.3.1 (Environmental Systems Research Institute, Inc., 2009). The 2005 and 2009 digital images were obtained from the USGS Colorado Geospatial Liaison as orthorectified compressed county mosaics (U.S. Department of Agriculture, 2009) and required no modification or additional rectification.

Planimetric Geomorphology

Planimetric geomorphic characteristics of Elkhead Creek, and changes over time, were quantified by Elliott and Gyetvai (1999) using topographic maps and six sets of aerial photographs spanning several decades. These characteristics, and changes since the 1993 aerial photographs, are updated through 2009 in this report.

Channel changes from 1938 through 1993 (Elliott and Gyetvai, 1999), and from 1994 through 2009 (this report), 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 typically 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.

Thirty meander bends included in the previous study were selected to be representative of other meanders in the Elkhead Creek valley (Elliott and Gyetvai, 1999, their fig. 3 and table 3); the same meander bends were evaluated in this study for the period 1994 through 2009. Seventeen meanders were selected in the reach downstream from Elkhead Dam, and 13 meanders were selected in the reach upstream from the

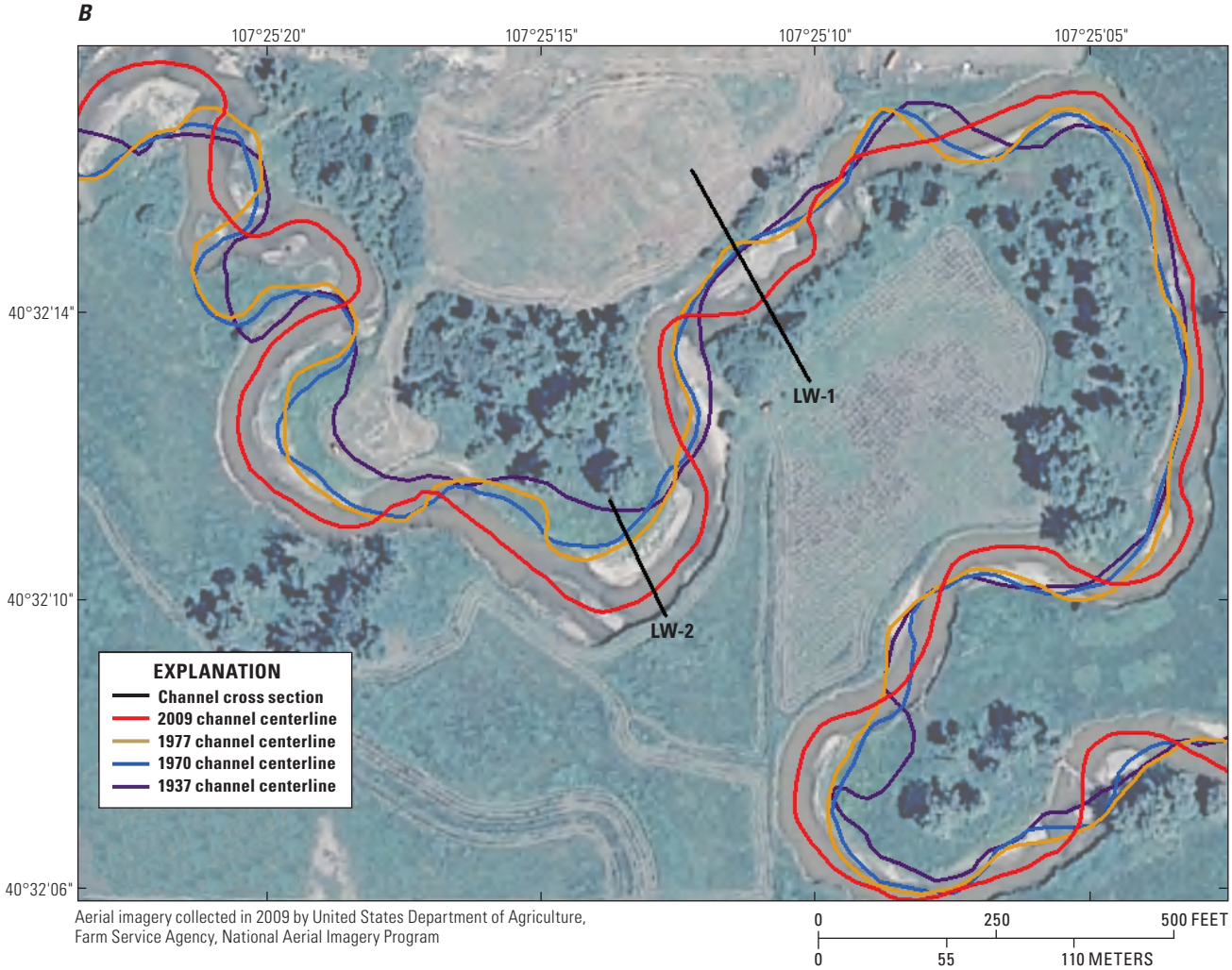

Figure 3. Aerial photographs of Elkhead Creek in 2009 with plots of the channel centerline in 1937, 1970, 1977, and 2009, (*B*) Cross sections LW-2 and LW-1 downstream from Elkhead Reservoir.—Continued

backwater effects of Elkhead Reservoir (fig. 1). The upstream reach was considered the control reach, unaffected by Elkhead Reservoir. 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 typically resulted in a directional change in meander migration (Elliott and Gyetvai, 1999, their figs. 3*C* and 4), and was 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. Both studies 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 (Elliott and Gyetvai, 1999, their fig. 3*A*).

Elkhead Creek meander migration rates were calculated using a variation of the method developed by Hickin (1974) and Hickin and Nanson (1984) and are described in greater detail in Elliott and Gyetvai (1999). 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.

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 aerial 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. Potential error in locating the channel center line partly is a function of the aerial-photograph-rectification precision 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 at discharges from 16 to 18 ft^3/s (Elliott and Gyetvai, 1999, their fig. 5), and 35 to 63 ft when channel surveys were made in 2009 at discharges from 13 to 14 ft^3/s.

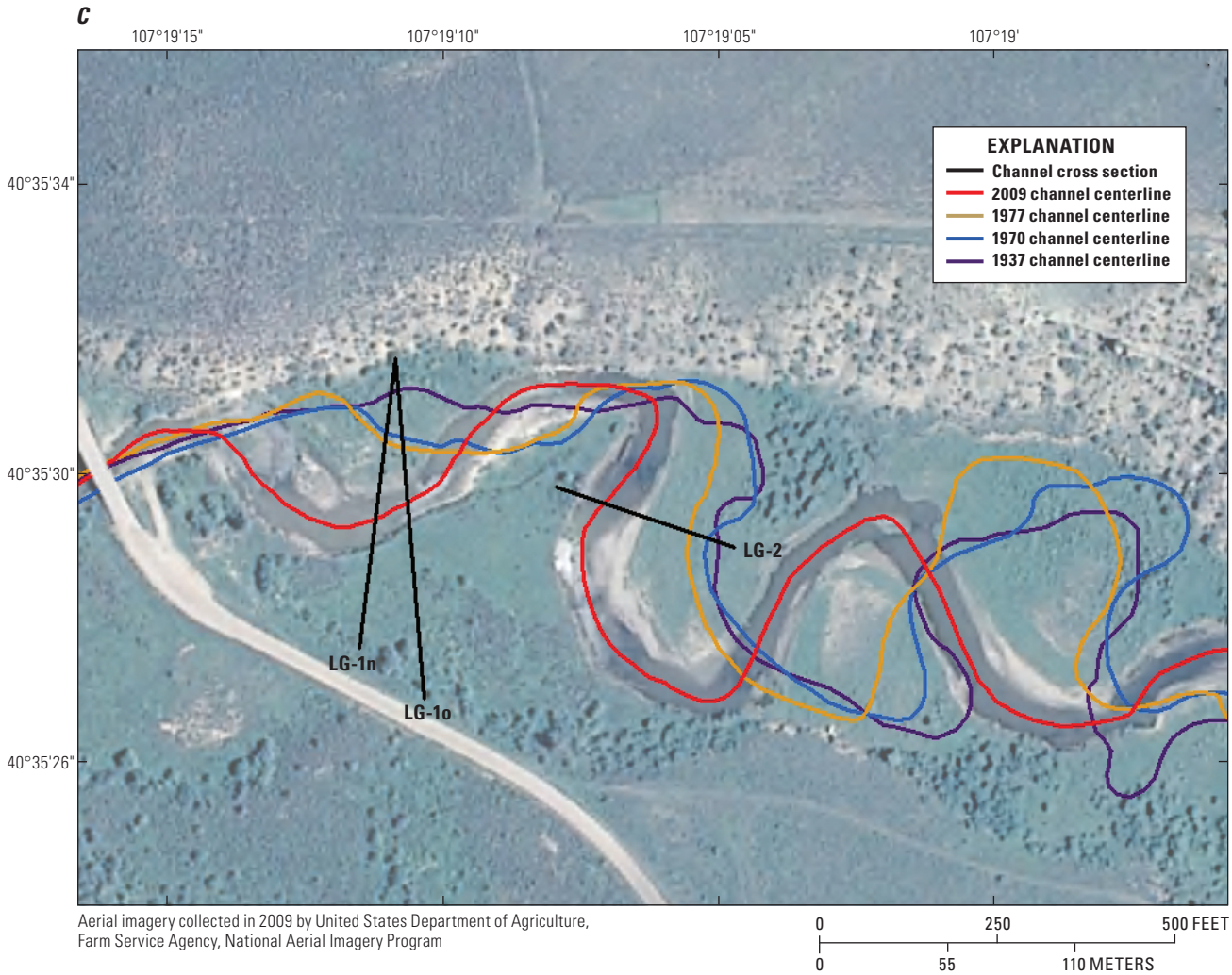

Figure 3. Aerial photographs of Elkhead Creek in 2009 with plots of the channel centerline in 1937, 1970, 1977, and 2009, (*C*) Cross sections LG-1.n, LG-1.o, and LG-2 upstream from Elkhead Reservoir.—Continued

Meander migration rates since 1993 were determined for three shorter subperiods defined by aerial photos taken in 1993, 1999, 2005, and 2009 (subperiods 4A, 1994–99; 4B, 2000–05; and 4C, 2006–09). Because the Elkhead Creek photographs are separated by several years, the channel position changes quantified for this, and the previous, analysis reflect average meander migration rates for the time intervals.

Cross-Sectional Geomorphology and Streambed Sediment

Channel-geometry characteristics and the water-surface slope of Elkhead Creek were surveyed at eight cross sections in 1997 using a Topcon total-station laser theodolite to determine geomorphic and hydraulic properties that affect sediment-entrainment potential and channel instability (Elliott and Gyetvai, 1999, their figs. 3*A*–*C*). Seven of these cross sections (VT-1, VT-2, LW-1, LW-2, LG-2, PT-1, and PT-2) were located and resurveyed in 2009. Only the right cross-section headpin of an eighth cross section surveyed in 1997, LG-1, was relocated. Subsequently, a new left headpin was established at LG-1 resulting in a slight realignment of the cross section. Consequently, the 1997 cross section was renumbered LG-1.o (old), and the 2009 cross section was numbered LG-1.n (new). The 2009 channel surveys were made using a Trimble real-time kinetic (RTK) global positioning system (GPS) surveying instrument. These cross sections were representative of the channel morphology upstream and downstream from Elkhead Reservoir. The replicate surveys were made to quantify channel changes between the dates of the two studies.

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. Bankfull discharge was estimated to be approximately 1,800 ft^3/s, based on surveyed channel characteristics at the cross sections and discharge measurements at the gaging station on Elkhead Creek above Long Gulch (09246200). Water-surface slope and cross-sectional characteristics were used to estimate boundary shear stress for selected streamflows.

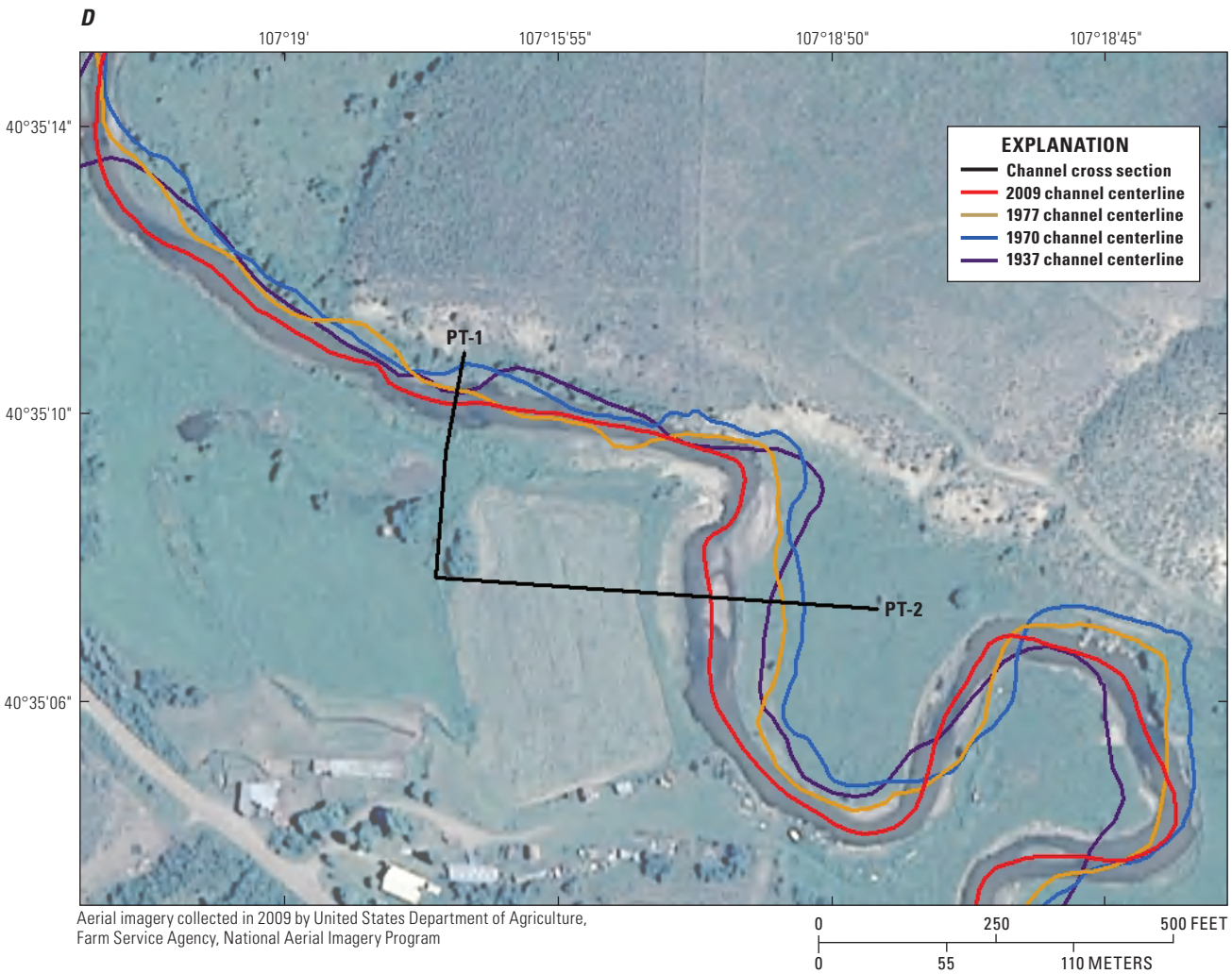

Figure 3. Aerial photographs of Elkhead Creek in 2009 with plots of the channel centerline in 1937, 1970, 1977, and 2009, (*D*) Cross sections PT-1 and PT-2 upstream from Elkhead Reservoir.—Continued

Characteristics of sediment in the channel and the stratigraphy of the valley-fill material were determined from onsite inspection during the channel surveys. Sediment from the streambed surface was sampled in 1997 and 2009 at the Elkhead Creek cross sections using the Wolman method for measuring the sediment-size characteristics of coarse bed material (Wolman, 1954). The sediment particle intermediate dimension (b-axis) was measured directly with a meter stick. Direct measurement of the particle b-axis determines sediment-size characteristics "based upon an analysis of the relative area covered by given sizes, rather than upon their relative weights" (Wolman, 1954, p. 951), as does a bulk-sample sieve analysis for which a gravelometer is a surrogate. Aerial sampling "gives a more representative sample" of the bed material (Wolman, 1954, p. 956).

The 1997 sediment measurements were made at regularly spaced intervals across the channel from bank to bank and included the streambed and 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, but did include the finer streambank material. The 2009 measurements were made at the same locations as the 1997 measurements but were limited to only the streambed. In order to compare the 2009 and 1997 streambed-sediment-size characteristics, the original annotated 1997 measurement field notes were reviewed and the sample median particle size (d_{50}) was recalculated using only individual measurements of streambed particles.

Channel-Pattern Changes, 1938–2009

Channel-pattern changes were evaluated over periods of approximately equal length that were defined by aerial-photography dates. Period 1, 1938 through 1953 (defined by aerial photographs taken in 1937 and 1953), and period 2, 1954 through 1970 (defined by aerial photographs taken in 1953 and 1970), are representative of the time before

streamflow regulation by Elkhead Reservoir. Period 3, 1978 through 1993 (defined by aerial photographs taken in 1977 and 1993), follows the construction of Elkhead Dam and Reservoir in 1974 and is representative of the period of flow regulation downstream from the reservoir. Period 4, 1994 through 2009 (defined by aerial photographs taken in 1993 and 2009), includes the enlargement of Elkhead Dam and Reservoir in 2005–06. Because additional images were available from aerial photographs taken in 1999 and 2005, channel pattern changes for the shorter subperiods 4A, 1994–99; 4B, 2000–05; and 4C, 2006–09 also were evaluated.

Elkhead Creek meanders included in this study were fully developed meander bends as shown in the 1937 and subsequent aerial photographs. Two predominant meander migration modes were observed in the study areas—amplitude increase and translational shift (Hickin, 1974). Amplitude increase involved lateral migration, typically 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 (cross section VT-1, fig. 3*A*). The meander amplitude increased, more or less, along an orthogonal that bisected the point bar and was typical of the migration of Canadian river meanders studied by Hickin (1974). 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 meander-bend limbs migrated laterally along with the location of minimum radius of curvature when the meander bend underwent a translational shift (cross section LG-2, fig. 3*C*).

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 streambed and bank scour (Schumm, 1977). Over time, some of these local effects are mitigated by additional changes upstream and downstream from the avulsion in gradient, sinuosity, channel cross section, and roughness. Human-induced, mechanical cutoffs produce similar channel and pattern changes over time, although the specific effects may be unpredictable. 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. None of the monitored meanders included in the previous study (Elliott and Gyetvai, 1999) that underwent avulsion after 1993 were included in subsequent meander-migration calculations in this study.

Meander migration rates were calculated for 17 meanders in the reach downstream from Elkhead Dam and for 13 meanders upstream from Elkhead Reservoir (figs. 4*A* and 4*B* and table 1). 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. Negative meander migration rates were recorded in some time periods when the channel reversed its lateral movement (in either amplitude increase or translational shift). An assumption was made that, by assigning negative values to channel-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 or infrastructure than would a meander that initially increased in amplitude but subsequently decreased in amplitude (through channel-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 migration rates for 30 individual meanders are presented in table 1. Meander migration rate means and variances were calculated for two groups (upstream and downstream from Elkhead Reservoir) and for four periods and three subperiods from 1938 to 2009 in order to investigate the potential effects of the reservoir and multi-year streamflow trends on meander migration.

Meander migration rates in the reach downstream from Elkhead Reservoir were compared to rates upstream from the reservoir to investigate possible effects of reservoir impoundment on channel-pattern changes (table 2). Meander migration rates for periods 1 though 4 ranged from –3.2 to 12.1ft/yr in the reach downstream from Elkhead Reservoir, and ranged from –6.3 to 14.2 ft/yr in the reach upstream from the reservoir (table 1). Comparisons were made between reaches in each of the four, previously defined periods of 16 to 17 years duration. The equality of meander migration rate variances was examined with an F-test at the 0.05 significance level (p equal to 0.05) (Davis, 1973). Downstream meander migration rate variances were statistically indistinguishable (p greater than (>) 0.05) from upstream variances in all periods except period 2, where variance was much greater (p less than (<) 0.05) in the upstream reach than in the downstream reach (table 2). The equality, or inequality, of the variance determines the form of the subsequent test for equality of means (Davis, 1973).

The equality of meander migration rate means in the two reaches was examined with a t-test at the 0.05 significance level. Downstream meander migration rate means were statistically indistinguishable from upstream means in all periods (p >0.05) (table 2). Downstream and upstream meander migration rates were statistically indistinguishable in the two periods preceding construction of Elkhead Reservoir (periods 1 and 2), and in the two periods following construction of the reservoir (periods 3 and 4), indicating that the presence of Elkhead Reservoir has had no apparent long-term effect on channel-pattern changes.

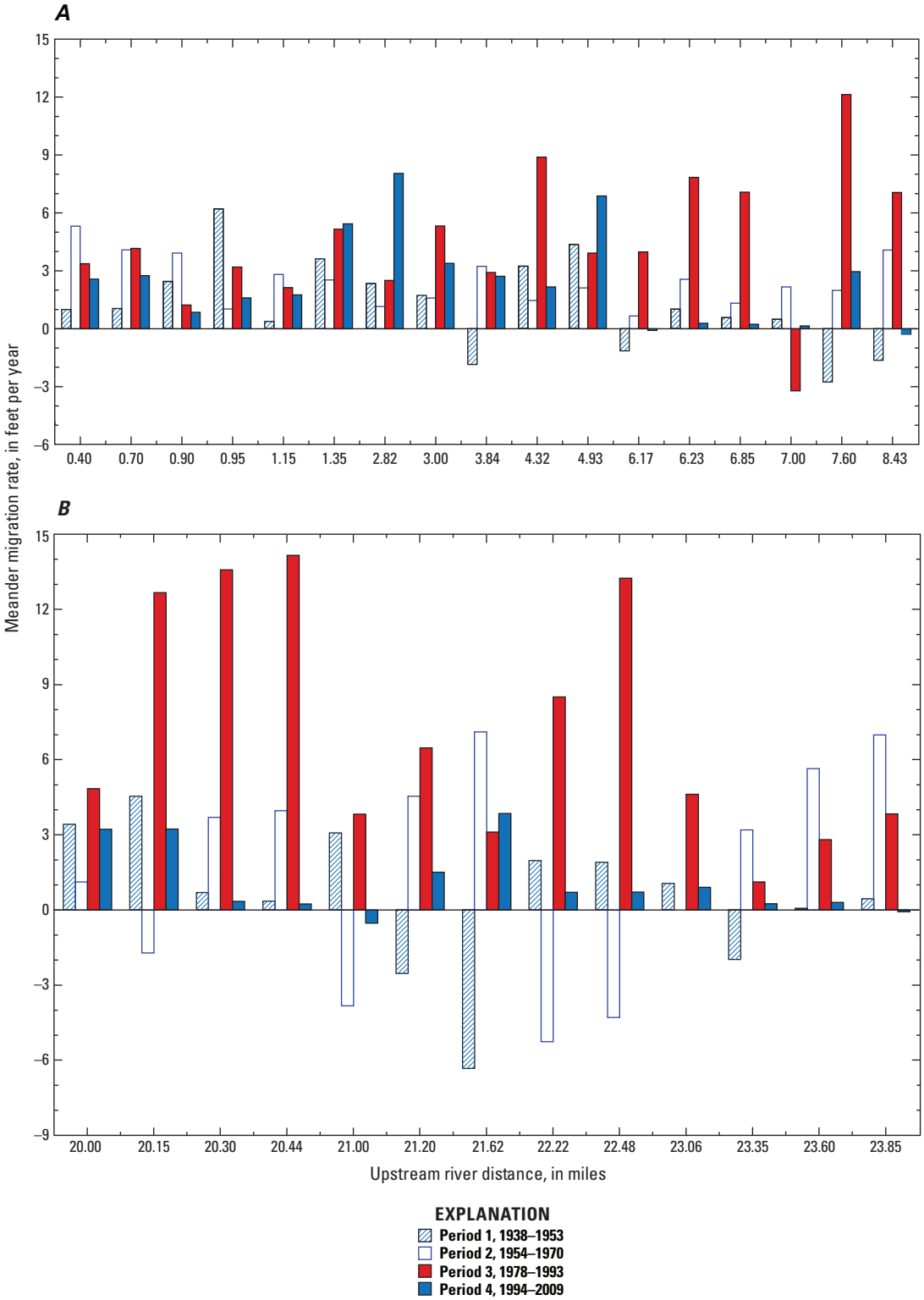

Figure 4. Graphs showing Elkhead Creek meander migration rates for time intervals of equal duration, (*A*) Reach downstream from Elkhead Reservoir, (*B*) Reach upstream from Elkhead Reservoir.

Table 1. Elkhead Creek meander migration rates.

[River mile, channel distance upstream from confluence with Yampa River; ft/yr, feet per year; mean, mean migration rate; stan dev, standard deviation; na, not applicable]

River mile and meander code	Period 1 1938–1953 Meander migration rate (ft/yr)	Period 2 1954–1970 Meander migration rate (ft/yr)	Period 3 1978–1993 Meander migration rate (ft/yr)	Period 4 1994–2009 Mender migration rate (ft/yr)	Subperiod 4A 1994–1999 Meander migration rate (ft/yr)	Subperiod 4B 2000–2005 Meander migration rate (ft/yr)	Subperiod 4C 2006–2009 Meander migration rate (ft/yr)	Remarks
Meanders downstream from Elkhead Reservoir								
0.40	1.0	5.3	3.4	2.6	3.5	1.6	2.6	
0.70	1.0	4.1	4.2	2.7	5.1	0.7	2.2	
0.90	2.4	3.9	1.2	0.8	0.9	0.9	0.7	
0.95	6.2	1.0	3.2	1.6	1.6	0.9	2.7	
1.15	0.4	2.8	2.1	1.8	2.5	0.6	2.5	
1.35	3.6	2.5	5.2	5.4	9.0	5.5	na	Avulsion 2005–09
2.82	2.3	1.2	2.5	8.0	12.9	7.6	1.5	Pattern reversal 1977–81
3.00	1.7	1.6	5.3	3.4	1.8	0.5	10.2	
3.84	–1.9	3.2	2.9	2.7	3.4	4.5	–1.0	Pattern reversal 1937–53, shift 1953
4.32	3.2	1.5	8.9	2.2	1.1	4.2	0.7	
4.93	4.4	2.1	3.9	6.9	13.8	2.2	3.5	Avulsion downsteam 1993–1999
6.17	–1.1	0.7	4.0	–0.1	0.8	–1.7	1.1	
6.23	1.0	2.6	7.8	0.3	–0.4	1.7	–0.8	
6.85	0.6	1.3	7.1	0.2	0.8	1.0	–1.7	
7.00	0.5	2.2	–3.2	0.1	–0.1	0.1	0.5	
7.60	–2.8	2.0	12.1	3.0	7.1	–0.5	1.9	
8.43	–1.6	4.1	7.1	–0.3	–0.4	–1.6	1.8	
Mean	1.2	2.5	4.6	2.4	3.7	1.7	1.8	
Stan dev	2.4	1.3	3.4	2.4	4.5	2.5	2.7	
Meanders upstream from Elkhead Reservoir								
20.00	3.4	1.1	4.8	3.2	2.4	2.4	5.8	
20.15	4.5	–1.7	12.7	3.2	–1.6	8.2	2.9	
20.30	0.7	3.7	13.6	0.3	4.1	–7.6	6.5	
20.44	0.3	4.0	14.2	0.2	0.0	–2.8	5.1	
21.00	3.1	–3.8	3.8	–0.5	–1.5	0.4	–0.4	
21.20	–2.5	4.5	6.5	1.5	11.8	–7.3	–0.7	
21.62	–6.3	7.1	3.1	3.8	3.1	5.5	2.5	
22.22	2.0	–5.3	8.5	0.7	0.4	2.9	–2.1	
22.48	1.9	–4.3	13.2	0.7	–0.6	1.7	1.2	
23.06	1.1	0.0	4.6	0.9	0.1	2.3	na	Avulsion 2005–09
23.35	–2.0	3.2	1.1	0.2	–0.2	–0.5	2.1	
23.60	0.0	5.6	2.8	0.3	–0.8	1.5	0.3	
23.85	0.4	7.0	3.8	–0.1	–0.9	0.6	0.1	
Mean	0.5	1.6	7.1	1.1	1.3	0.5	2.0	
Stan dev	2.9	4.3	4.7	1.4	3.6	4.5	2.7	

Meander migration rates in different periods were compared to investigate possible effects of annual streamflow, peak discharge, or other external variables unrelated to reservoir operation on channel-pattern changes (table 3). Although the significance of differences in variances and means between some periods was marginal (p-value very close to 0.05), some general observations are noteworthy. The means in periods 1, 2, and 4 statistically were indistinguishable within the downstream reach and within the upstream reach; however, the mean of period 3 was different from the means of periods 1, 2, and 4 (t-test, table 3). Similarities and differences in period variances (F-test) showed a less consistent pattern than did means.

Period 3 had the greatest mean and variance in meander migration rates in both the downstream and upstream reaches (table 2). A possible explanation for the statistically greater mean meander migration rate in period 3 for both the downstream and upstream reaches could be due to the large annual peak discharges in Elkhead Creek during period 3 (1978–93) that affected all reaches in the watershed. Four of the largest measured and estimated annual peak discharges occurred during this period (fig. 2).

Meander migration rates in period 4 also were calculated over shorter, 4- to 6-year, time intervals (table 1) to evaluate the potential effect of the 2005–06 Elkhead Reservoir enlargement on downstream channel changes. As with the

Table 2. Comparison of meander migration rates by reach within period.

[>, greater than]

Reach statistics	Period 1 1938–1953	Period 2 1954–1970	Period 3 1978–1993	Period 4 1994–2009
Downstream reach meander migration rate				
Number of meanders	17	17	17	17
Mean	1.2	2.5	4.6	2.4
Standard deviation	2.4	1.3	3.4	2.4
Variance	5.5	1.7	11.8	5.9
Upstream reach meander migration rate				
Number of meanders	13	13	13	13
Mean	0.5	1.6	7.1	1.1
Standard deviation	2.9	4.3	4.7	1.4
Variance	8.2	18.5	22.1	2.0
Reach comparison (downstream compared to upstream) (p-value)				
t-test (means equal if p >0.05)	0.452	0.506	0.094	0.094
F-test (variances equal if p >0.05)	0.457	0.00003	0.239	0.064

longer 16- to 17-year periods, meander migration rates in subperiods 4A (1994–99), 4B (2000–05) and 4C (2006–09) were examined with F-tests and t-tests at the 0.05 significance level (results not shown). These tests showed no statistically significant differences in the meander migration rates between the subperiods, indicating the enlargement of Elkhead Reservoir has had no apparent effect on channel change through 2009.

Cross-Section Changes, 1997–2009

The valley floor of Elkhead Creek preserves a history of channel changes not only in the channel pattern (in the form of meander migration), but also in streambed elevation and cross-section dimensions. Elliott and Gyetvai (1999) found anecdotal evidence from local landowners and residents that suggested the channel of Elkhead Creek may have incised in the late 20th century both upstream and downstream from Elkhead Reservoir (Donald Van Tassel and Leroy Lawton, local residents, oral commun., 1997). Using the broad, valley-floor terrace as a vertical reference to a former flood-plain surface (fig. 5), Elliott and Gyetvai (1999) determined that the bankfull surface in 1997 ranged from 2.5 to 3.8 ft below the terrace surface at cross sections upstream from Elkhead Reservoir and 2.9 to 6.2 ft below the terrace at cross sections downstream from the reservoir, indicating the channel was adjusting to a lower base level.

Other evidence pointed to past periods of vertical channel and flood-plain aggradation. Buried, intact tree trunks and dense root masses were observed in the valley-fill material exposed by the cutbank at one downstream cross section, indicating vertical aggradation of a former flood-plain surface in that reach, possibly within the last century, and subsequent incision to a lower elevation (Elliott and Gyetvai, 1999, their fig. 5*F*). Stratigraphic evidence in flood-plain sediment also indicated that Elkhead Creek had undergone vertical channel

Table 3. Comparison of meander migration rates by period within downstream or upstream reach.

[>, greater than]

	Period 1 1938–1953 p-value	Period 2 1954–1970 p-value	Period 3 1978–1993 p-value	Period 4 1994–2009 p-value
Downstream reach meander migration rate				
Period 1 1938–1953				
t-test (means equal if p >0.05)		0.069	0.002	0.152
F-test (variances equal if p >0.05)		0.022	0.139	0.908
Period 2 1954–1970				
t-test (means equal if p >0.05)	0.069		0.029	0.959
F-test (variances equal if p >0.05)	0.022		0.0003	0.016
Period 3 1978–1993				
t-test (means equal if p >0.05)	0.002	0.029		0.045
F-test (variances equal if p >0.05)	0.139	0.0003		0.172
Period 4 1994–2009				
t-test (means equal if p >0.05)	0.152	0.959	0.045	
F-test (variances equal if p >0.05)	0.908	0.016	0.172	
Upstream reach meander migration rate				
Period 1 1938–1953				
t-test (means equal if p >0.05)		0.442	0.0003	0.494
F-test (variances equal if p >0.05)		0.172	0.098	0.021
Period 2 1954–1970				
t-test (means equal if p >0.05)	0.442		0.005	0.696
F-test (variances equal if p >0.05)	0.172		0.760	0.0005
Period 3 1978–1993				
t-test (means equal if p >0.05)	0.0002	0.005		0.0006
F-test (variances equal if p >0.05)	0.098	0.760		0.0002
Period 4 1994–2009				
t-test (means equal if p >0.05)	0.494	0.696	0.0006	
F-test (variances equal if p >0.05)	0.021	0.0005	0.0002	

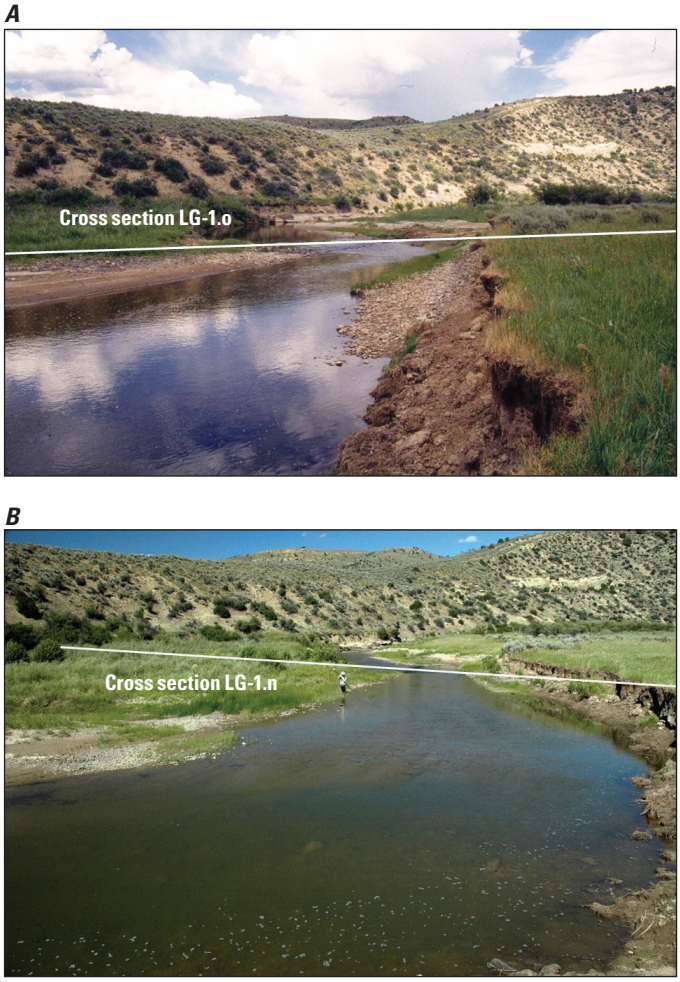

Figure 5. Photographs of Elkhead Creek above Long Gulch reach at cross sections LG-1.o and LG-1.n showing lateral erosion and channel migration, view is upstream, (*A*) July 17, 1997, (*B*) July 21, 2009. Photographs by John G. Elliott, U.S. Geological Survey.

changes and sediment-size changes. The 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 (Elliott and Gyetvai, 1999, their figs. 5*A*–5*H*).

Several channel cross sections were monumented and surveyed in 1997, and seven of these were located and resurveyed in 2009 (figs. 3 and 6). The replicate surveys provided a means to quantify lateral and vertical channel adjustments at the cross-section scale over a 12-year period (figs. 6*A*–6*H*). One of the 1997 reference marks (the left headpin) at cross section LG-1 could not be located in 2009 and a new cross section (LG-1.n) with a different alignment was surveyed using the remaining reference mark (the right headpin) (fig. 3*C*).

One monumented cross section, PT-2, had been mechanically altered by the landowner who reduced the angle of a formerly vertical left bank (figs. 3*D* and 6*H*). Some of the monumented cross sections showed little change in bank location between the 1997 and 2009 surveys; for example cross sections VT-1 (fig. 6*A*), VT-2 (fig. 6*B*), and PT-1 (fig. 6*G*). Other cross sections revealed several feet of lateral erosion resulting from streamflow and sediment transport, for example cross sections LW-2 (fig. 6*C*), LW-1 (fig. 6*D*), and LG-2 (fig. 6*F*). Most cross sections showed evidence of bed-material deposition in the form of alluvial bars (fig. 6*G*) or bank accretion (figs. 6*A*, 6*B*, 6*C*, and 6*F*).

Changes in streambed elevation, incision depth, and lateral erosion from 1997 to 2009 are summarized in table 4. The incision depth at each cross section was defined as the difference between the mean terrace (or valley-floor) elevation and the thalweg (or deepest part of the channel) elevation. Incision depths changed very little between the two surveys, averaging 10.0 ft in cross sections downstream from Elkhead Reservoir and 8.8 feet in cross sections upstream from the reservoir in both 1997 and 2009.

Lateral erosion for all cross sections ranged from –3.5 to 29.7 ft (table 4). Cross-section PT-1 had a negative lateral erosion because both banks showed lateral accretion as the channel narrowed between 1997 and 2009 (fig. 6*G*). The mean lateral erosion was 6.5 ft at cross sections downstream from the reservoir and 13.1 ft at cross sections upstream from the reservoir. The lateral-erosion rate, calculated over the 12-year period from 1997 to 2009, ranged from 0.1 to 1.3 ft/yr in four cross sections downstream from the reservoir, and from –0.3 to 2.5 ft/yr in two cross sections upstream from the reservoir. Lateral-erosion rates measured at cross sections in both reaches were within the ranges of meander migration rates measured in aerial photographs for period 4, 1994–2009 (table 1), indicating that channel changes surveyed at the eight selected monitoring cross sections were representative of other Elkhead Creek reaches.

Sediment from the streambed was sampled in 2009 to determine the size distributions at each surveyed cross section. The median particle sizes (d_{50}) from the 2009 samples were compared with recalculated streambed measurements from 1997 (table 4). The streambed in both periods was predominantly in the gravel particle-size range (defined as d_{50} greater than 2 mm to 64 mm), although most cross sections had some sediment in the sand-size range (d_{50} greater than 0.0625 mm to 2.0 mm) and all cross sections had sediment in the cobble-size range (d_{50} greater than 64 mm to 256 mm). No definitive conclusions can be made from changes in the median sediment size between 1997 and 2009. Some sites became coarser, whereas other sites became finer (table 4). The large increase in the median size at cross section PT-1 could be explained, in part, by the deposition of a coarse, subaqueous, mid-channel bar between 1997 and 2009 (fig. 6*G*).

Elliott and Gyetvai (1999) determined that sufficient shear stress was generated by the bankfull discharge to entrain gravels and some cobbles at all monitored cross sections. Annual peak discharges in Elkhead Creek exceeded the bankfull discharge in 4 of the 12 years between 1997 and 2009 (fig. 2), and streamflow during these years likely was associated with the erosion and deposition of streambed sediment discernable in replicate photographs (fig 5*A* and 5*B*) and replicate cross-section surveys (figs. 6*A*–6*H*).

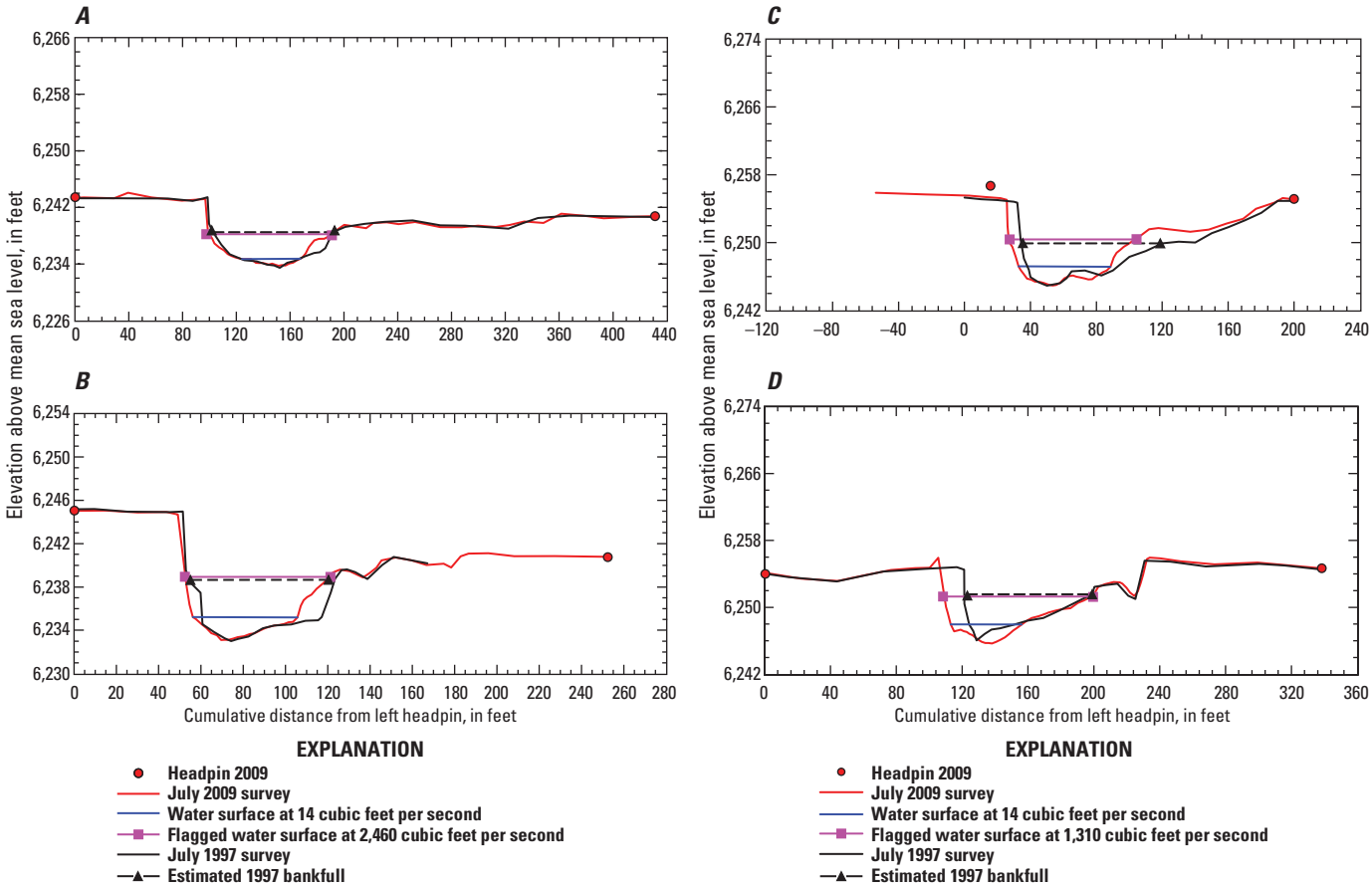

Figure 6. Elkhead Creek channel cross sections surveyed in 1997 and 2009, (*A*) Elkhead Creek at Van Tassel Ranch, cross-section VT-1, (*B*) Elkhead Creek at Van Tassel Ranch, cross-section VT-2, (*C*) Elkhead Creek at Lawton Ranch, cross-section LW-2, (*D*) Elkhead Creek at Lawton Ranch, cross-section LW-1.

Factors Affecting Channel Changes

Several variables affect channel stability and change in Elkhead Creek, including characteristics of the flood-plain and channel sediments, the variability of climate and streamflow, land-use practices, and intentional manipulation of the channel. 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 riparian vegetation characteristics), bank height, meander-bend radius of curvature, channel width, and sediment transport (Hickin and Nanson, 1984). Channel migration can be gradual, as a meander bend changes its cross-section form or bend radius of curvature through incremental bank erosion and point-bar growth, or it can be abrupt, by 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, roadway, or building site.

A large proportion of the streambed sediment in Elkhead Creek is sand and fine gravel that can be transported by relatively low discharges. Elliott and Gyetvai (1999) demonstrated that sand is entrainable at almost any discharge in Elkhead Creek, and that medium gravel (as much as 23 mm in diameter) can be entrained 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 ft^3/s). Larger or more frequent floods would be more effective at transporting sediment in Elkhead Creek.

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 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 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 and the calcium-carbonate cemented cobbles at cross section VT-1 (Elliott and Gyetvai, 1999, their figs. 5*A* and 5*H*), could make lateral erosion a more common channel adjustment than streambed scour.

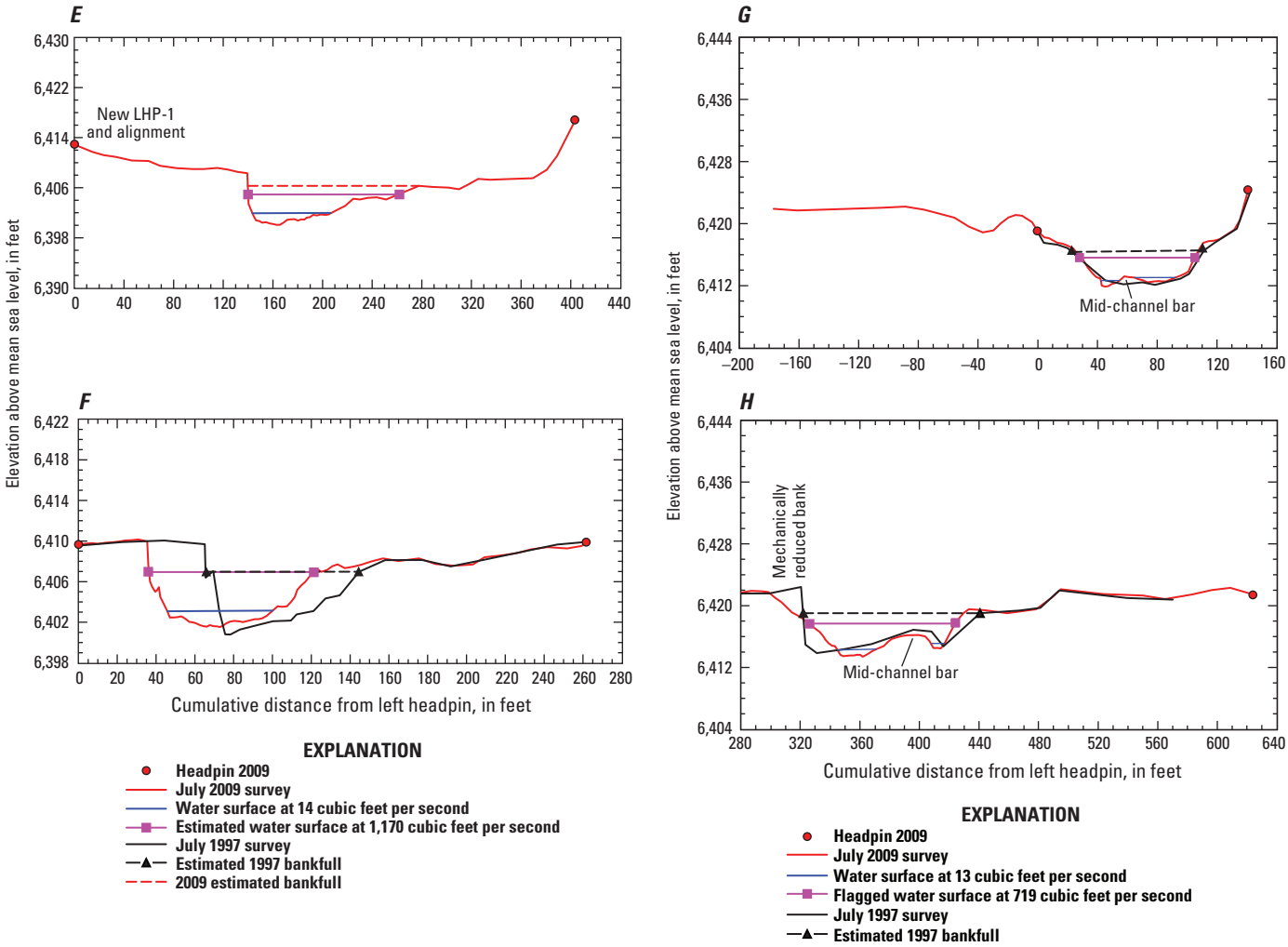

Figure 6. Elkhead Creek channel cross sections surveyed in 1997 and 2009, (*E*) Elkhead Creek above Long Gulch, cross-section LG-1.n (realigned), (*F*) Elkhead Creek above Long Gulch, cross-section LG-2, (*G*) Elkhead Creek at Pitney Ranch, cross-section PT-1, (*H*) Elkhead Creek at Pitney Ranch, cross-section PT-2.—Continued

The mean annual flood at station 09245000 was 30 percent greater in period 3 (1978–93), when the greatest meander migration rate means and variances were observed (table 1), than in period 2 (1954–70). Kuhn and others (2003) found that the variance in annual discharge was greater from 1975 through 1996 than from 1954 through 1974, years roughly corresponding to periods 3 and 2. These trends in the size of the instantaneous flood peaks and in the volume of annual streamflow support the interpretation of Elliott and Gyetvai (1999) that watershed-scale hydrologic conditions were influential in causing the large meander migration rates observed in the post-reservoir period (1978–93), both downstream and upstream from Elkhead Reservoir.

The presence and operational characteristics of Elkhead Reservoir probably have both mitigating and exacerbating effects on channel erosion downstream, as do reservoirs on other streams and rivers (Williams and Wolman, 1984). 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 (fig. 2). Elkhead Reservoir decreased the range of diurnal discharge fluctuations and attenuated the daily discharge peak downstream. Passage of flood events through a relatively full reservoir pool indicates that 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 (Elliott and Gyetvai, 1999).

Elkhead Reservoir is very efficient at trapping bedload-transported sediment, as illustrated by the growth of a delta where Elkhead Creek flows into the reservoir. The sediment-transport rate increased by 190 percent from the period of 1975 through 1981 to the period of 1982 through 1993. 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.

Table 4. Changes in Elkhead Creek cross-section and bed-material properties, 1997 to 2009.

[River mile, channel distance upstream from confluence with Yampa River; mi, mile; ft, feet; ft/yr, feet per year; mm, millimeter; change in incision, positive is incision, negative is aggradation; na, not applicable; L, left; R, right; LHP, left headpin]

Cross section code	River mile, approximate (mi)	Terrace mean elevation (ft)	Thalweg elevation 1997 (ft)	Incision depth 1997 (ft)	Thalweg elevation 2009 (ft)	Incision depth 2009 (ft)	Change in incision depth (ft)	Lateral erosion 1997 to 2009 (ft)	Lateral erosion rate (ft/yr)	[1]Median sediment size 1997 (mm)	Median sediment size 2009 (mm)	Change in median sediment size (mm)	Remark
Cross sections downstream from Elkhead Reservoir													
VT-1	0.95	6,243.2	6,233.4	9.7	6,233.7	9.4	–0.3	1.8	0.1	na	46.5	na	L scarp retreat. R bank accretion.
VT-2	1.00	6,244.9	6,233.0	11.9	6,233.1	11.8	–0.1	2.4	0.2	40.0	49.0	9.0	L scarp retreat. Toe slump erosion. R bank accretion.
LW-2	3.00	6,255.3	6,244.9	10.4	6,244.9	10.4	0.0	6.3	0.5	na	37.5	na	L scarp retreat. R bank accretion.
LW-1	3.10	6,254.1	6,246.0	8.0	6,245.7	8.4	0.4	15.7	1.3	48.0	39.0	–9.0	L scarp retreat. No change in R bank. Width increased.
Mean				10.0		10.0	0.0	6.5	0.5	44.0	43.0	0.0	
Cross sections upstream from Elkhead Reservoir													
LG-1.o	19.96	6,408.6	6,400.1	8.5	na	na	na	na	na	54.0	na	na	Cross section LG-1.o LHP was not relocated.
LG-1.n	19.96	6,408.8	na	na	6,400.1	8.7	0.2	na	na	na	64.0	10.0	Cross section LG-1.n realigned with new LHP-1.
LG-2	20.08	6,409.9	6,400.8	9.1	6,401.5	8.4	–0.7	29.7	2.5	29.0	30.0	1.0	L scarp retreat. R bank accretion.
PT-1	20.87	6,421.9	6,412.1	9.8	6,411.9	10.1	0.2	–3.5	–0.3	19.0	88.0	69.0	L and R banks accreted. Width decreased.
PT-2	20.95	6,421.4	6,413.8	7.6	6,413.4	8.0	0.5	na	na	53.0	32.5	–20.5	L bank mechanically altered. R bank accretion.
Mean				8.8		8.8	0.1	13.1	1.1	38.8	53.6	14.9	

[1]1997 sediment-size statistics recalculated for the streambed only; bank areas excluded.

Bedload-deficient, clear-water releases from Elkhead Reservoir may partly explain the increase in meander migration rates at several meanders downstream from Elkhead Dam in period 3 (1978–93). However, meander migration rates upstream from the reservoir increased by an even greater rate during this same period indicating that other factors were important, such as the difference in the magnitude of the annual flood peaks.

Williams and Wolman (1984) demonstrated that some downstream effects of a reservoir may continue to develop and propagate for years. Elkhead Creek meander migration rates for period 3, the period following construction of Elkhead Dam and Reservoir, were statistically different (table 3), and were greater (table 1), than migration rates from periods 1, 2, and 4 in both the downstream and upstream reaches. Meander migration rates, in both downstream and upstream reaches, decreased in period 4 to rates statistically indistinguishable from periods 1 and 2 (table 3). Reservoir effects on meander migration rates, if any, were not detectable in periods 3 and 4 when downstream and upstream reaches were compared (table 2).

Summary and Conclusions

Elkhead Creek is a sinuous, meandering tributary of the Yampa River in northwestern Colorado and flows through a relatively broad, alluvial valley. The USGS, in cooperation with the Colorado River Water Conservation District, conducted a study from 2009 to 2010 that evaluated channel-pattern changes, meander migration rates, and identified possible causes of streambank erosion in Elkhead Creek that could have been affected by the 2005–06 enlargement of Elkhead Dam and Reservoir. The study was a continuation of a 1999 USGS study that evaluated the effects of the original Elkhead Reservoir on the hydrology, sediment transport potential, and channel stability of Elkhead Creek for the period 1938 through 1993. This study covers the period from 1994–2009 and includes results from the previous study.

This report summarizes the study of channel changes for the period 1938 through 2009 and provides information useful in guiding decisions about erosion mitigation activities where appropriate. More specifically, the report describes the history of channel-pattern changes and the rate of meander-bend migration and cutoff since the previously published study that covered channel-pattern changes from 1938 through 1993, the relation between hydrology and channel-pattern changes resulting in streambank erosion, and whether these channel changes are unique to the reach downstream from Elkhead Reservoir or are common to all meandering reaches of Elkhead Creek.

Aerial photographs taken in 1937, 1953, 1970, 1977, 1981, 1993, 1999, 2005, and 2009 were used to determine channel position and to calculate meander migration rates during the intervening years. Photographs taken in 1937 and 1953 bracket a period (period 1, 1938–53) prior to the establishment of a streamflow-gaging station on Elkhead Creek. Photographs taken in 1953 and 1970 bracket a period (period 2, 1954–70) of relatively small annual flood peaks. Photographs taken in 1977 and 1993 bracket a comparable length of time (period 3, 1978–93) in which annual flood peaks exceeded the estimated bankfull discharge about the same number of times as in period 2, but with much greater magnitude. The photographs taken in 1977 and thereafter document the period since construction of Elkhead Reservoir in 1974. Photographs taken in 1993 and 2009 bracket a period (period 4, 1994–2009) in which annual flood peaks exceeded the estimated bankfull discharges about one-half of those years, but where the year-to-year variability was large. The 2009 photographs document the channel condition following the enlargement of Elkhead Dam and Reservoir in 2005–06.

Planimetric geomorphic characteristics from georectified aerial photographs were quantified at 30 meander bends from 1938 through 2009, and erosional trends were evaluated by calculating migration rates at these meanders. 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 was a minimum, and where the channel migration rate usually is greatest. Seventeen meanders were selected in the reach downstream from Elkhead Dam, and 13 meanders were selected in the reach upstream from the backwater effects of Elkhead Reservoir. The channel upstream from Elkhead Reservoir was unaffected by impoundment and was used as the control reach for investigating downstream reservoir effects. 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 aerial photographs than was the concave bank. Characteristics of sediment in the channel and the stratigraphy of the valley-fill material also were determined from onsite inspection during the channel surveys.

Meander migration rates for periods 1–4 ranged from –3.2 to 12.1 ft/yr in the reach downstream from Elkhead Reservoir, and ranged from –6.3 to 14.2 ft/yr in the reach upstream from the reservoir. Negative meander migration rates were recorded in some time periods when the channel reversed its lateral movement. Meander migration rates in the reach downstream from Elkhead Reservoir were compared to rates upstream from the reservoir to investigate possible effects of reservoir impoundment on channel-pattern changes. Downstream meander migration rate means were statistically indistinguishable from upstream means in all four periods. Downstream and upstream meander migration rates were statistically indistinguishable in the two periods preceding construction of Elkhead Reservoir (periods 1 and 2), and in the two periods following construction of the reservoir (periods 3 and 4), indicating that the presence of Elkhead Reservoir has had no apparent long-term effect on channel-pattern changes.

Meander migration rates in different periods were compared to investigate possible effects of annual streamflow, peak discharge, or other external variables unrelated to reservoir operation on channel-pattern changes. Whereas the means in periods 1, 2, and 4 statistically were indistinguishable within the downstream reach and within the upstream

reach, the mean of period 3 was different from the means of periods 1, 2, and 4. A possible explanation for the statistically greater mean meander migration rate in period 3 for both the downstream and upstream reaches could be due to the large annual peak discharges in Elkhead Creek in period 3 (1978–93), a period when four of the largest measured and estimated annual peak discharges occurred.

Meander migration rates in period 4 also were calculated over shorter, 4- to 6-year, time intervals to evaluate the potential effect of the 2005–06 Elkhead Reservoir enlargement on downstream channel changes. Meander migration rates in subperiods 4A (1994–99), 4B (2000–05), and 4C (2006–09) were found to be statistically indistinguishable, indicating the enlargement of Elkhead Reservoir has had no apparent effect on channel change through 2009.

Replicate surveys were made at representative and monumented channel cross sections to quantify lateral and vertical channel adjustments at the cross-section scale over the 12-year period between the two USGS studies. Most cross sections revisited in 2009 showed evidence of recent bed-material deposition in the form of alluvial bars or bank accretion. Incision depth at each cross section, defined as the difference between the mean terrace (or valley-floor) elevation and the thalweg (or deepest part of the channel) elevation, changed very little between the two surveys. The lateral-erosion rate for the period 1997–2009 ranged from 0.1 to 1.3 ft/yr in four cross sections downstream from the reservoir, and from –0.3 to 2.5 ft/yr in two cross sections upstream from the reservoir. The negative lateral-erosion rate occurred at a cross section where sediment was deposited on both streambanks between 1997 and 2009. Lateral-erosion rates measured at cross sections in both reaches were within the ranges of meander migration rates measured in aerial photographs for period 4, 1994–2009.

Annual peak discharges in Elkhead Creek exceeded the bankfull discharge in 4 of the 12 years between 1997 and 2009, and streamflow during these years likely was associated with the erosion and deposition of streambed sediment.

Channel stability and meander migration rates in Elkhead Creek are affected by characteristics of the flood-plain and channel sediments, the variability of climate and streamflow, land-use practices, and intentional manipulation of the channel. Watershed-scale hydrologic conditions, such as trends in the size of the instantaneous flood peaks and in the volume of annual streamflow, likely were influential in causing the large meander migration rates observed in post-reservoir period 3 (1978–93), both downstream and upstream from Elkhead Reservoir. The mean annual flood was 30 percent greater in period 3 (1978–93), when the greatest meander migration rate means and variances were observed, than it was in period 2 (1954–70).

The presence and operational characteristics of Elkhead Reservoir probably have both mitigating and exacerbating effects on channel erosion downstream. Maintenance of a relatively stable, full pool and spillway passage of excess inflow attenuates but does not eliminate floods downstream. Elkhead Reservoir is very efficient at trapping bedload-transported sediment, and bedload-deficient, clear-water releases from Elkhead Reservoir may partly explain the increase in meander migration rates at several meanders downstream from Elkhead Dam in period 3 (1978–93). However, meander migration rates upstream from the reservoir increased by an even greater rate during this same period indicating that other factors were important, such as the difference in the magnitude of the annual flood peaks.

Reservoir effects on meander migration rates, if any, were not detectable in periods 3 (1978–93) and 4 (1994–2009). Elkhead Creek meander migration rates, in both downstream and upstream reaches, decreased in period 4 to rates statistically indistinguishable from periods 1 and 2, and statistically different and lesser than in period 3, the period following construction of Elkhead Dam and Reservoir.

Acknowledgments

The study was made possible with the cooperation of the many landowners and residents along Elkhead Creek who granted access to the channel. Kyle C. Davis, Michael R. Stevens, and Barbara C. Ruddy (USGS) and Andrea Althoff (formerly USGS) were instrumental in channel surveys and sediment measurements in 2009. Reviews of the manuscript by Barbara C. Ruddy and Keelin R. Schaffrath (USGS) greatly improved this report.

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Publishing support provided by:
Denver Publishing Service Center, Denver, Colorado

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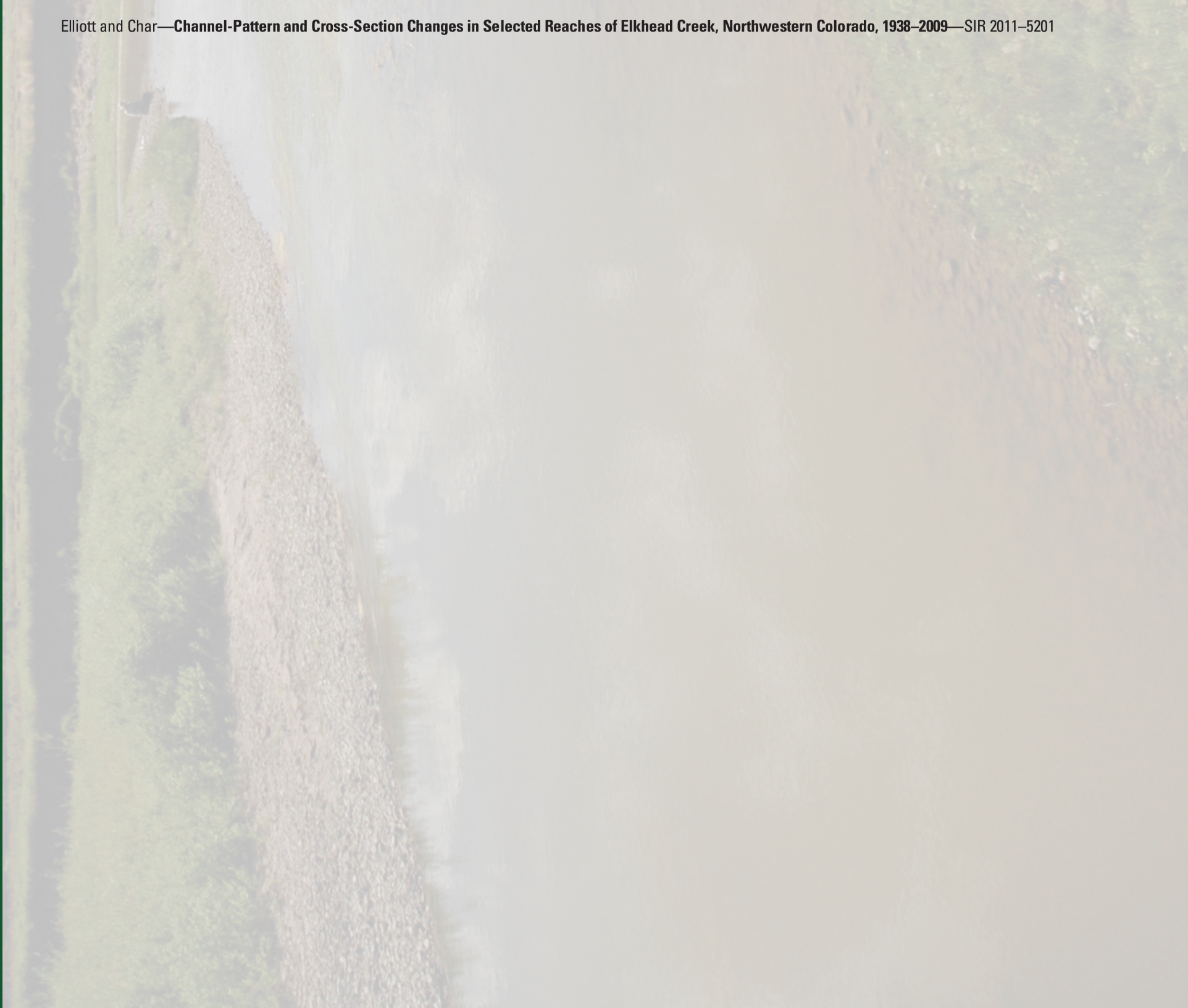
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