

**In cooperation with the Colorado Water Conservation Board and
Colorado River Water Conservation District**

Hydraulic, Geomorphic, and Trout Habitat Characteristics of the Lake Fork of the Gunnison River in Hinsdale County, Lake City, Colorado, Water Years 2010–2011

Scientific Investigations Report 2015–5043

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By Cory A. Williams, Rodney J. Richards, and Keelin R. Schaffrath

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Conversion Factors

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
inch (in.)	2.54	centimeter (cm)
feet (ft)	0.3048	meter (m)
miles (mi)	1.609	kilometer (km)
Area		
square meter (m ²)	0.0002471	acre
square meter (m ²)	10.76	square foot (ft ²)
Volume		
cubic meter (m ³)	35.31	cubic foot (ft ³)
Flow rate		
cubic meter per second (m ³ /s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
cubic meter per day (m ³ /d)	35.31	cubic foot per day (ft ³ /d)
cubic feet per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
Mass		
kilogram (kg)	2.205	pound avoirdupois (lb)
Pressure		
pascal (Pa)	1	Newton per square meter

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and Geoid 2003 (US Conus). Horizontal coordinate information was referenced to the North American Horizontal Datum of 1983 (NAD83).

Water Year (WY) is defined as beginning October 1 and continuing through September 30 of the following year.

Acronyms and Abbreviations

CDOT	Colorado Department of Transportation
ft ³ /s	cubic feet per second
RTK-GPS	Real-Time Kinematic mode Global Positioning System
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

Hydraulic, Geomorphic, and Trout Habitat Characteristics of the Lake Fork of the Gunnison River in Hinsdale County, Lake City, Colorado, Water Years 2010–2011

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Abstract

Channel rehabilitation, or reconfiguration, to mitigate a variety of riverine problems has become a common practice in the western United States. However, additional work to monitor and assess the channel response to, and the effectiveness of, these modifications over longer periods of time (decadal or longer) is still needed. The Lake Fork of the Gunnison River has been an area of active channel modification to accommodate the needs of the Lake City community since the 1950s. The Lake Fork Valley Conservancy District began a planning process to assess restoration options for a reach of the Lake Fork in Lake City to enhance hydraulic and ecologic characteristics of the reach. Geomorphic channel form is affected by land-use changes within the basin and geologic controls within the reach. The historic channel was defined as a dynamic, braided channel with an active flood plain. This can result in a natural tendency for the channel to braid. A braided channel can affect channel stability of reconfigured reaches when a single-thread meandering channel is imposed on the stream. The U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board and Colorado River Water Conservation District, began a study in 2010 to quantify existing hydraulic and habitat conditions for a reach of the Lake Fork of the Gunnison River in Lake City, Colorado. The purpose of this report is to quantify existing Lake Fork hydraulic and habitat conditions and establish a baseline against which post-reconfiguration conditions can be compared. This report (1) quantifies the existing hydraulic and geomorphic conditions in a 1.1-kilometer section of the Lake Fork at Lake City that has been proposed as a location for future channel-rehabilitation efforts, (2) characterizes the habitat suitability of the reach for two trout species based on physical conditions within the stream, and (3) characterizes the current riparian canopy density.

The FaSTMECH computational flow-model within MD_SWMS was selected to characterize the effects of streamflow on hydraulic and habitat-suitability conditions for a study reach of the Lake Fork. Habitat suitability was evaluated for cutthroat (*Oncorhynchus clarkii*) and brown trout (*Salmo trutta morpha fario*) fry, juveniles, and adults. Microscale

(point locations) and mesoscale (reach features) habitats were assessed using the combination of field observations, measurements, and hydraulic simulations within the study reach of the Lake Fork. Microscale trout habitat, presented as weighted usable area, generally increased as streamflow increased for both trout species and all life stages. Areas of suitable microscale habitat occur along the banks for flows of 900 cubic feet per second (ft³/s) and less. Out-of-bank areas became more substantial contributors to overall habitat availability for flows of 1,300 ft³/s or more when compared to other features. Adult habitat, for both trout species, was the most abundant habitat type for nearly all streamflows. In general, the upper reach provided 2–3 times more available habitat than the lower reach for both trout species.

Mesoscale trout habitat of the Lake Fork was assessed based on the conditions present in the 150 ft³/s flow simulation as well as field observation. Both the upper and lower reach is primarily characterized as riffle/run habitat. The presence of pool habitat was limited throughout both reaches and occurred along the channel margins. For both reaches, the pool habitat was less than 5 percent of the total wetted area, a percentage that is substantially lower than the recommendations for sustainable populations of 40–70 percent. Areas of cover were adjacent to potential drift feeding areas in the lower reach, and often occurred within the same pool habitat. This may favor energy expenditure ratios of both fish species, wherein little energy is needed to acquire adequate food sources.

Sediment mobility is an important process for flushing fine sediments from within the gravel frameworks. Evaluations of channel and flow characteristics at cross-section locations 2–8 show a range of streambed mobility. In general, boundary shear stress and streambed mobility increase with increases in streamflow. Within the cross sections, the greatest boundary shear stress occurs towards the center of the channel. Reach-scale assessment of sediment mobility in the lower reach shows increased streambed mobility. This is due in part to smaller grain sizes in the lower reach, but may also reflect the greater extent of channel alterations, specifically the temporary berms constructed by CDOT in the late 1980s and 1990s, present in this reach.

Introduction

The Lake Fork of the Gunnison River (hereafter, Lake Fork) has been an area of active channel modification since the 1950s to accommodate the needs of the Lake City community (Lake Fork Valley Conservancy, 2010). Historically, the Lake Fork was characterized by its braided channel which frequently overtopped its banks and created an active and dynamic flood plain (Lake Fork Valley Conservancy, 2010). However, beginning in the 1950s, increased rates of land-use change within Lake City resulted in the straightening and channelization of the Lake Fork to promote channel stability and development of riverfront properties (Lake Fork Valley Conservancy, 2010).

Reduced channel width, sinuosity, and riparian habitat have been noted in the Lake Fork as well as Henson Creek, a smaller tributary located upstream from Lake City (Lake Fork Valley Conservancy, 2010) (fig. 1). Failures of sediment-retention structures (cribbing piles) on Henson Creek in the 1960s and 1970s have contributed large volumes of sediment into the fluvial system. In the late 1980s and early 1990s, the Colorado Department of Transportation (CDOT) constructed temporary berm structures along the river on the north side of town to protect the highway from channel migration until permanent structures could be completed (Lake Fork Valley Conservancy, 2010). The constructed berms may be a potential source of channel instability and sediment inputs, because they were not designed to withstand high-flow conditions. Additional areas along the north side of town were also straightened by CDOT and U.S. Army Corps of Engineers in the 1980s (Lake Fork Valley Conservancy, 2010).

The Lake Fork Valley Conservancy District began a planning process to assess restoration options for a reach of the Lake Fork in Lake City to enhance hydraulic and ecologic characteristics of the reach (Lake Fork Valley Conservancy, 2010). In part, candidacy for the proposed channel-restoration efforts is based on the effects of similar efforts in other areas of the Lake Fork. Beginning in the last few decades, several groups have completed channel reconfiguration efforts downstream from the study area on the Lake Fork to improve aquatic habitat and channel stability. In 1997, 35 kilometers (km) downstream from Lake City, a 3-km reach of the Lake Fork was reconfigured. The objectives of these earlier efforts were to improve habitat for brown and rainbow trout (Lake Fork Valley Conservancy, 2010).

Reshaping the downstream channel banks and river pools during this earlier effort was done to improve riparian habitat, vegetation, and streambank stability and to reduce sediment sources that were believed to be impairing the fisheries (Lake Fork Valley Conservancy, 2010). Reconfigured channel efforts carried out by the Colorado Division of Wildlife and the Bureau of Land Management included reshaping of the channel and placing large boulders to improve fish habitat and increasing channel stability (Lake Fork Valley Conservancy, 2010). Additional planting of riparian vegetation was expanded in areas where the channel widths were decreased

Figure 1. Map of study area for the Lake Fork of the Gunnison River at Lake City, Colorado.—Following page

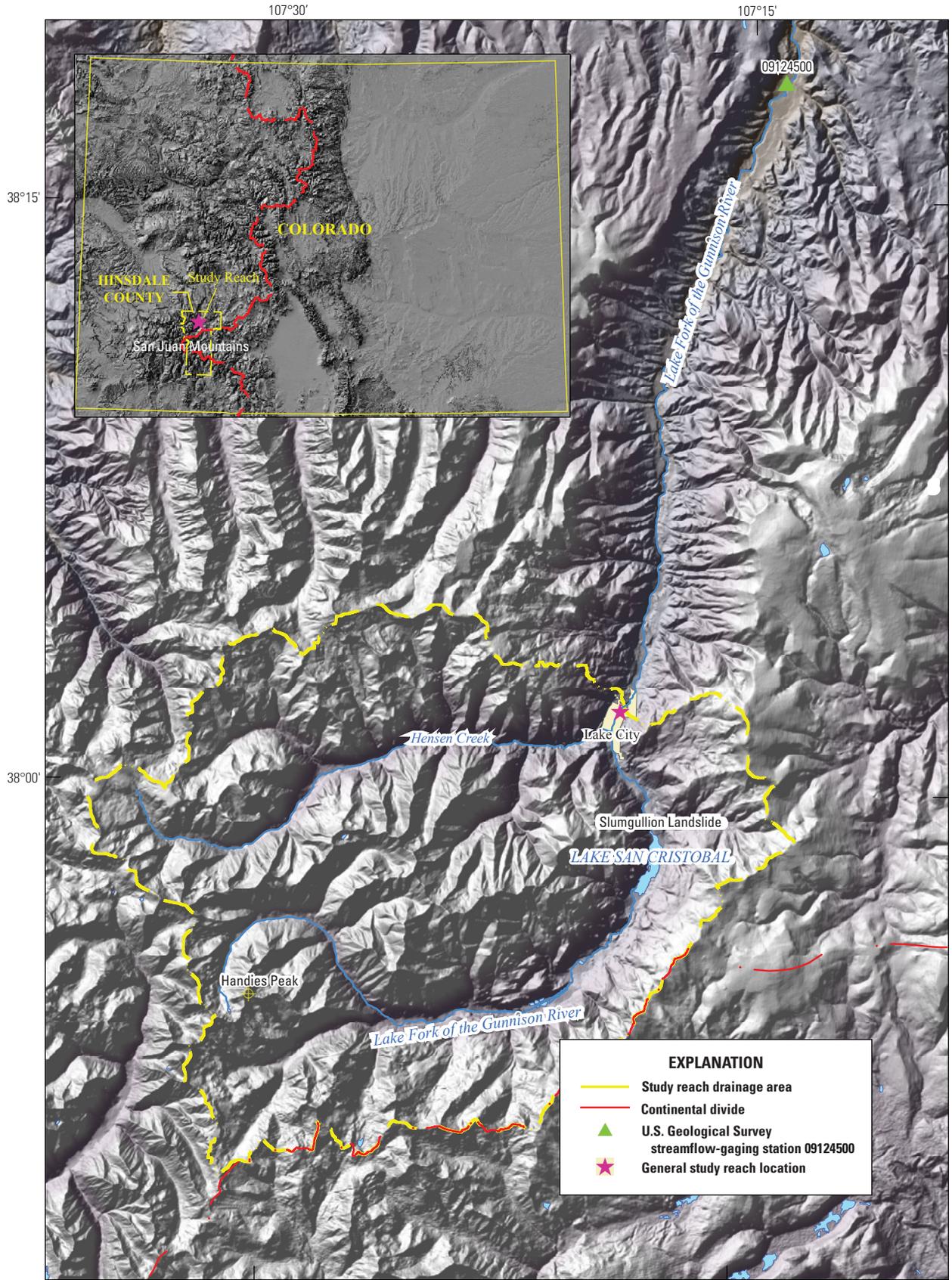
during channel reshaping. Following reconfigured channel efforts, the total fish biomass (weight of fish across all age classes per acre of stream, in pounds per acre [lbs/acre]) increased from approximately 40 to 100 lbs/acre, an indication that the reconfiguration efforts improved fish habitat (Lake Fork Valley Conservancy, 2010).

Channel rehabilitation, or reconfiguration, to mitigate a variety of riverine problems has become a common practice in the western United States. Reasons for channel rehabilitation include restoration to more natural or historical conditions, improved water conveyance in flood-prone areas, mitigation of unstable streambeds and streambanks, increased sediment transport, enhancement of aquatic and riparian habitat, improved water quality, and recreation. Numerous private entities and resource-management agencies have attempted to modify stream channels by using designs based on different geomorphic philosophies and classification schemes. However, additional work to monitor and assess the channel response to, and the effectiveness of, these modifications over longer periods of time (decadal or longer) is still needed. To address this need, the U.S. Geological Survey (USGS) is engaged in a program designed to monitor and assess selected river reaches that have undergone reconfiguration (Elliott and Parker, 1999).

The basis for determining the “success” of a channel-reconfiguration project is often not made through analysis of quantifiable metrics, leaving little information for resource managers, planners, and designers to use to determine the effectiveness and durability of channel restoration techniques used for stream rehabilitation (including biological response) and channel stability. The U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board and Colorado River Water Conservation District, began a study in 2010 to quantify existing hydraulic and habitat conditions for a reach of the Lake Fork in Lake City, Colorado (Colo.).

Purpose and Scope

The purpose of this report is to quantify existing Lake Fork hydraulic and habitat conditions and establish a baseline against which post-reconfiguration conditions can be compared. This report (1) quantifies the existing hydraulic and geomorphic conditions in a 1.1-kilometer (km) section of the Lake Fork at Lake City that has been proposed as a location for future channel-rehabilitation efforts, (2) characterizes the habitat suitability of the reach for two trout species based on physical conditions within the stream, and (3) characterizes the current riparian canopy density. This characterization describes existing channel conditions and establishes a baseline for post-reconfiguration comparisons for resource managers to evaluate restoration project success.



Base from U.S. Geological Survey National Elevation Dataset 30 meter elevation model showing land surface elevations shaded at 2-meter intervals scale 1:265,000



EXPLANATION	
	Study reach drainage area
	Continental divide
	U.S. Geological Survey streamflow-gaging station 09124500
	General study reach location

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This report does not aim to determine limiting conditions for these species. Instead, this report quantifies the availability of trout habitat characteristics based on physical conditions within the stream. No considerations were made related to inter-species interactions.

Description of Study Area

The study reach is located in the town of Lake City, Colo., along the Lake Fork. Lake City is a small mountain town with a population of 375 year-round residents (U.S. Census Bureau, 2011). The Lake Fork originates in the northern portion of the San Juan Mountain Range and flows in a northern direction (fig. 1). The study reach is located at an elevation of 2,643 meters (m) and the drainage area upstream from the study reach encompasses 544 square kilometers (km²) of the 1,144-km² Lake Fork Basin (U.S. Geological Survey, 2010b). Most of the land in the Lake Fork Basin is federally owned and managed by the Bureau of Land Management and U.S. Department of Agriculture Forest Service. The remainder of land is privately owned except for Lake San Cristobal, which is owned and managed by the local government.

Land cover in the basin varies with elevation (Homer and others, 2004) and the highest elevations include barren and grassland classifications. Tree line in Colorado occurs at an elevation of approximately 3,500 m (Pielke and others, 2003). Both deciduous and coniferous forests are found throughout the basin and along stream margins (Homer and others, 2004).

Local climate is typical of other mountainous areas of western Colorado. Precipitation tends to increase with elevation while temperatures decrease with elevation (Pielke and others, 2003). The majority of precipitation falls as snow and is stored as snowpack through the winter months. The average annual precipitation in Lake City is 14.1 inches (in.) of water, and the average annual snowfall accumulation is 82.8 in. (based on data from August 1, 1948 through December 21, 2008 from the Western Regional Climate Center, 2011). Average annual maximum temperature in Lake City is 55.7 °F, and the average annual minimum is 22.4 °F (Western Regional Climate Center, 2011).

The hydrology of the Lake Fork is governed by snowpack accumulations and spring temperatures which drive snowmelt-runoff. The annual streamflow pattern is characterized by streamflow increases that begin in April, peak in May and June, and finally decrease in July and August (U.S. Geological Survey, 2010a). The Lake Fork of the Gunnison River is monitored at USGS streamflow-gaging station 09124500, Lake Fork at Gateview, Colo. (hereafter, Gateview). The drainage area of Gateview is 964 km², and it is located approximately 35 river km downstream from the study reach. No major tributaries or diversions occur in the Lake Fork between the study reach and the streamflowgaging station. A summary of daily streamflow conditions is shown in figure 2 including: maximum, 75th percentile, mean, 25th percentile, and minimum. The highest recorded streamflow was 2,720 cubic feet per second (ft³/s), July 10, 1983, with the lowest

daily mean streamflow of 21 ft³/s, recorded January 3, 2002 (U.S. Geological Survey, 2010a). Additional water-quality and streamflow data are available from the USGS National Water Information System (NWIS) website at <http://waterdata.usgs.gov/co/nwis>.

The dominating geology in and around Lake City is Tertiary volcanic deposits (Tweto, 1979). The extensive volcanic activity, along with intrusions and mineralization, created widespread distributions of ore bodies in the San Juan Mountains that were deposited during the late-Tertiary period (Tweto and Sims, 1963; Burbank and others, 1947). Historical mining activities in the region were driven by the discovery of gold and silver deposits near Lake City. Relic mining cribbing piles have introduced sediment into Henson Creek, which transported it into the study reach (Lake Fork Valley Conservancy, 2010). This sediment may affect channel form, habitat, and toxicity.

Instabilities associated with geologic formation sequences have resulted in the unique history of the Lake Fork Valley and a history of large landslides (Tweto, 1979). Most notably, the Slumgullion landslide which occurred roughly 700 years (yr) ago was large enough to dam the Lake Fork. This landslide deposit resulted in the creation and persistence of Lake San Cristobal, the second largest natural lake in Colorado (Guzzi and Parise, 1992).

Topographical Surveying Techniques

Topographical surveying was used to map water-surface and stream channel elevations for a 1.1-km reach at Lake Fork at Lake City (figs. 1 and 3). The majority of the surveying occurred August 2–6, 2010, with additional flood-plain surveying on May 24, 2011. Topographical surveying of water-surface elevations includes conditions present during each day of surveying as well as preserved high-flow conditions (high-water marks) from spring 2010 and 2011 identified through interpretation of sediment deposits and debris lines. Eight monumented cross sections were established in the study reach for long-term channel monitoring (fig. 3).

Surveying was completed using survey-grade Global Positioning System (GPS) equipment, operated in Real-Time Kinematic mode (RTK-GPS) to determine the elevation and coordinate locations of each surveyed point (Trimble Navigation Limited, 2009). The RTK-GPS used a stationary GPS receiver (base station) positioned over a reference benchmark and roving GPS receivers (rovers) operated by separate hand-held computers (data collectors). The RTK-GPS system calculates the locations of the rovers in real time, using the positions of orbiting NAVigation Signal Timing And Ranging (NAVSTAR) GPS satellites and a known base-station location.

All surveyed elevations (RTK-GPS) were output to a spreadsheet program in metric Northing, Easting, and Elevation format using a Universal Transverse Mercator coordinate system (UTM, Zone 12 North). Horizontal coordinate information was referenced to the North American Horizontal Datum of

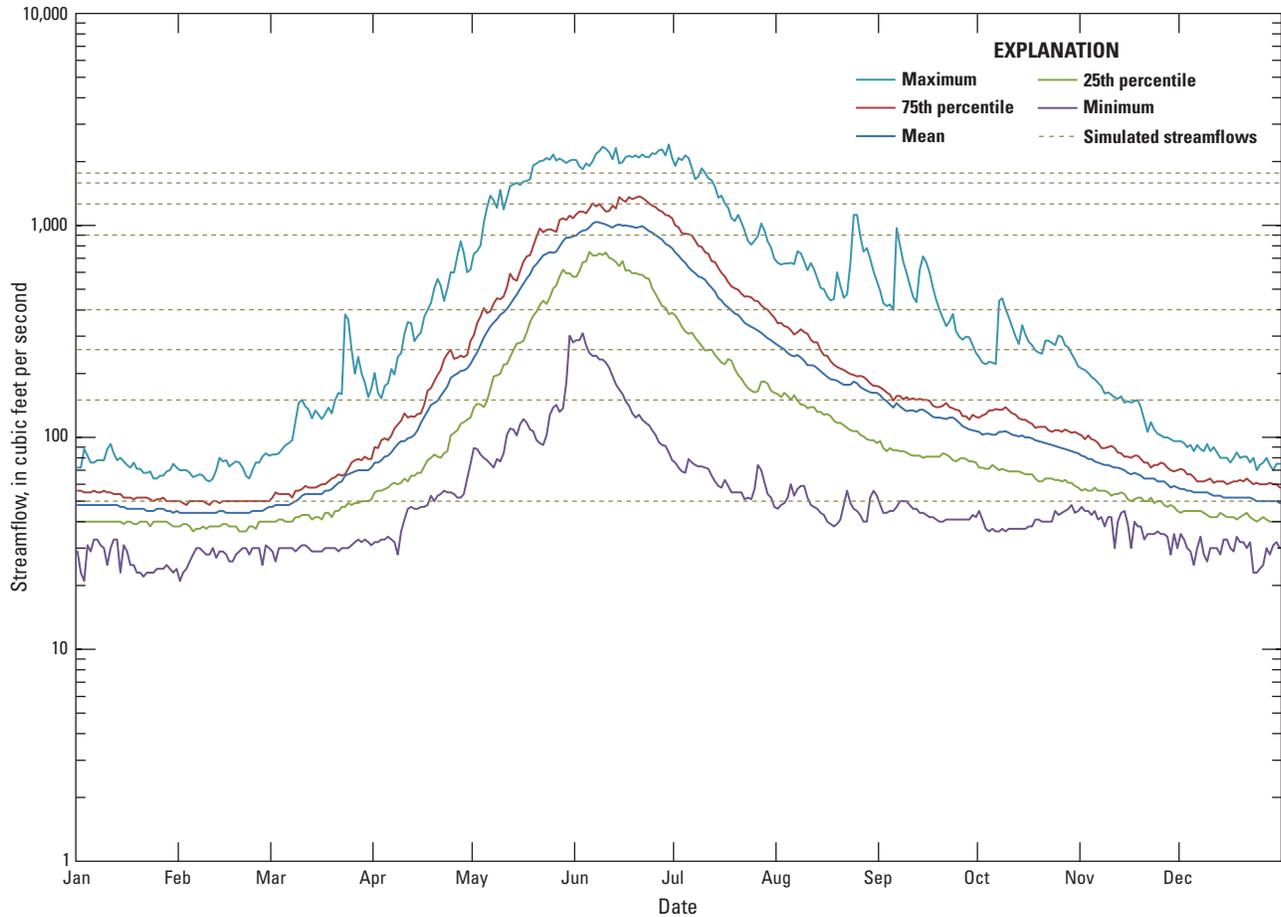


Figure 2. Hydrograph showing daily statistics for the Lake Fork of the Gunnison River at U.S. Geological Survey streamflow-gaging station 09124500, water years 1938 through 2010.

1983 (NAD83). Vertical coordinate information was referenced to the North American Vertical Datum of 1988 (NAVD 88) and Geoid 2003 (US Conus). Elevation values were visually examined for relative accuracy graphically and through inspection of GPS positional precision and diagnostic parameters.

Hydraulic Data Collection Techniques

Streamflow was measured using a FlowTracker® Hand-held Acoustic Doppler Velocimeter (ADV) for wadable stream conditions and followed standard techniques outlined in Turnipseed and Sauer (2010). For unwadable flows, an Acoustic Doppler Current Profiler (ADCP) was used to measure streamflow from the 5th Street pedestrian bridge (near GS1, fig. 3) using a tethered boat, following standard techniques outlined in Mueller and Wagner (2009). Streamflow measurements were made at 40; 150; 270; 760; and 1,400 ft³/s between August 5, 2010 and August 1, 2011.

Onset Hobo water level loggers (model U20-001-01, unvented, pressure transducer) were used in conjunction with

local vertical elevation reference markers (staff-plates) to monitor water-surface elevation at selected locations within the study reach. Pressure transducers were deployed at the upstream study-reach boundary, at approximately halfway through the study reach, and at the downstream study-reach boundary (fig. 3). Pressure transducers were placed in protective polyvinyl chloride (PVC) casings and attached to T-posts which were secured to the river bed. A fourth pressure transducer was located outside the stream at cross-section 8 (fig. 3) to record barometric-pressure changes for post-processing corrections of the unvented, pressure-transducer readings (Freeman and others, 2004). This process resulted in a continuous record (30-minute intervals) of water-surface elevations at these three locations from August 2 to October 28, 2010; and from March 24 to August 1, 2011.

A stage-discharge rating curve based on the relation between the measured streamflow and water-surface elevation pairs was determined for the upstream study-reach boundary at cross-section 1 through least-squares regression techniques, as described by Rantz and others (1982) (fig. 3). At the remaining pressure-transducer locations, water-surface elevations corresponding to 50; 150; 260; 400; 900; 1,300; 1,600; and

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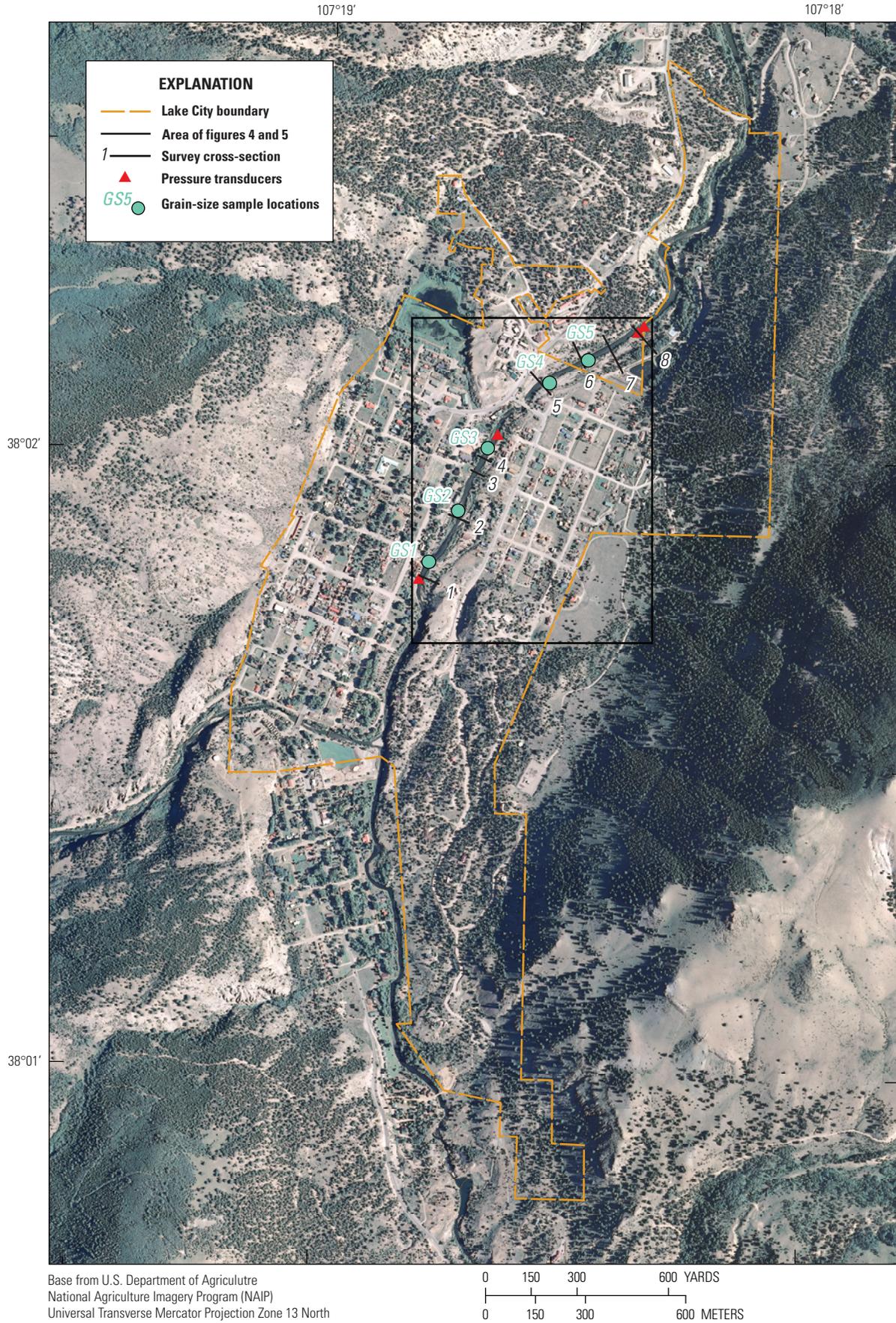


Figure 3. Map of study reach with pressure transducers, grain-size sample locations, and cross-section locations for the Lake Fork of the Gunnison River at Lake City, Colorado.—Previous page

1,800 ft³/s were determined based upon the date and time of the estimated streamflow at the upstream boundary. Based on field observations, it was assumed that the streamflow at the downstream boundary was equal to the streamflow at the upstream boundary, because there were no large inflows or diversions within the reach.

High-water marks from the water year 2010 (October 1, 2009, through September 30, 2010) peak flow were identified and surveyed within the study reach; however, streamflow data were unavailable within the study reach to relate these water-surface elevations to discharge. The Gateview dataset was used to estimate the corresponding streamflow through a Maintenance of Variance 1 (hereafter, MOVE.1) equation analysis (Hirsch, 1982). The MOVE.1 equation uses data from an adjacent site (downstream in this instance) to predict streamflow for the site of interest. This methodology uses an algorithm to relate the streamflow values between sites while maintaining the natural variations in each dataset.

To determine how often a specific flow occurs each year, flow-duration curves were used to determine flow frequencies as percent of year. The flow frequency for cross-section 1 was calculated using 30 arithmetic bins following the regionalized-duration curve method for estimating flow-durations for ungaged sites (U.S. Department of Agriculture, 2009). The regionalized flow-duration curve method relates flow between two sites (a gaged site and an ungaged site of interest) by transferring a nondimensional flow-duration curve. This technique preserves the shape of the flow-duration curve and allows the magnitude of the streamflows to be scaled appropriately between sites based on standardized peak-flow values between sites. Peak-flow magnitudes (2-, 5-, 10-yr floods) were estimated based on regional regression analysis (Capesius and Stephens, 2009; U.S. Geological Survey, 2010b). The 2-yr recurrence interval peak streamflow was selected for use in this technique for consistency in methodology between the two sites (Capesius and Stephens, 2009; U.S. Geological Survey, 2010b).

Streambed Sediment Characterization Techniques

Sediment particles were measured from August 4 to August 6, 2010, and August 18, 2011 (GS1-GS4 and GS-5, respectively) at five locations in the study reach (fig. 3) to characterize the grain size of different geomorphic surfaces and to estimate channel roughness. Bars and channel margins were chosen because these areas are inundated most of the year and represent the coarser material transported within the river

channel. Grain size was determined in the field using areal techniques (pebble-counts) as described by Wolman (1954). A minimum of 100 clasts were measured during each pebble count, and sampling was performed parallel to the direction of streamflow at one- or two-pace intervals along the streambed or alluvial bars. The intermediate, or “b-axis,” of each sediment particle was measured to the nearest millimeter for gravel and small cobbles, and to the nearest 5 millimeters for large cobbles and small boulders. Grain-size statistics (d_{50} , size at the 50th percentile, and d_{84} , size at the 84th percentile; d_n is the size at the n th percentile) were determined from the cumulative-frequency distribution function of b-axis measurements.

Riparian Canopy Characterization Techniques

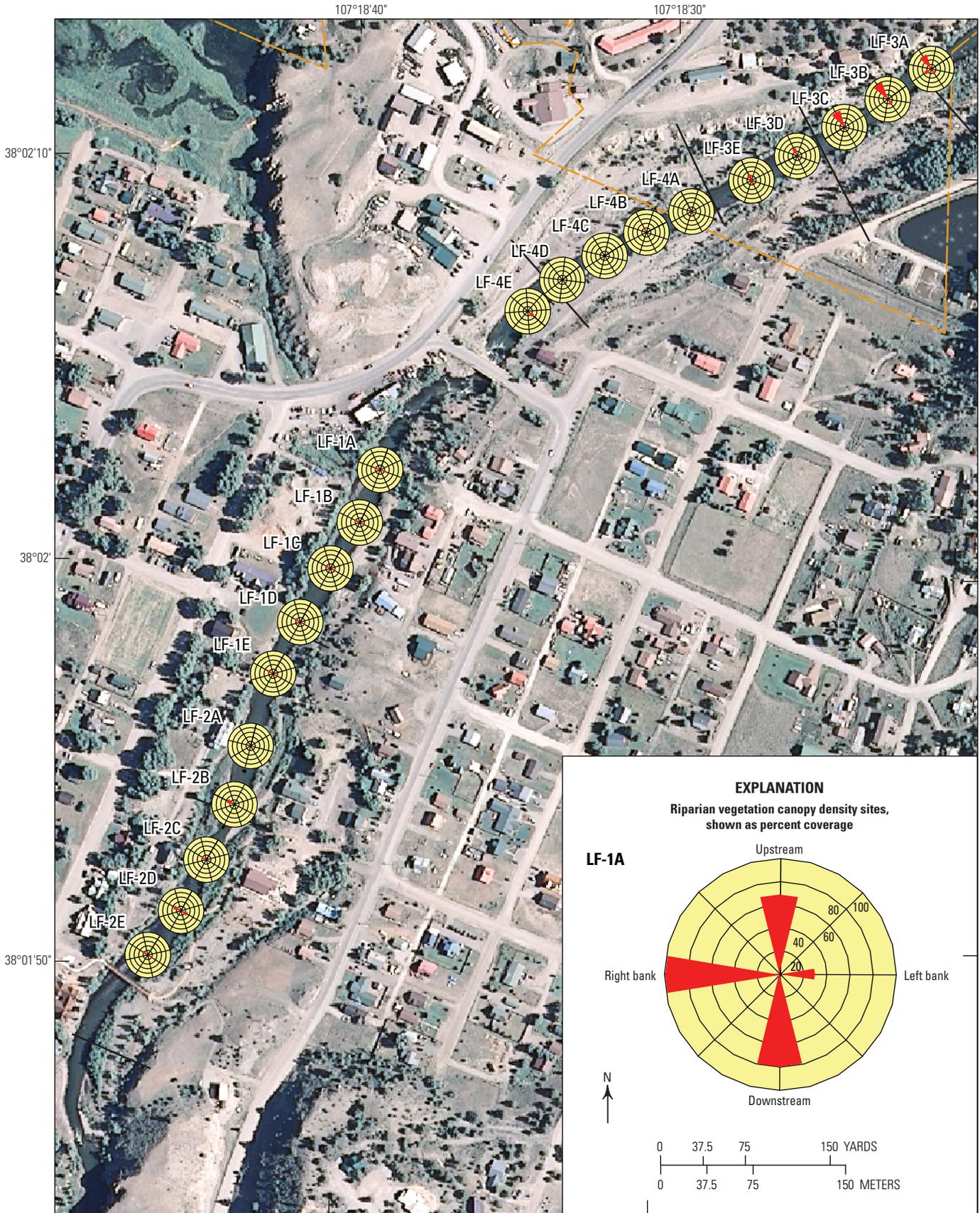
Canopy density was characterized during a low-flow period (August 17–18, 2011) at multiple locations within the study area using a spherical densiometer (Model A) (Lemmon, 1956). Differences in canopy density can affect habitat cover as well as water temperatures, terrestrial insect inputs, and leafy organic inputs into the aquatic system (Lindsey and others, 1998). Four measurements were taken at each location from the center of the stream with the operator facing: upstream, downstream, towards left bank, and towards right bank (Lemmon, 1956). The percentage of the densiometer view field that was obstructed was recorded for each measurement. This provides a standardized methodology to characterize the canopy density within the stream reach. Observations are presented as rose diagrams within the study reach (fig. 4).

Two-Dimensional Hydraulic and Habitat Modeling Techniques

The Multidimensional Surface Water Modeling System (MD_SWMS) is a graphical user interface that was developed by the USGS to aid in pre- and post-processing two-dimensional streamflow analysis (McDonald and others, 2001; 2005; 2006). The FaSTMECH computational flow-model within MD_SWMS was selected to characterize the effects of streamflow on hydraulic and habitat-suitability conditions for the 1.1-km study reach of the Lake Fork (Nelson and McDonald, 1997; Thompson and others, 1998; Lisle and others, 2000; Nelson and others, 2003; McDonald and others, 2005; 2006).

The FaSTMECH model uses a curvilinear orthogonal grid built upon a user-defined centerline and width that fits the path of the modeled reach. FaSTMECH is a vertically averaged two-dimensional model that simulates spatially distributed values of depth, velocity, and total bed shear stress. The resolution of the grid was defined such that there were no fewer than 10 locations along any cross-section within the wetted-channel area at the lowest simulated flow (or a spatial

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Base from U.S. Department of Agriculture
 National Agriculture Imagery Program (NAIP)
 Universal Transverse Mercator Projection Zone 13 North

Figure 4. Riparian canopy density assessment locations in the Lake Fork of the Gunnison River near Lake City, Colorado, August 2011.—Previous page

resolution of 1.0- by 1.0-m grid). Additional information on the interface and the model can be found in McDonald and others (2001; 2006), Nelson and McDonald (1997), and Nelson and others (2003).

Channel geometry was obtained from the topographical survey of the channel. Interpolation between measured data points was completed within the model interface elevation data to generate a suitable dataset. Aerial images were obtained from the U.S. Department of Agriculture National Agricultural Imagery Program (2011) and were used in conjunction with the survey data to best define the channel topography. Elevation data within the stream channel were interpolated in a stream-wise direction between surveyed cross sections. Otherwise, interpolation of elevation data was in a cross-sectional direction. The final elevation dataset was a densely spaced set of topographic data from which a final dataset for channel geometry was created using the Triangulated Irregular Network (TIN) method (Environmental Systems Research Institute, Inc., 2010). For computational efficiency, the FastMECH model grid, derived from the final elevation dataset, was divided into upper and lower reaches (fig. 5). The grid cells in the computational grids for both reaches approximated 1.0- by 1.0-m. The grid in the upper reach was approximately 455 m long and 60 m wide (fig. 5). The grid in the lower reach was approximately 411 m long and 100 m wide (fig. 5).

Two-Dimensional Hydraulic Model Calibration

FaSTMECH model calibration was achieved through iterative adjustments of the roughness until the root mean squared error (RMSE) between the observed and simulated water-surface elevations was minimized. The RMSE was calculated following standard techniques (Helsel and Hirsch, 2002). Multiple techniques are available to the user for selection of the roughness parameter within the model interface. The Z_0 parameter was selected to calculate roughness, where Z_0 is defined as the distance above the streambed at which the velocity is zero (Julien, 2010).

The Z_0 parameter is calculated as the quotient of the grain roughness height and 30 (Julien, 2010). The grain roughness height in gravel bed rivers has been characterized as a function of grain size in a variety of ways including: $3.5 \times d_{84}$ and $6.8 \times d_{50}$ (Bray, 1982) and $1.25 \times d_{35}$ and $3.5 \times d_{90}$ (Millar and Quick, 1994). The d_{84} was calculated from the five grain-size samples (three samples in the upper reach and two samples in the lower reach) which are discussed in the “Streambed Sediment Characterization Techniques” section. The average Z_0 , calculated from the d_{84} of the five grain-size samples, was 0.013 m, and the same average resulted when the two reaches were considered separately.

FaSTMECH uses a constant Z_0 to calculate a variable drag coefficient as a function of depth for the study reach (Rich McDonald, U.S. Geological Survey, oral commun., September 2011), where the drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid. The Z_0 parameter was chosen to determine channel roughness because it is based on the grain size of the streambed (a persistent condition within gravel streams for moderate time steps); Z_0 is also advantageous because it is less subjective than other roughness estimates (Manning’s n or Darcy-Weisbach friction factor) that are made based on visual comparisons to reference values which integrate roughness sources along the entire cross section or reach (Barnes, 1977). Another benefit to using Z_0 over other roughness estimates is that it does not change with stream depth and so requires a single characterization for the entire range of flow conditions (Julien, 2010). However, when using Z_0 , the characteristic roughness height for a channel is a function of scales that range from as large as the channel form to as small as the characteristic grain size of the channel, and the streambed is discretized onto a grid that may be coarser than some of the roughness scales of the channel. The model is therefore calibrated by varying the roughness height as described above.

Eight streamflow conditions were simulated: 50; 150; 260; 400; 900; 1,300; 1,600; and 1,800 ft^3/s . Five of the simulated streamflows had one measured water-surface elevation available located at the upstream boundary of each reach. For streamflow conditions of 150; 260; and 1,600 ft^3/s , multiple measured water-surface elevations distributed throughout the reach allowed for more rigorous calibration of these flow simulations (fig. 6). There were 183 surveyed water-surface elevations (data points) for the 150 ft^3/s simulation; 110 data points for the 260 ft^3/s simulation; and 40 data points for the 1,600 ft^3/s simulation (the data points used for the 1,600 ft^3/s simulation were 2010 high-water marks).

For all of the flow simulations except 1,600 ft^3/s (in the lower reach), the root mean squared error of the water-surface elevation was 0.09 m or less. The 1,600 ft^3/s flow simulation in the upper reach had a root mean squared error of 0.24 m, and the predictions of water-surface elevation were consistently higher than the data points. The largest differences between the predictions and data points for this simulation occurred in the middle of the study reach (maximum was 0.58 m), while the up- and downstream boundaries had smaller differences (0.11 m or less) (fig. 6C). This may indicate additional streamflow within that section of the reach that occurs outside of the simulated flow area or over estimation of channel roughness based on estimates of Z_0 .

Within the hydraulic model calibration procedure, the RMSE in streamflow is used to aid in the assessment of flow simulation convergence. The RMSE in streamflow compares the observed and mean simulated streamflow for each flow condition along the computational grids. For most flow simulations, the RMSE in streamflow was less than 1.0 percent (table 1). The 50 ft^3/s simulation had the largest RMSE in both

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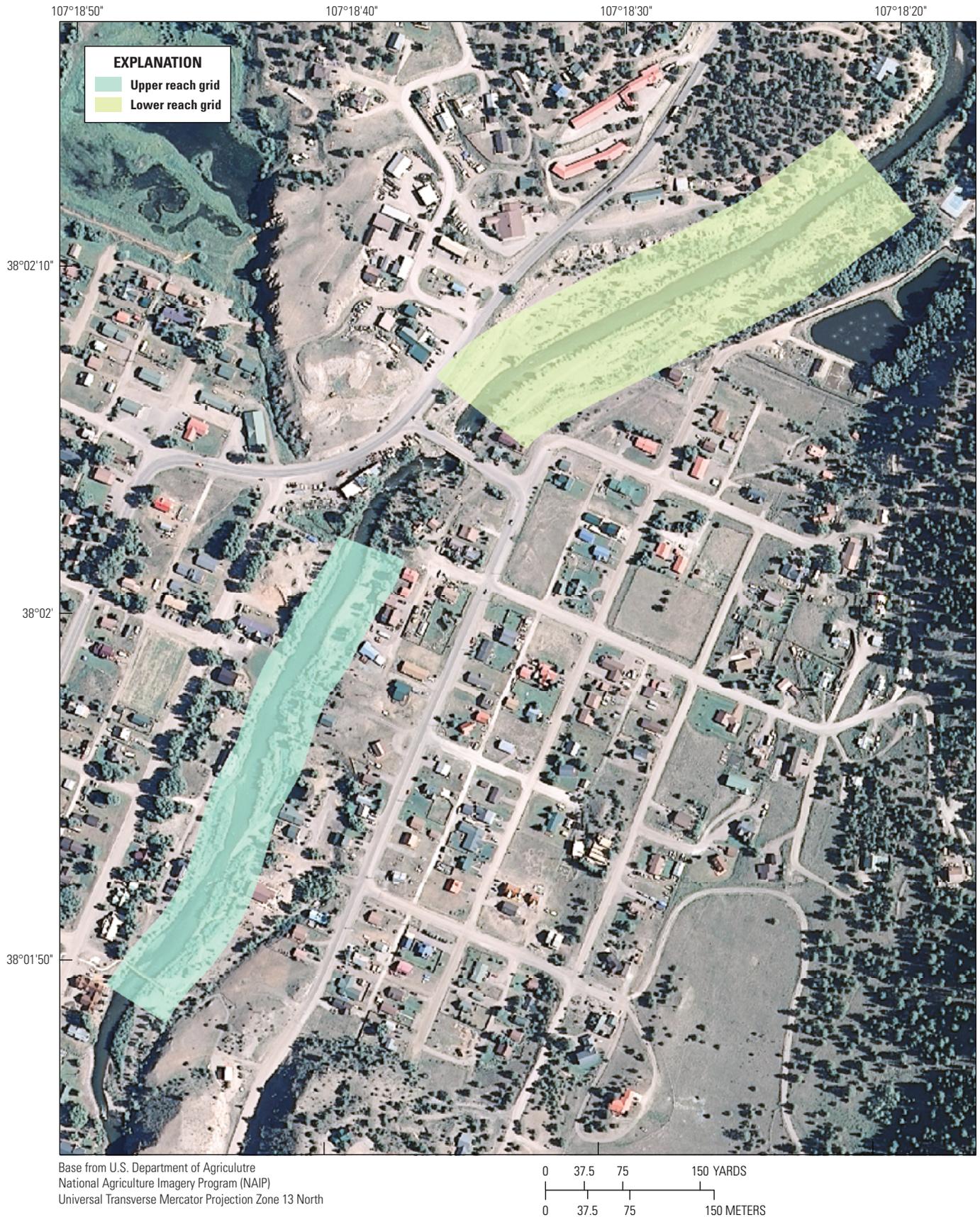


Figure 5. Map of Multidimensional Surface Water Modeling System grids of the upper and lower reaches.

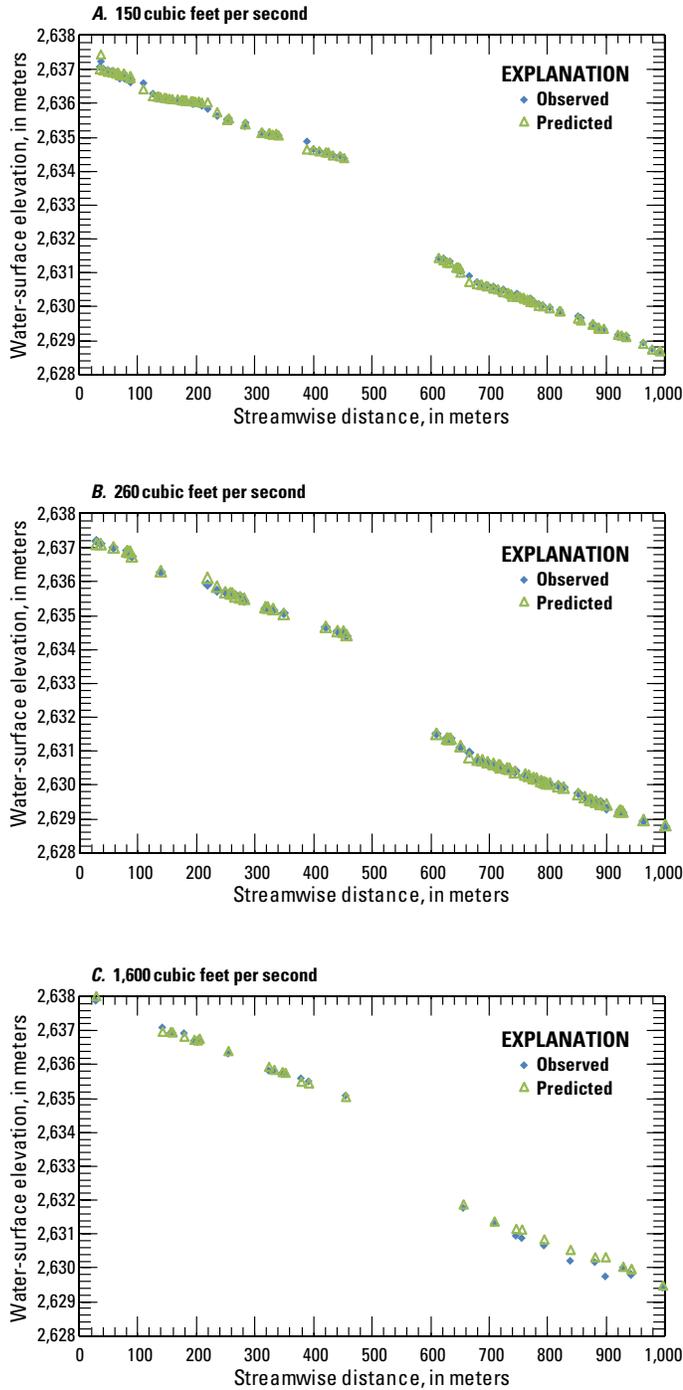


Figure 6. Graph showing water-surface elevations for the best-fit flow simulations for A, 150 cubic feet per second; B, 260 cubic feet per second; and C, 1,600 cubic feet per second streamflows.

study reaches. Roughness (Z_0) was varied over a range until the smallest RMSE was achieved for each flow simulation. The final value fit within the bounds of the literature values mentioned previously in this section.

Sediment Mobility

Fluvial transport of sediment particles is an important component of the assessment of channel stability. In general, sediment transport occurs within a stream when the forces acting to move a particle exceed the resisting forces of the particle. Analysis of each particle within a stream is unfeasible and dependent on the relative positioning of other particles within the stream, so a more generalized assessment of sediment mobility is presented in this report as a function of the median grain size (d_{50}).

In natural river systems, the portion of the boundary shear stress available to move sediment particles (grains) can be referred to as the grain shear stress (Julien, 2010). In wide, straight streams the boundary shear stress is equal to the grain shear stress. In other instances, additional energy losses reduce the shear stress available to move sediment particles. Substantial losses of energy in coarse-bed streams (gravel-sized particles and larger) can be the result of turbulent eddy formation, bedforms, vegetation, and changes in channel geometry (channel expansions and contractions, alluvial bars, and meander bends). The equations within FaSTMECH, in conjunction with the computational grid density used for this analysis, inherently account for these energy losses (except those induced by vegetation). Therefore, within this analysis, the boundary shear stress estimates within the wetted channel (free of vegetation) are equal to the grain shear stress of those areas. FaSTMECH calculates boundary shear stress based on the following equation (Nelson and McDonald, 1997):

$$\tau_b = \rho C_d (u^2 + v^2) \quad (1)$$

where

- τ_b is the total boundary shear stress, in Newtons per square meter;
- ρ is the fluid density, in kilograms per cubic meter;
- C_d is the non-dimensional drag coefficient;
- u is the vertically averaged stream-wise velocity, in meters per second; and
- v is the vertically averaged cross-stream velocity, in meters per second.

In order to determine the precise conditions that will result in the initiation of motion for more than one particle of interest, reasonable generalizations of the particle shape, orientation, submerged weight, and protrusion into flow must be assessed. The critical shear stress (τ_c) for a particle is the minimum shear stress needed for general movement of the particle to begin. Critical shear stress should be considered the minimum value for motion of the streambed because only a small fraction of the sediments will be in motion over short time periods (Milhous, 1982). Substantial mobilization of sediments has been shown to occur at roughly two times the critical shear stress (Wilcock and McArdell, 1993).

Within this report, a comparison of the boundary shear stress to critical shear stress of the median grain size (d_{50}) is used to determine when sediments within the channel are

Table 1. Summary of the lateral eddy viscosity and model diagnostics for the best-fit two-dimensional hydraulic and habitat model simulations.

[RMSE, root mean squared error; --, insufficient data]

Observed streamflow, in cubic feet per second	Lateral eddy viscosity, in square meters per second	RMSE for streamflow, in percent	RMSE for water-surface elevation, in meters	Minimum percent deviation from observed streamflow	Maximum percent deviation from observed streamflow
Upper reach					
50	0.003	3.3	--	-9.0	12.0
150	0.005	0.8	0.07	-5.0	3.0
260	0.005	0.7	0.06	-3.0	1.0
400	0.005	1.1	0.00	-5.0	3.0
900	0.010	0.8	0.01	-5.0	4.0
1,300	0.006	0.8	0.02	-2.5	2.0
1,600	0.007	0.8	0.08	-3.5	2.5
1,800	0.007	0.8	0.02	-3.0	3.0
Lower reach					
50	0.003	1.1	0.04	-3.0	8.0
150	0.002	0.3	0.04	-1.6	1.0
260	0.005	0.7	0.04	-1.5	2.5
400	0.008	0.4	0.01	-2.0	0.8
900	0.009	0.4	0.05	-0.7	1.2
1,300	0.015	0.2	0.09	-0.4	0.7
1,600	0.015	0.2	0.24	-0.3	0.6
1,800	0.015	0.4	0.06	-1.5	0.6

mobile. This accounts for the continuum of possible interactions of particles including hiding (conditions when mixtures of coarse and fine particles are positioned such that the finer material is sheltered by larger particles, thereby decreasing sediment mobility of the finer particles) or increased mobility (when larger particles are surrounded in a matrix of finer material, thereby increasing sediment mobility of the larger particles) (Julien, 2010).

Multiple dimensionless critical shear-stress values were selected for the sediment mobility analyses to cover the range of conditions within the reach. Based on the d_{50} , the dimensionless critical shear stress was 0.047 using equations 2 and 3 from Julien (2010)

$$\tau_{*c} \approx 0.3e^{-\frac{d_*}{3}} + 0.06 \tan \phi \left(1 - e^{-\frac{d_*}{20}} \right) \quad (2)$$

where

- τ_{*c} is the dimensionless critical shear stress;
- ϕ is the sediment particle angle of repose (assumed to be 38 degrees); and

$$d_* = d_s \left[\frac{(G-1)g}{v_m^2} \right]^{1/3} \quad (3)$$

where

- d_* is the dimensionless sediment particle diameter;
- d_s is the median grain size (d_{50}), in meters;
- G is the specific gravity of sediment (2.65, dimensionless);

- g is gravitational acceleration (9.81 meters per second per second); and
- v_m is the kinematic viscosity at 20 degrees Celsius (1.0×10^{-6} square meters per second).

A dimensionless critical shear value of 0.060 was selected to represent areas where the streambed was tightly structured or where the particles were strongly imbricated (Parker and others, 1982; Andrews, 1983; Komar, 1987; Powell and Ashworth, 1995). These two values cover a range of potential transport conditions within the stream based on field observations of streambed conditions. These values were used to estimate sediment mobility at the surveyed cross-sections.

The dimensional critical shear stress needed to initiate motion of the streambed was calculated relative to the d_{50} using equation 4. In this report, comparisons are made to the d_{50} within each reach. As previously mentioned, this method represents the general condition of sediment motion within the channel by accounting for occurrence of particle hiding and increased mobility of differently-sized particles.

$$\tau_c = \tau_{*c} (\gamma_s - \gamma) d_s \quad (4)$$

- τ_c is the critical shear stress, in Newtons per square meter (pascal);
- τ_{*c} is the dimensionless critical shear stress or Shields parameter;
- γ_s is the specific weight of sediment (25,996.5 Newtons per cubic meter);

- γ is the specific weight of water (9,810 Newtons per cubic meter); and
 d_s is the particle size of interest (d_{50}), in meters.

An assessment of sediment mobility was done through an assessment of transport strength using FaSTMECH. This method is most sensitive to the potential for sediment mobility because it uses the lowest threshold value for motion (dimensionless critical shear stress value of 0.03). This is a reasonable threshold accounting for conditions possibly present that were not observed in the cross-section locations. Sediment mobility is reported using equation 5 to calculate the transport strength (T), where $T=0$ is the threshold of motion and $T=1$ is the threshold for substantial motion for the d_{50} :

$$T = (\tau_b - \tau_c) / \tau_c \quad (5)$$

where

- T is the transport strength, dimensionless,
 τ_b is the boundary shear stress or grain shear stress, in pascals; and
 τ_c is the critical shear stress, in pascals.

Trout Habitat Suitability

Habitat suitability was evaluated for cutthroat (*Oncorhynchus clarkii*) and brown trout (*Salmo trutta morpha fario*) fry, juveniles, and adults. These species were chosen because they represent the two extremes of trout found in Colorado mountain streams and also because they represent a comparison between native (cutthroat trout) and introduced (brown trout) salmonids in Colorado. A longitudinal stratification of these species often occurs in stream systems where multiple species of trout are present. Typically, cutthroat trout are found in headwater areas with cooler water temperatures, lower sediment concentrations, and less biological production (Hickman and Raleigh, 1982). Brown trout are usually found at the lowest reaches, where warmer water temperatures, higher sediment concentration, and higher biological production are typical (Raleigh and others, 1986).

Microscale (point locations) and mesoscale (reach features) habitat was assessed using the combination of field observations, measurements, and hydraulic simulations within the study reach of the Lake Fork. This provides resource managers with tools to assess the effects of hydrologic conditions (wet, average, and dry years) and flow alterations on habitat availability for specific streamflows or over annual timescales. To assess how habitat availability changes with streamflow, microscale-habitat quantification was done for each simulated streamflow and was also reported as a time-weighted annual total (based on typical flow frequencies).

Habitat builder in MD_SWMS was used to quantify microscale habitat availability following methodologies similar to the Habitat Suitability Index method (Hickman and Raleigh, 1982; Raleigh and others, 1986). Suitability criteria were defined based on published values for three life stages of the two fish species: (1) adult, (2) juvenile, and (3) fry, based on depth and velocity ranges (fig. 7). Habitat suitability

curves, scaled from 0 to 1, were developed for each of the three life stages based on depth and velocity conditions. A value of zero indicates that the velocity or depth condition is not acceptable; whereas a value of 1 indicates that the condition is optimal. Between 0 and 1, habitat suitability values were interpolated linearly to indicate increasing or decreasing acceptability of the condition. For each streamflow and life stage, the habitat builder provides a map of the calculated geometric mean of the suitability curves and total weighted usable area as the sum of the area of each grid cell multiplied by the geometric mean of the grid node.

Mesoscale habitat quantification was done through the separation of each reach into features of specific habitat type (pool or riffle/run habitat) based on the geomorphology and hydraulic characteristics of larger, continuous features within each reach. Separation of these habitat types was done in a geographic information system based on velocity, depth, and visual inspection of morphological form. Separation of the reaches into two habitat types provides a comparison between the observed proportions of habitat and general guidelines derived from observations of reaches with sustained populations of each species (Hickman and Raleigh, 1982; Raleigh and others, 1986) (table 2).

A vital component of habitat for fish includes available cover. Fishes use different cover types depending on what types are available, the location of cover relative to other important habitat features (such as feeding habitat or refuge), time of year, and life stage. Cover can vary from rubble bed substrate, aquatic vegetation or plant debris, or deep pools and surface disturbances that obscure visibility from terrestrial or avian predators. Cover estimates were limited to adult life stages in this analysis. Cover estimates were quantified as a function of the distance to cover from drift feeding areas within each reach. Feeding areas were selected as areas that could provide access to food sources while requiring little exertion. These were typically lower-velocity areas adjacent to or downstream from higher velocity areas that could funnel benthic invertebrates and terrestrial insects to these fish from the current. Cover was identified as pool areas or vegetated channel banks within each reach.

Two-Dimensional Hydraulic Model Sensitivity Analysis

FaSTMECH model sensitivity was analyzed for two parameters: the lateral eddy viscosity and channel roughness based on Z_0 , for 150; 260; and 1,600 ft³/s flow simulations, because water-surface elevation data were available along the entire length of each reach for these flows. Sensitivity of the two parameters was evaluated by holding all parameters constant in best-fit flow simulations and then individually adjusting the lateral eddy viscosity and Z_0 by -25 and +25 percent. Model results from the sensitivity analysis were compared to original best-fit flow simulations (tables 3 and 4). Water-surface

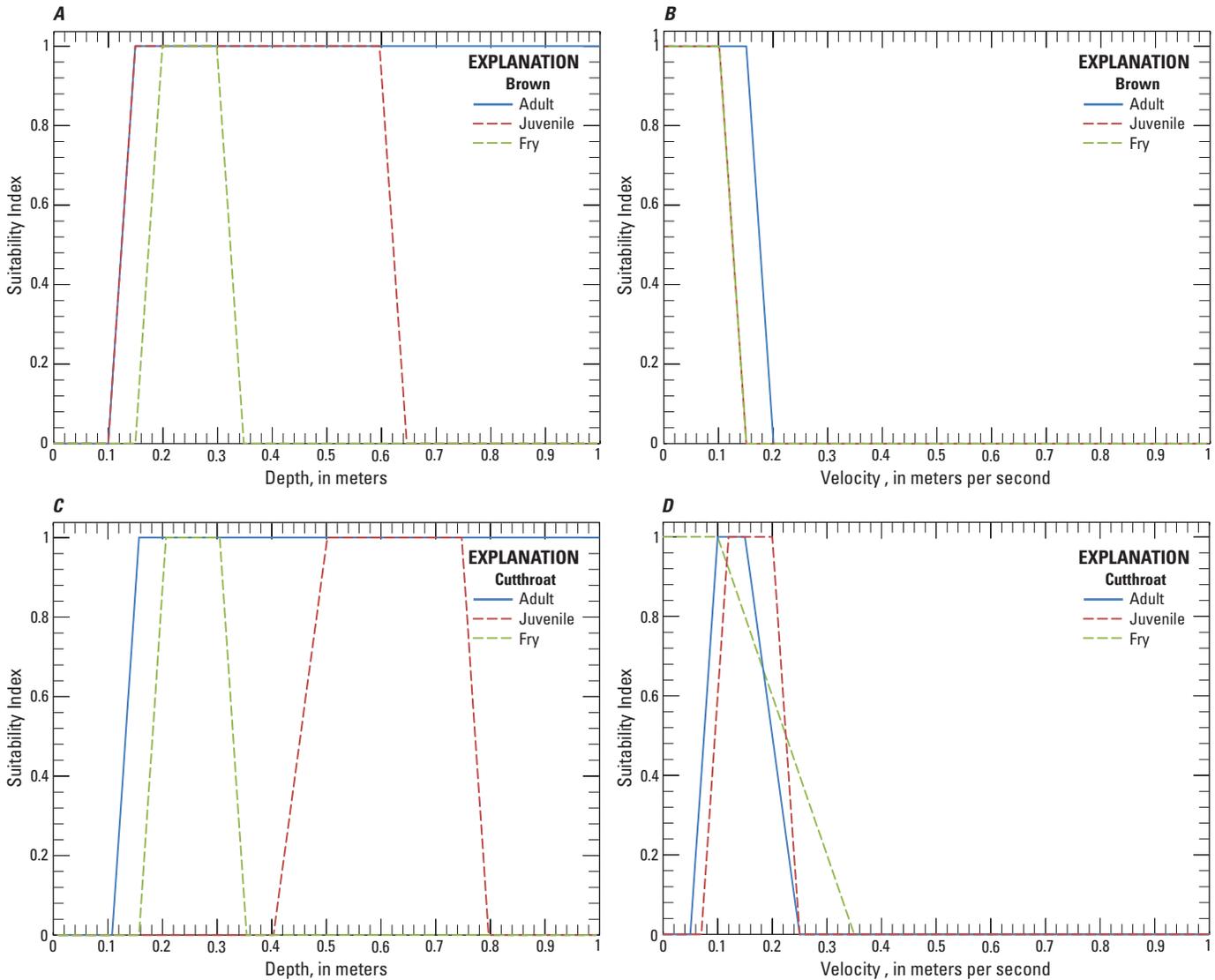


Figure 7. Habitat suitability curves for the three life stages of brown trout and cutthroat trout. *A*, habitat suitability for brown trout based on depth; *B*, habitat suitability for brown trout based on velocity; *C*, habitat suitability for cutthroat trout based on depth; *D*, habitat suitability for cutthroat trout based on velocity.

elevations, velocity, and shear stress are calculated from means of all wetted nodes in each flow simulation. Differences between the two flow simulations were reported from means of the differences in values between wetted node-pairs from each flow simulation. Percent difference was calculated as the mean difference between the two flow simulations, relative to the mean value of the best-fit flow simulation. Larger differences indicate greater sensitivity of the model parameter.

None of the flow simulations showed substantial sensitivity to changes in lateral eddy viscosity (table 3). The percent difference between flow simulations ranged from -0.3 percent to +0.5 percent. The extremes occurred in boundary shear stress in the lower reach for the 1,600 ft³/s simulation and the upper reach for the 1,600 ft³/s simulation, and in mean

water-surface elevation in the upper reach for the 260 ft³/s simulation. In the 1,600 ft³/s simulation at the upper reach, the +0.5 percent for mean boundary shear stress corresponded to +0.20 pascal. The largest change in mean velocity was +0.01 meters per second and the largest change in mean depth (and mean water-surface elevation) was +0.01 m (table 3).

Flow simulations showed increased sensitivity to changes in Z_0 (table 4). Most model outputs changed by less than 10 percent. Shear stress was generally the most sensitive of model outputs, where the difference from the mean boundary shear stress ranged from -59.4 percent to +8.0 percent. Percent difference from mean velocity ranged from -1.6 to +19.5 percent; whereas, the percent difference of mean water-surface elevation ranged from -24.2 to +5.6 percent (table 4).

Table 2. Mesoscale-habitat suitability ranges of habitat type for cutthroat and brown trout (from Hickman and Raleigh, 1982; Raleigh and others, 1986).

Trout species	Mesoscale habitat suitability	
	Pool, percent	Riffle/Run, percent
Brown	50–70	30–50
Cutthroat	40–60	40–60

Table 3. Results from the analysis of the sensitivity of the lateral eddy viscosity parameter for three of the streamflows simulated in the multidimensional flow model for the upper and lower study reaches on the Lake Fork.

[Sensitivity analysis of the lateral eddy viscosity parameter were made at 75 (italicized values) and 125 (bolded values) percent of the calibrated lateral eddy viscosity value. Percent differences are relative to the mean of the calibrated model and percent difference in water-surface elevation is relative to the mean depth. The mean values are based on all of the wet nodes in the model. RMSE, root mean squared error; -- insufficient data]

Observed streamflow, in cubic feet per second ¹	Lateral eddy viscosity, in square meters per second	Model output					Percent difference from the mean		
		Mean depth, in meters	Mean water-surface elevation, in meters	Mean velocity, in meters per second	Mean boundary-shear stress, in Pascals	RMSE for water-surface elevation, in meters	Water-surface elevation, in percent	Velocity, in percent	Boundary shear stress, in percent
Upper Reach									
<i>150</i>	<i>0.010</i>	<i>0.31</i>	<i>2,635.82</i>	<i>0.76</i>	<i>13.81</i>	<i>0.07</i>	<i>0.2</i>	<i>0.0</i>	<i>0.2</i>
150	0.008	0.31	2,635.82	0.76	13.77	0.07	--	--	--
150	0.006	0.31	2,635.82	0.76	13.77	0.07	0.3	-0.0	-0.0
<i>260</i>	<i>0.007</i>	<i>0.38</i>	<i>2,635.92</i>	<i>0.95</i>	<i>18.27</i>	<i>0.06</i>	<i>0.5</i>	<i>0.1</i>	<i>0.3</i>
260	0.006	0.37	2,635.92	0.95	18.20	0.06	--	--	--
260	0.004	0.37	2,635.92	0.95	18.19	0.06	0.1	-0.0	-0.1
<i>1,600</i>	<i>0.006</i>	<i>0.66</i>	<i>2,636.52</i>	<i>1.52</i>	<i>32.29</i>	<i>0.08</i>	<i>-0.1</i>	<i>0.1</i>	<i>0.5</i>
1,600	0.005	0.66	2,636.52	1.51	32.09	0.08	--	--	--
1,600	0.003	0.66	2,636.52	1.52	32.20	0.08	0.0	0.1	0.3
Lower Reach									
<i>150</i>	<i>0.002</i>	<i>0.30</i>	<i>2,629.96</i>	<i>0.78</i>	<i>17.52</i>	<i>0.04</i>	<i>-0.0</i>	<i>-0.0</i>	<i>-0.0</i>
150	0.002	0.30	2,629.96	0.78	17.52	0.04	--	--	--
150	0.003	0.30	2,629.96	0.78	17.51	0.04	0.0	-0.0	-0.1
<i>260</i>	<i>0.004</i>	<i>0.38</i>	<i>2,630.06</i>	<i>0.99</i>	<i>21.87</i>	<i>0.04</i>	<i>-0.1</i>	<i>-0.0</i>	<i>-0.1</i>
260	0.005	0.38	2,630.06	0.99	21.89	0.04	--	--	--
260	0.006	0.38	2,630.06	0.99	21.85	0.04	0.0	-0.0	-0.2
<i>1,600</i>	<i>0.011</i>	<i>0.94</i>	<i>2,630.74</i>	<i>1.93</i>	<i>54.69</i>	<i>0.24</i>	<i>-0.0</i>	<i>0.0</i>	<i>0.1</i>
1,600	0.015	0.94	2,630.74	1.93	54.61	0.24	--	--	--
1,600	0.019	0.94	2,630.75	1.92	54.48	0.24	0.1	-0.0	-0.3

¹To convert from cubic feet per second to cubic meters per second divide by 35.31.

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Table 4. Results from the analysis of the sensitivity of the roughness parameter (Z_0) for three of the streamflows simulated in the two-dimensional flow model for the upper and lower study reaches on the Lake Fork.

[Sensitivity analysis of the roughness parameter (Z_0) were made at 75 (italicized values) and 125 (bolded values) percent of the calibrated Z_0 value. Percent differences are relative to the mean of the calibrated model and percent difference in water surface elevation is relative to the mean depth. The mean values are based on all of the wet nodes in the model. RMSE, root mean squared error; -- insufficient data]

Observed streamflow, in cubic feet per second ¹	Z_0 , in meters	Model output					Percent difference from the mean		
		Mean depth, in meters	Mean water-surface elevation, in meters	Mean velocity, in meters per second	Mean boundary-shear stress, in Pascals	RMSE for water-surface elevation, in meters	Water-surface elevation, in percent	Velocity, in percent	Boundary shear stress, in percent
Upper Reach									
150	<i>0.010</i>	0.30	2,635.80	0.81	12.65	0.07	-5.0	1.6	-9.5
150	0.013	0.31	2,635.82	0.76	13.77	0.07	--	--	--
150	0.016	0.30	2,635.84	0.71	14.25	0.08	2.4	-0.8	7.5
260	<i>0.010</i>	0.36	2,635.91	1.00	16.52	0.06	-4.0	1.4	-10.0
260	0.013	0.37	2,635.92	0.95	18.20	0.06	--	--	--
260	0.016	0.38	2,635.93	0.92	19.35	0.06	3.1	-0.8	7.2
1,600	<i>0.010</i>	0.64	2,636.37	2.10	20.17	0.16	-24.2	19.5	-59.4
1,600	0.013	0.66	2,636.52	1.51	32.09	0.08	--	--	--
1,600	0.016	0.67	2,636.54	1.47	33.42	0.08	2.9	-1.6	5.9
Lower Reach									
150	<i>0.010</i>	0.31	2,629.98	0.75	18.92	0.04	5.6	-1.4	8.0
150	0.013	0.30	2,629.96	0.78	17.52	0.04	--	--	--
150	0.016	0.28	2,629.94	0.84	16.22	0.06	-6.2	1.7	-9.0
260	<i>0.010</i>	0.39	2,630.07	0.96	23.27	0.04	4.1	-1.1	6.3
260	0.013	0.38	2,630.06	0.99	21.89	0.04	--	--	--
260	0.016	0.37	2,630.03	1.06	20.24	0.05	-5.8	1.7	-9.2
1,600	<i>0.010</i>	0.98	2,630.78	1.86	58.06	0.27	4.3	-1.1	6.3
1,600	0.013	0.94	2,630.74	1.93	54.61	0.24	--	--	--
1,600	0.016	0.90	2,630.70	2.02	51.02	0.20	-4.9	1.4	-7.1

¹To convert from cubic feet per second to cubic meters per second divide by 35.31.

Hydraulic and Geomorphic Conditions

The existing hydraulic and geomorphic conditions for a 1.1-km section of the Lake Fork at Lake City are summarized as a function of the current streamflow regime based on model simulations for eight streamflows that cover the range of streamflow conditions typically observed at the site (figs. 2 and 8). Comparisons and evaluation of differences in sediment mobility and habitat suitability will provide resource managers with information to evaluate existing channel stability and habitat conditions of the reach as well as provide a baseline to compare with future conditions.

Within these systems, limiting fine-sediment deposition and removal of fine sediments (sizes less than 2 millimeters [mm]) within framework grain interstitial spaces enhances habitat suitability for both fish and invertebrates. Gravel substrates used for spawning redds (spawning habitat) are most suitable when free of finer sediments (Hickman and Raleigh, 1982; Raleigh and others, 1986). Benthic invertebrates productivity and abundance, as well as larval and fry refugia, are optimized when fine sediments are limited to less than 5 percent (Hickman and Raleigh, 1982; Raleigh and others, 1986). Sediment mobility is an important process for flushing fine sediments from within the gravel frameworks.

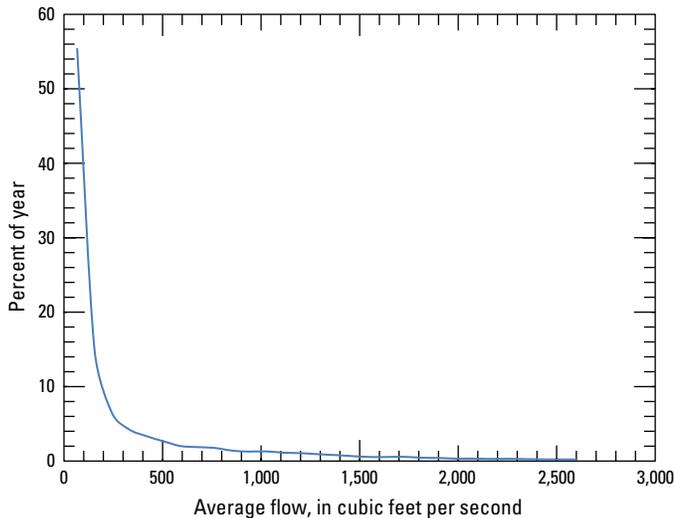


Figure 8. Flow frequency curve for the Lake Fork of the Gunnison River at Lake City, Colorado.

Sediment Mobility

Boundary shear stress calculated from each flow simulation was compared to the critical shear stress of mean d_{50} in each reach to determine streambed mobility (fig. 9 and table 5). In this report, where boundary shear stress was equal to critical shear, sediment transport conditions are reported as potentially mobile; where the boundary shear stress exceeded two times the critical shear stress, sediment transport conditions are reported as substantially mobile.

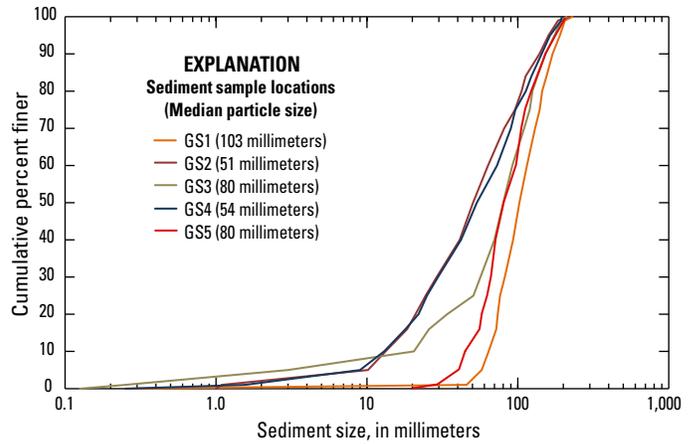


Figure 9. Sediment-size characteristics of the five sampling sites.

Table 5. Sediment particle-size characteristics for the five sites sampled from August 4 to August 6, 2010, and August 18, 2011 (GS1-GS4 and GS-5, respectively) in the Lake Fork study area. (Grain-size sample locations [GS1–GS5] are shown in fig. 3.)

[Easting and Northing datum is Universal Transverse Mercator Zone 13 North American Datum 1983; d_{50} , median (50th percentile) particle diameter; d_{84} , 84th percentile particle diameter]

Site short name	Easting, in meters	Northing, in meters	d_{50} , in millimeters	d_{84} , in millimeters
GS1	296,993	4,211,721	103	155
GS2	297,083	4,211,874	51	113
GS3	297,172	4,212,064	80	135
Upper reach average			78	134
GS4	297,358	4,212,262	54	123
GS5	297,476	4,212,329	80	132
Lower reach average			67	128

Evaluations of channel and flow characteristics at cross-section locations 2–8, presented in downstream order, show a range of streambed mobility (figs. 10 and 11). In general, boundary shear stress and streambed mobility increase with increases in streamflow. At streamflows of 50, 150, and 260 ft^3/s the streambed is not mobile (figs. 10 and 11). However, the streambed is potentially mobile for the 400 ft^3/s streamflow at cross-sections 4–8 depending on which dimensionless critical-shear stress value is referenced (0.03, 0.047, or 0.06) (figs. 10 and 11). At cross sections 2–8, sediment is potentially mobile at streamflows of 900 ft^3/s . The streambed is substantially mobile at cross sections 4–8 at streamflows of 1,300 to 1,600 ft^3/s with all cross sections being substantially mobile at 1,800 ft^3/s (figs. 10–11). Within the cross sections, the greatest boundary shear stress occurs towards the center of the channel. Sediments are generally less mobile near the channel margins for all flow simulations.

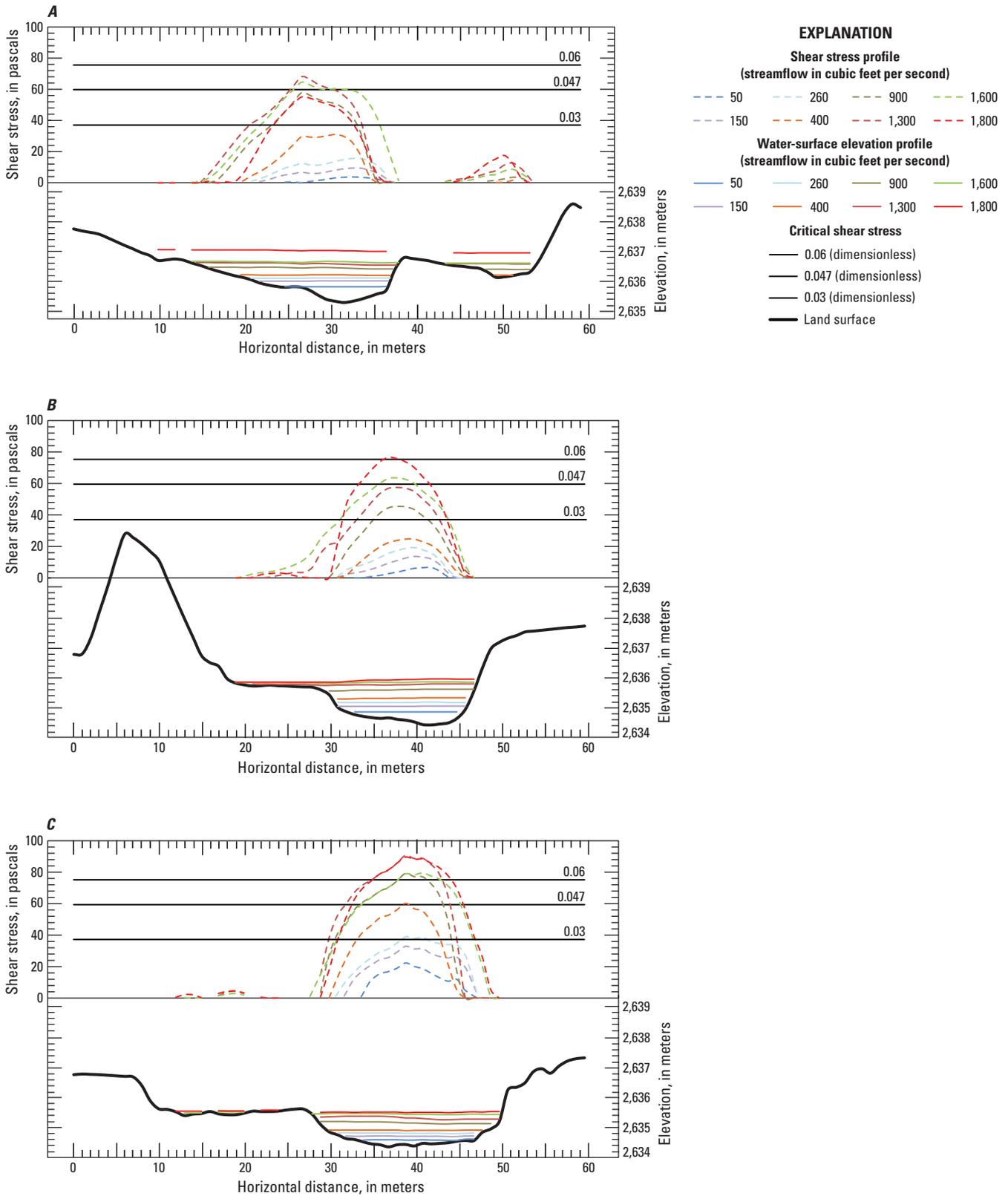


Figure 10. Shear stress and water-surface elevation plots at A, cross-section 2; B, cross-section 3; and C, cross-section 4.

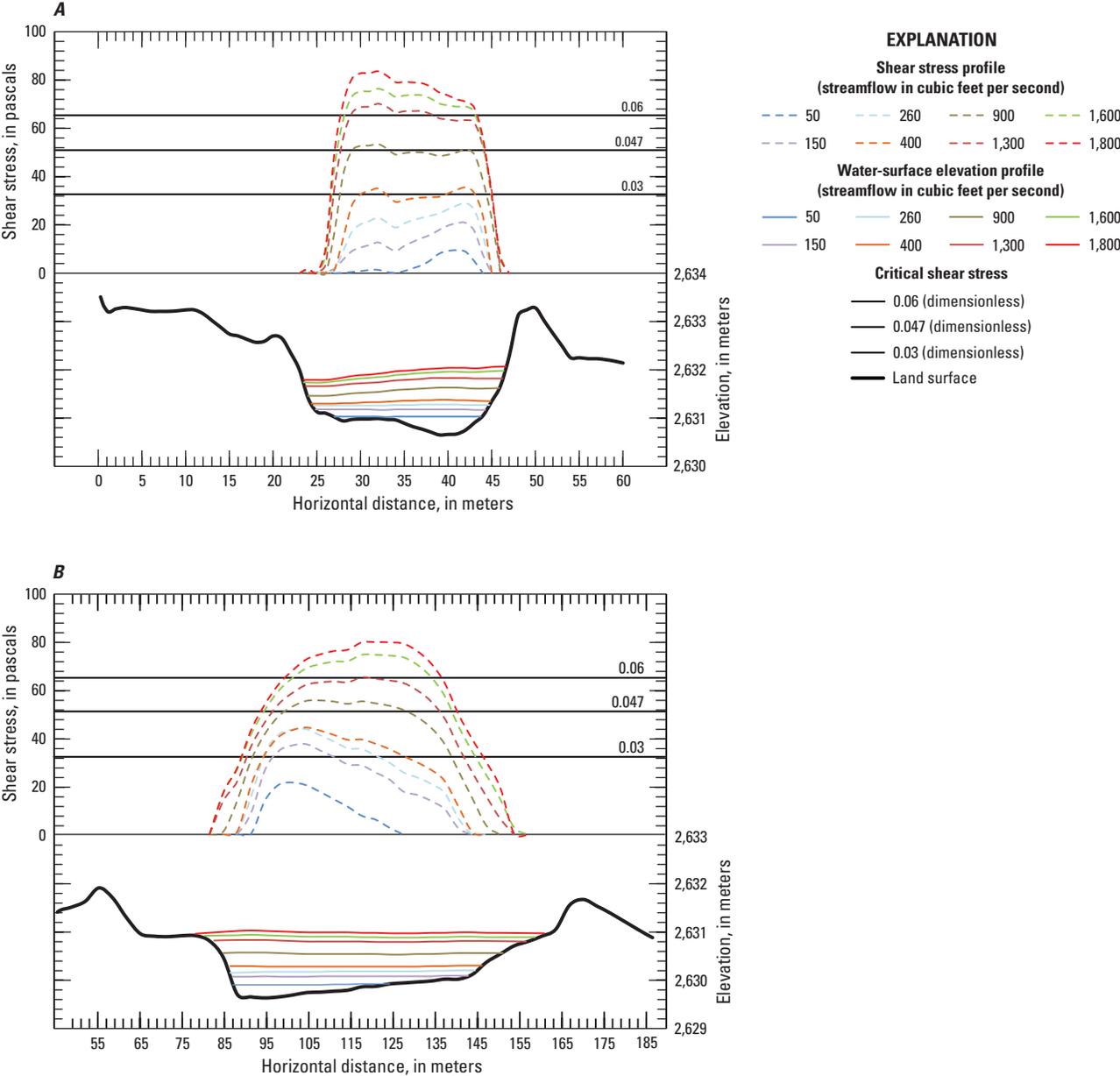


Figure 11. Shear stress and water-surface elevation plots at A, cross-section 5; B, cross-section 6; C, cross-section 7; and D, cross-section 8.

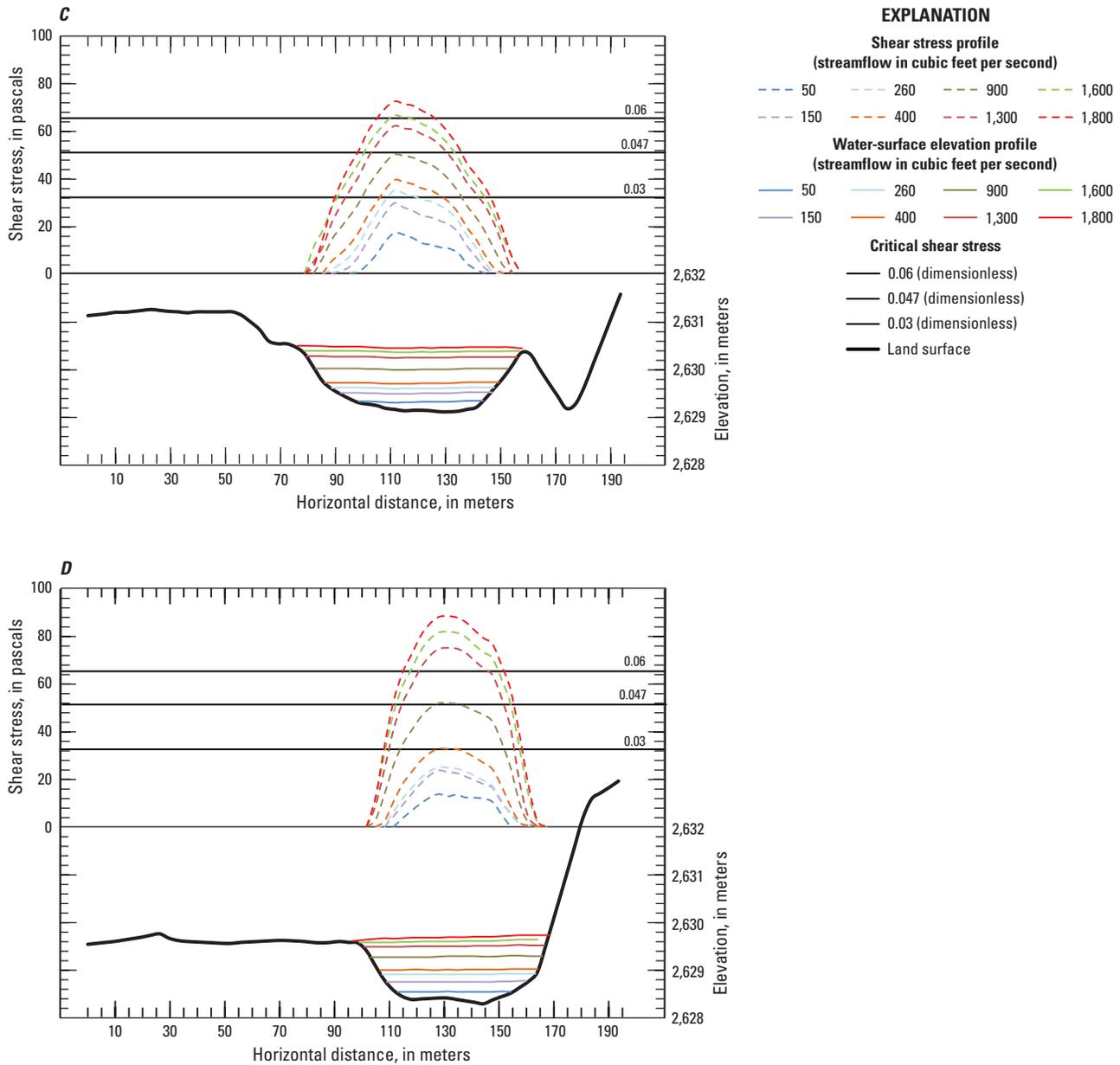
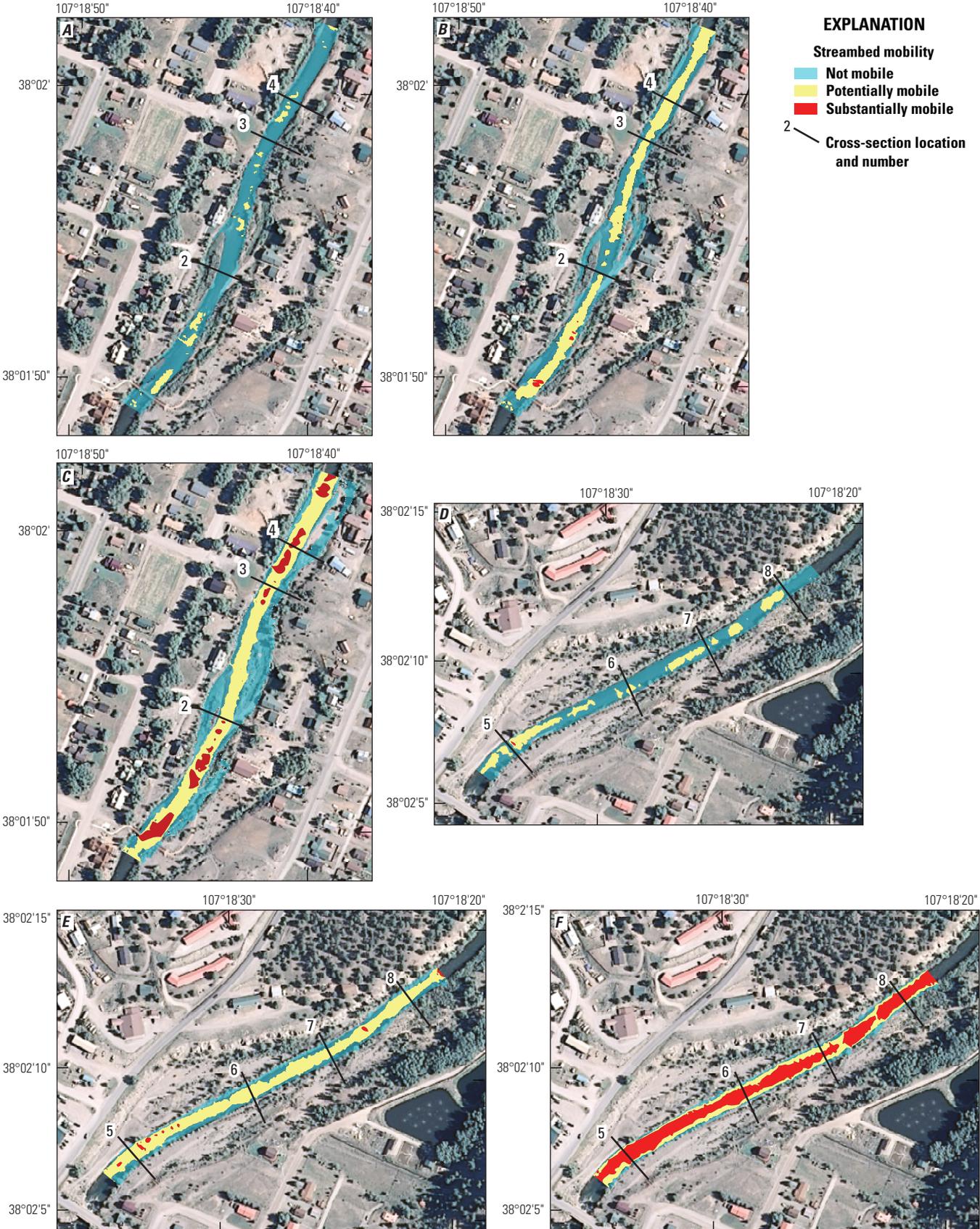


Figure 11. Shear stress and water-surface elevation plots at *A*, cross-section 5; *B*, cross-section 6; *C*, cross-section 7; and *D*, cross-section 8.—Continued

Reach-scale assessment of sediment mobility in the upper reach shows that there are areas where the streambed is potentially mobile for all streamflow simulations and that boundary shear stress and streambed mobility increase as streamflow increases (fig. 12*A–C*). For streamflows of 400 ft³/s or less, the streambed is potentially mobile in some areas. Areas where the streambed is substantially mobile began to appear in flow simulations of 900 ft³/s and greater, and the size of these areas increase as streamflow increases. At streamflows of 1,300 ft³/s or greater, the majority of the channel is potentially mobile except areas along the channel margins.

Reach-scale assessment of sediment mobility in the lower reach shows increased streambed mobility (fig. 12*D–F*). This is due in part to smaller grain sizes in the lower reach (mean d_{50} is 11 mm smaller than the upper reach mean d_{50} , [table 5]) but may also reflect the greater extent of channel

Figure 12. Reach-scale assessment of sediment mobility in the upper reach (*A–C*) and lower reach (*D–F*) of the Lake Fork of the Gunnison River at streamflows of 400; 900; and 1,800 ft³/s, respectively.—Following page



Base from U.S. Department of Agriculture
National Agriculture Imagery Program (NAIP)
Universal Transverse Mercator Projection Zone 13 North

alterations, specifically the temporary berms constructed by CDOT in the late 1980s and early 1990s, present in this reach. In the 400 ft³/s flow simulation, some areas within the channel become substantially mobile with additional areas of potential mobility appearing downstream throughout the reach. In the 900 ft³/s flow simulation, the entire length of the channel becomes potentially mobile with small patches of the streambed that are substantially mobile. In the 1,800 ft³/s flow simulation, the majority of the channel along its entire length is substantially mobile except along the channel margins which are potentially mobile.

Geomorphic Channel Form

Geomorphic channel form is affected by land-use changes within the basin and geologic controls within the reach (Lake Fork Valley Conservancy, 2010). The historic channel was defined as a dynamic, braided channel (multiple, bifurcating channels) with an active flood plain (Lake Fork Valley Conservancy, 2010). Comparisons of the channel slope, high-flow conditions, or floods (Capesius and Stephens, 2009; U.S. Geological Survey, 2010b), and d_{50} of each reach to channel-form thresholds (meandering and braided channel) indicated that current channel characteristics may favor a braided channel form (fig. 13) (Leopold and Wolman, 1957; Richards, 1982). This can result in a natural tendency for the channel to braid, which can affect channel stability of reconfigured reaches when a single-thread meandering channel is imposed on the stream (Elliott and Capesius, 2009). The similarities of channel slope, total stream power index (streamflow times channel slope), and median bed-material size for the upper and lower reaches and at Gateview, which was historically a braided reach and is considered a reference reach for this report, support a natural tendency for the channels to braid in both reaches (fig. 13).

Additional constraints on channel form include natural and artificial impingement of the active channel occurring from placement of boulder revetments, cobble-boulder berms, and bedrock outcrops along the channel margins. Boulder revetments are common between cross-sections 1 and 5 along the left bank of the river, with limited use along the right bank. Cobble-boulder berms occur between cross-sections 4 and 8 along both banks. Bedrock constraints occur along both banks for much of the channel between cross-sections 4 and 5, and along the left bank between cross-sections 6 and 8. These features constrain the channel from lateral migration and channel adjustments and potentially limit the capability of geomorphic channel response to alterations in this area.

Trout Habitat Characteristics

Habitat suitability analysis can include an evaluation of several inter-related stream conditions (Bovee, 1982). Dissolved oxygen, water temperature, pH, and other water-chemistry constituents (nutrients, metals, and total dissolved

solids) are important to overall aquatic habitat suitability; however, this analysis will focus on the physical habitat elements of the reach such as depth, velocity, and distance to cover. Model output for each streamflow was used to quantify trout habitat abundance.

Microscale Trout Habitat

Microscale trout habitat, defined as weighted-usable area, generally increased as streamflow increased for both trout species and all life stages (fig. 14). Areas of suitable microscale habitat occur along the banks for flows of 900 ft³/s and less. Out-of-bank areas contributed more substantially to overall habitat availability for flows of 1,300 ft³/s or more when compared to other features. Adult habitat, for both trout species, was the most abundant habitat type for nearly all streamflows. Habitat for juvenile cutthroat trout and brown trout fry was the least abundant in both reaches. In general, the upper reach provided 2–3 times more available habitat than the lower reach for both trout species.

In order to determine the interaction of flow frequency and habitat abundance within the current flow regime, a combination of the available habitat was related to the probability of that flow occurring each year. This relation provides a measure of the overall habitat for each life stage over the course of an average flow year. The results are summarized by species and life stage in table 6.

There are seasonal differences between the two species when fry are present in the stream (Hickman and Raleigh, 1982; Raleigh and others, 1986). Both species construct redds when spawning in small gravelly areas with good hyporheic flows and minimal fine sediments. However, cutthroat trout do so in early spring (February or later, based on water temperatures) and the larvae typically hatch within 28–49 days depending on water temperatures (Hickman and Raleigh, 1982). Brown trout construct redds in late summer to early fall; this makes the redds more susceptible to over-wintering conditions within the gravels and possible smothering due to fine sediment deposition (Raleigh and others, 1986). However, when brown trout emerge in the spring they are larger and typically better able to out-compete cutthroat fry if resources are limited (Raleigh and others, 1986). The flows that typically occur during these two different time periods were used to calculate the total weighted-usable habitat in a typical year for the fry of both species (table 6).

Mesoscale Trout Habitat

Mesoscale trout habitat assessment of the Lake Fork was done based on the conditions present in the 150 ft³/s flow simulation as well as field observation. Both the upper and lower reaches are primarily characterized as riffle/run habitat; however, in the upper reach, the total available pool habitat (total wetted area) is greater (table 7). The presence of pool habitat was limited throughout both reaches and occurred along the channel margins. For both reaches, the pool habitat was less

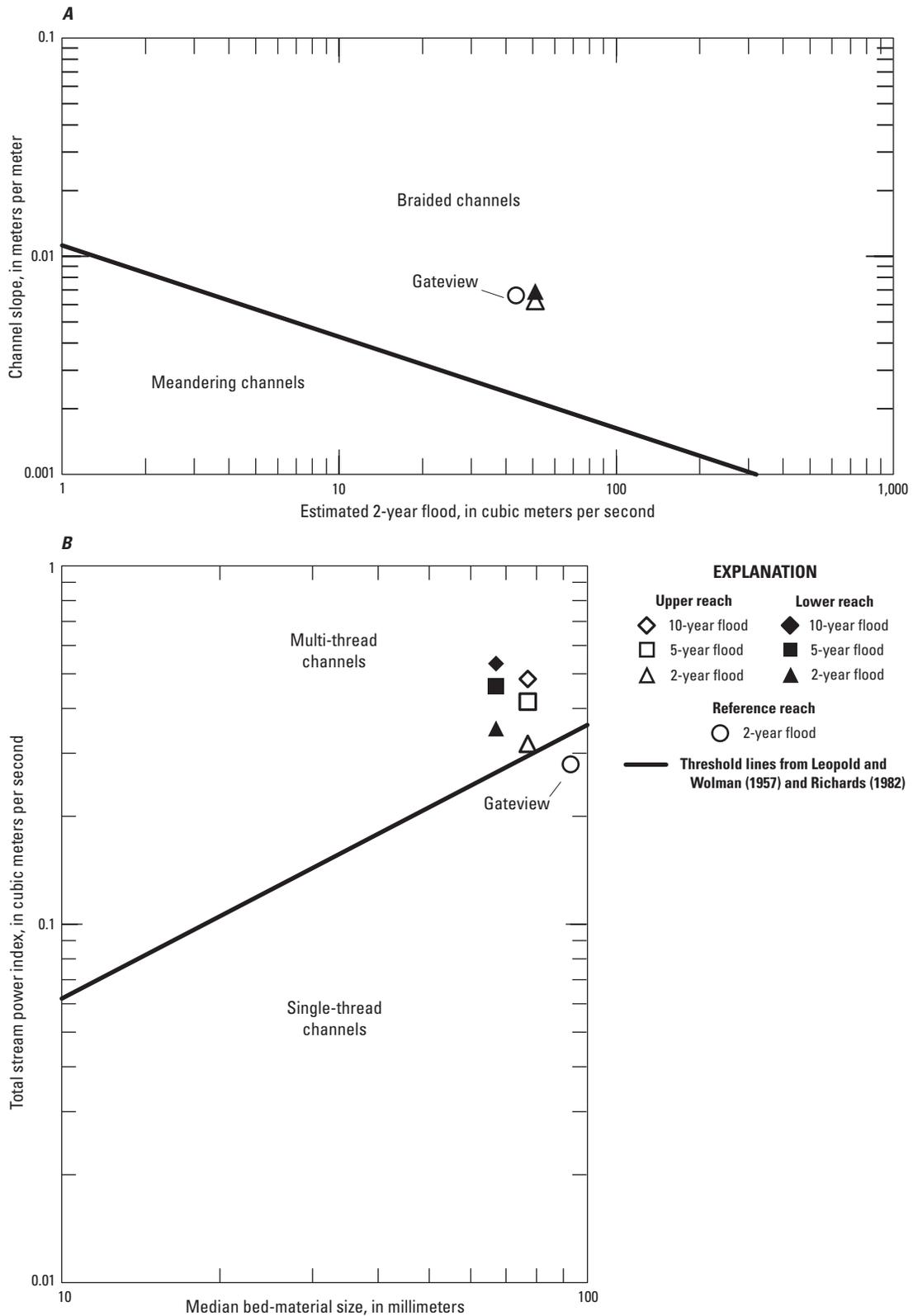


Figure 13. Plotting positions of two surveyed reaches of the Lake Fork of the Gunnison River near Lake City, Colorado, in comparison to thresholds for meandering and braided channel patterns based on findings from A, Leopold and Wolman (1957) and B, Richards (1982).

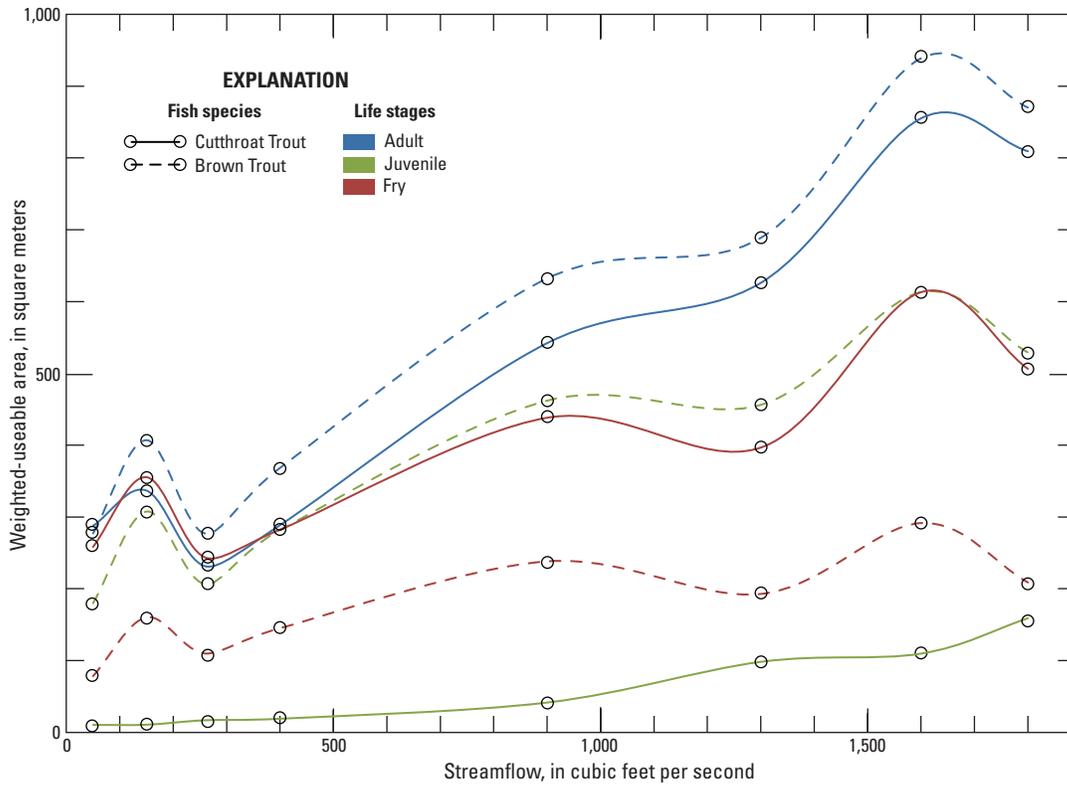


Figure 14. Weighted-useable habitat for the adult, juvenile, and fry life stages of the cutthroat and brown trout in the study reach of the Lake Fork of the Gunnison River.

Table 6. Results from flow-frequency curves and simulation results from the multidimensional flow model showing microscale-habitat suitability total weighted-useable habitat in a typical year for cutthroat and brown trout.

Trout species	Life stage		
	Adult square meters	Juvenile square meters	Fry square meters
Brown	358	249	96
Cutthroat	332	19	279

Table 7. Mesoscale-habitat characteristics for cutthroat and brown trout during typical base-flow conditions in the Lake Fork near Lake City, Colorado.

Reach	Total wetted area, in square meters	Pool area, in square meters	Pool, in percent	Riffle/Run, in percent	Distance to cover from feeding areas, in meters
Upper	7,126	315	4.4	95.6	15
Lower	6,231	47	0.7	99.3	less than 1

than 5 percent of the total wetted area. This percentage is substantially lower than the recommendations for sustainable populations of 40–70 percent (tables 2 and 7) (Hickman and Raleigh, 1982; Raleigh and others, 1986). An exception to this is an isolated scour pool located outside of the modeled area (between the two reaches) below a waterfall which was not quantified in this analysis.

Riparian canopy study results show differences between the upper and lower reaches. Riparian canopy density measurements were consistent in the upper reach, with approximately 20 percent coverage occurring along both banks throughout (fig. 4). Vegetation patterns in the lower reach were less consistent and demonstrate local effects of topography. The large hillslope along the left bank between cross-sections 7 and 8 produced greater canopy density and shading than other areas (fig. 4).

Assessment of the distance of various in-stream habitats to cover (pool areas or vegetated channel banks within each reach) from potential feeding areas shows differences between the characteristics of the two reaches. Areas of cover were adjacent to potential drift feeding areas in the lower reach, and often occurred within the same pool habitat (distance to cover from feeding areas were less than 1 m). This condition may favor energy expenditure ratios of both fish species, wherein little energy is needed to acquire adequate food sources (table 7). In the upper reach, distances from drift feeding areas to cover were much greater (15 m), a condition that is less conducive to cutthroat trout which tend to occupy drift feeding areas where cover is located nearby (Hickman and Raleigh, 1982).

Summary

Since the 1950s, the Lake Fork of the Gunnison River has been an area of active channel modification to accommodate the needs of the Lake City community. The Lake Fork Valley Conservancy District began a planning process to assess restoration options for a reach of the Lake Fork in Lake City to enhance hydraulic and ecologic characteristics of the reach.

Channel rehabilitation, or reconfiguration, to mitigate a variety of riverine problems has become a common practice in the western United States. Reasons for channel rehabilitation include restoration to more natural or historical conditions, improved water conveyance in flood-prone areas, mitigation of unstable streambeds and streambanks, increased sediment transport, enhancement of aquatic and riparian habitat, improved water quality, and recreation. Numerous private entities and resource-management agencies have attempted to modify stream channels by using designs based on different geomorphic philosophies and classification schemes. However, additional work to monitor and assess the channel response to, and the effectiveness of, these modifications over longer periods of time (decadal or longer) is still needed. To address this need, the U.S. Geological Survey is engaged in a program designed to monitor and assess selected river reaches

that have undergone reconfiguration. The U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board and Colorado River Water Conservation District, began a study in 2010 to quantify existing hydraulic and habitat conditions for a reach of the Lake Fork of the Gunnison River in Lake City, Colorado.

The purpose of this report is to quantify existing Lake Fork hydraulic and habitat conditions and establish a baseline against which post-reconfiguration conditions can be compared. This report (1) quantifies the existing hydraulic and geomorphic conditions in a 1.1-km section of the Lake Fork at Lake City that has been proposed as a location for future channel-rehabilitation efforts, (2) characterizes the habitat suitability of the reach for two trout species based on physical conditions within the stream, and (3) characterizes the current riparian canopy density. This characterization describes existing channel conditions and establishes a baseline for post-reconfiguration comparisons for resource managers to evaluate restoration project success.

Sediment particles were measured at five locations in the study reach to characterize the grain size of different geomorphic surfaces and to estimate channel roughness. Bars and channel margins were chosen because these areas are inundated most of the year and represent the coarser material transported within the river channel.

Canopy density was characterized during a low-flow period at multiple locations within the study area using a spherical densiometer. Differences in canopy density can affect water temperatures, terrestrial insect and leafy organic inputs into the aquatic system, and habitat cover. Four measurements were taken at each location from the center of the stream with the operator facing: upstream, downstream, towards left bank, and towards right bank.

The FaSTMECH computational flow-model within MD_SWMS was selected to characterize the effects of stream-flow on hydraulic and habitat-suitability conditions for the 1.1-km study reach of the Lake Fork. Channel geometry was obtained from the topographical survey of the channel. Model calibration was achieved through iterative adjustments of the roughness until the root mean squared error between the observed and simulated water-surface elevations was minimized.

Within this report, a comparison of the boundary shear stress to critical shear stress of the median grain size (d_{50}) is used to determine when sediments within the channel are mobile. Multiple dimensionless critical shear-stress values were selected for the sediment mobility analyses to cover the range of conditions within the reach (dimensionless critical shear-stress values of 0.047 and 0.060). An assessment of sediment mobility was done through an assessment of transport strength using FaSTMECH.

Habitat suitability was evaluated for cutthroat (*Oncorhynchus clarkii*) and brown trout (*Salmo trutta morpha fario*) fry, juveniles, and adults. These species were chosen because they represent the two extremes of trout found in Colorado mountain streams and also because they represent a comparison between native (cutthroat trout) and introduced (brown

trout) salmonids in Colorado. Microscale (point locations) and mesoscale (reach features) habitat was assessed using the combination of field observations, measurements, and hydraulic simulations within the study reach of the Lake Fork.

FaSTMECH model sensitivity was analyzed for two parameters: the lateral eddy viscosity and channel roughness based on Z_0 , for 150; 260; and 1,600 ft³/s flow simulations, because water-surface elevation data were available along the entire length of each reach for these flows. Shear stress was generally the most sensitive of model outputs, where the difference from the mean boundary shear stress ranged from –59.4 percent to +8.0 percent. Percent difference from mean velocity ranged from –1.6 to +19.5 percent, whereas the percent difference of mean water-surface elevation ranged from –24.2 to +5.6 percent.

The existing hydraulic and geomorphic conditions for a 1.1-km section of the Lake Fork at Lake City are summarized as a function of the current streamflow regime based on model simulations for eight streamflows that cover the range of streamflow conditions typically observed at the site. Comparisons and evaluation of differences in sediment mobility and habitat suitability will provide resource managers with information to evaluate existing channel stability and habitat conditions of the reach as well as provide a baseline to compare with future conditions.

Within these systems, limiting fine sediment deposition and removal of fine sediments (sizes less than 2 mm) within framework grain interstitial spaces enhances habitat suitability for both fish and invertebrates. Sediment mobility is an important process for flushing fine sediments from within the gravel frameworks. Evaluations of channel and flow characteristics at cross-section locations 2–8 show a range of streambed mobility. In general, boundary shear stress and streambed mobility increase with increases in streamflow. At cross sections 2–8, sediment is potentially mobile at streamflows of 900 ft³/s. The streambed is substantially mobile at cross sections 4–8 at streamflows of 1,300 to 1,600 ft³/s with all cross sections being substantially mobile at 1,800 ft³/s. Within the cross sections, the greatest boundary shear stress occurs towards the center of the channel. Reach-scale assessment of sediment mobility in the lower reach shows increased streambed mobility. This is due in part to smaller grain sizes in the lower reach but may also reflect the greater extent of channel alterations, specifically the temporary berms constructed by CDOT in the late 1980s and early 1990s, present in this reach.

Geomorphic channel form is affected by land-use changes within the basin and geologic controls within the reach. The historic channel was defined as a dynamic, braided channel with an active flood plain. Comparisons of the channel characteristics to channel-form thresholds indicated that current channel characteristics may favor a braided channel form. This can result in a natural tendency for the channel to braid, which can affect channel stability of reconfigured reaches when a single-thread meandering channel is imposed on the stream.

Microscale trout habitat, presented as weighted usable area, generally increased as streamflow increased for both

trout species and all life stages. Areas of suitable microscale habitat occur along the banks for flows of 900 ft³/s and less. Out-of-bank areas become more substantial contributors to overall habitat availability for flows of 1,300 ft³/s or more when compared to other features. Adult habitat, for both trout species, was the most abundant habitat type for nearly all streamflows. In general, the upper reach provided 2–3 times more available habitat than the lower reach for both trout species.

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