CHANNEL-FORMING DISCHARGE ON THE DOLORES RIVER AND YAMPA RIVER, COLORADO

STATE OF COLORADO - DIVISION OF WILDLIFE

COVER PHOTO

Point-bar surface on Lily Park Reach, Yampa River, CO

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CONTENTS

TABLES

FIGURES

FIGURES - *continued*

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ABSTRACT

Channel-forming discharge can be defined as a range of discharges that determines the shape and form of an alluvial channel, and therefore also determines the available physical habitat for fish. In this study we estimated channel-forming discharge for three study sites on the Yampa River and Dolores River in Colorado via four different methods and compared the results with results from previous studies. The Dolores River is regulated by a major dam, and the Yampa River is impacted by grazing and diversions. The first method estimated the bankfull discharge utilizing GPS survey data, GIS mapping and HEC-RAS modeling to determine the flow that begins to inundate the floodplains or reaches the top of banks. The second method determined the effective discharge using discharge and sediment data at USGS gaging stations to determine the flow that transports the most sediment over a long period of time. The third method involved development of flood-frequency curves from annual peak flow data and determination of the two-year frequency flow. The final method estimated the flows necessary for marginal transport and for significant motion of the bed material using the Shields equation and the average boundary shear stress.

On the Dolores River, the flow that inundates most of the floodplain areas and the flow that begins to mobilize the bed material are in the range of 2,600 to 3,400 cfs (74 to 96 m^3/s) corresponding to 1.8 to 2.5-year frequencies in the post-dam flow regime. The flow regime and resulting morphology of the Dolores River have been affected by McPhee dam, which reduced the two-year discharge by 27% and the mean annual flood by nearly 50%. On the Yampa River, the flow that inundates most of the floodplain areas and the flow that begins to mobilize the bed material range from 11,000 to 13,000 cfs (311-368 m^3/s) corresponding to 2.5 to 5.4 year frequencies. The effective discharge on the Yampa River, however, was estimated to be 8,100 cfs (230 m^3/s and 1.4-year frequency, which differs from previous studies that suggested that bankfull and effective discharges are equivalent. Based on an analysis of historic aerial photos of the Yampa River, the channel has widened up to 20% and undergone bank erosion of as much as 20 to 30 meters.

INTRODUCTION

As rivers in the western United States undergo modification by diversion and regulation, it is important to understand what flow rates are responsible for the geomorphic processes that create the channel. Most engineers and scientists accept that a range of flows or a flow regime is responsible for channel formation and maintenance rather than a single flow rate. However, representation of the channel-forming discharge as a single flow rate that represents the cumulative effects of a range of discharges is a useful tool for designing management strategies for regulated rivers (Biedenharn et al., 1999, 2001).

Channel-forming discharge determines the shape and form of the channel and therefore shapes the available habitat for fish. Understanding the changes in a river's flow regime and the related changes in geomorphology and stability of the channel may aid in understanding changes in fish populations.

Many rivers in the western US have undergone modification by humans including dams, grazing and diversions which may alter the channel-forming discharge. The result may be a different geomorphic form from the river's pre-modification state. It is important to understand the pre- and post-modification channel-forming discharge in these modified systems to support maintenance of natural riparian and aquatic habitats. For instance, in years of high water yield, management of a dam could be altered to allow peak flow releases that mobilize channel bed material, transport significant amounts of sediment and inundate the floodplains.

Channel-forming discharge can be estimated in different ways, including: 1) the bankfull discharge, 2) the effective discharge, 3) the discharge which begins to mobilize the bed material, and 4) flows of certain recurrence intervals. The bankfull discharge is the flow which just begins to inundate the active floodplain of the river, or just fills the channel to the tops of the banks (Williams, 1978). Effective discharge is the flow which transports more sediment than any other discharge (Wolman and Miller, 1960). The flow that breaks up and entrains the bed material of the channel bed helps to maintain the channel dimensions (Milhous, 1982; Andrews, 1983, 1984) and has been used as

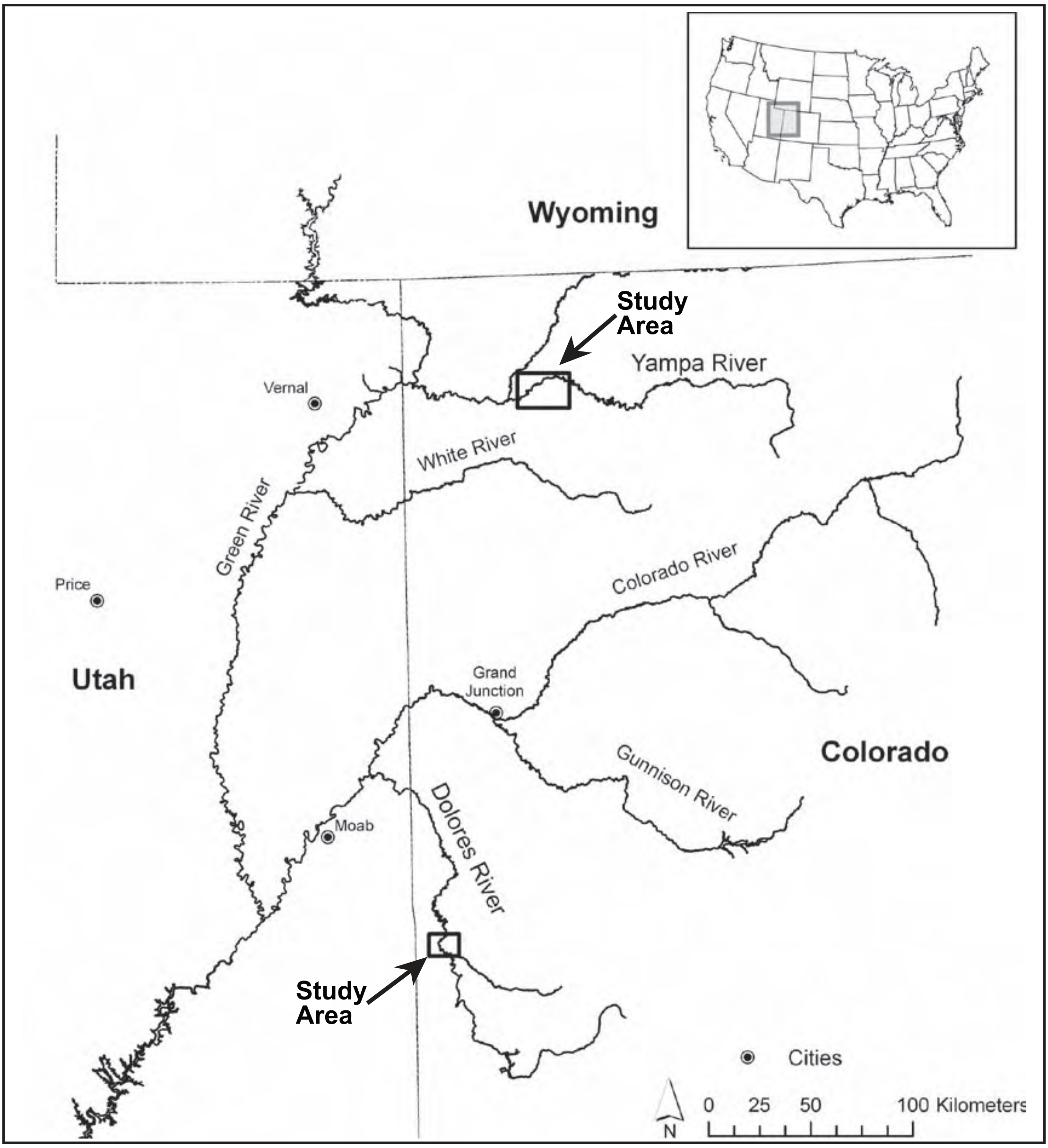

FIGURE 1. Location map of study areas

an estimate of channel-forming discharge (Elliott and Hammack, 1999; Pitlick and VanSteeter, 1998; Vandas et al. 1990). Both the bankfull and effective discharges have been shown to occur relatively frequently (Emmett and Wolman, 2001; Andrews, 1980; Carling, 1988; Leopold and Wolman, 1957). Other studies suggest that the recurrence intervals of both bankfull and effective discharge are highly variable (Nash, 1994; Pickup and Warner, 1976), however with caution, values between one and three year recurrence intervals may be used to estimate channel-forming discharge (Biedenharn et al., 2001).

The Yampa River and the Dolores River are both important rivers in western Colorado (Figure 1) for native fish habitat and have been studied and surveyed extensively by the Colorado Division of Wildlife (CDOW) (Anderson and Stewart, 2003, 2004). The Yampa River is the largest free-flowing tributary to the Colorado River. While not regulated by a large dam, the lower Yampa River has been impacted by agricultural diversions, land use changes and grazing. The flows in the lower Dolores River, also a major tributary to the Colorado River, were controlled by McPhee dam in 1985 resulting in a decrease in peak flows since completion of the dam (Wilcox and Merritt, 2005). Understanding of the channel-forming discharge and the processes that form the channel on both of these rivers can contribute to improvement of ecological integrity and sustaining native biodiversity (Poff et al., 1997).

The purpose of this paper was threefold. The first objective was to establish a methodology for identifying bankfull discharge using Global Positioning System (GPS) survey points, Geographic Information System (GIS) mapping, and HEC-RAS modeling to determine the discharge that begins to inundate floodplain areas. Detailed GPS survey data of channel bathymetry, riparian topography, floodplains and banks for three reaches on the Yampa and Dolores Rivers were used in the analysis. The second objective was to compare the bankfull discharge results for the three reaches with other channel-forming discharge results. The effective discharge, two-year discharge, and the discharge necessary to mobilize bed material were estimated for the study reaches. The resulting channel-forming discharge estimates were compared with those from previous studies (Andrews, 1980; Vandas et al., 1990). Lastly, the current and historic morphology of the reaches were studied from HEC-RAS results and historic aerial photos.

STUDY SITES

Dolores River, Colorado

The Dolores River is a major tributary to the Colorado River beginning high in the San Juan Mountains in southwest Colorado and draining a northwest-southeast trending basin. A majority of the annual peak flows result from spring snowmelt from the headwaters, but in the lower reaches, high intensity thunderstorms can cause peaks in July, August and September. The lower semi-arid Dolores River is characterized by a series of steep-walled canyons, separated briefly by broad structural valleys, such as the Big Gypsum Valley, through which the river flows (Wilcox and Merritt, 2005).

Two major tributaries enter the Dolores River in the lower portion, Disappointment Creek and the San Miguel River (Figure 2). Disappointment Creek contributes a significant amount of sediment and enters the Dolores River about 27 km upstream of the study reach. The drainage area of Disappoinment Creek is comprised of highly erodible saline soils resulting in the creek being the primary sediment contributor to the Dolores River in the study area (Vandas et al., 1990). In addition, the high erosion potential of the lower Dolores basin results in a progressive downstream increase in total suspended sediment load in the Dolores River (Vandas et al., 1990).

Dolores river water has been diverted and used for irrigation since early settlement of the San Juan river valley. In 1968 the Dolores Project was authorized and included approval for McPhee dam (Figure 3), which was completed in 1984. McPhee Dam stores water from the Dolores River for irrigation, municipal and industrial use, recreation, fish and wildlife, flood control and production of hydroelectric power (USBR, 2006). With a storage capacity of 470 million cubic meters (381,195 acre-feet), McPhee Dam has substantially altered the flow regime of the Dolores River downstream of the dam. In particular, geomorphically important peak flows have been reduced and baseflows have been increased (Wilcox and Merritt, 2005).

Most pertinent to this study are the changes in the peak flows downstream from McPhee reservoir because of their importance in determining the shape and form of the channel and therefore the availability of native fish habitat. At the Bedrock gage on the Dolores River, the mean annual flood decreased by nearly 50% from the pre-dam to post-dam period (Figure 4). Vandas et al.

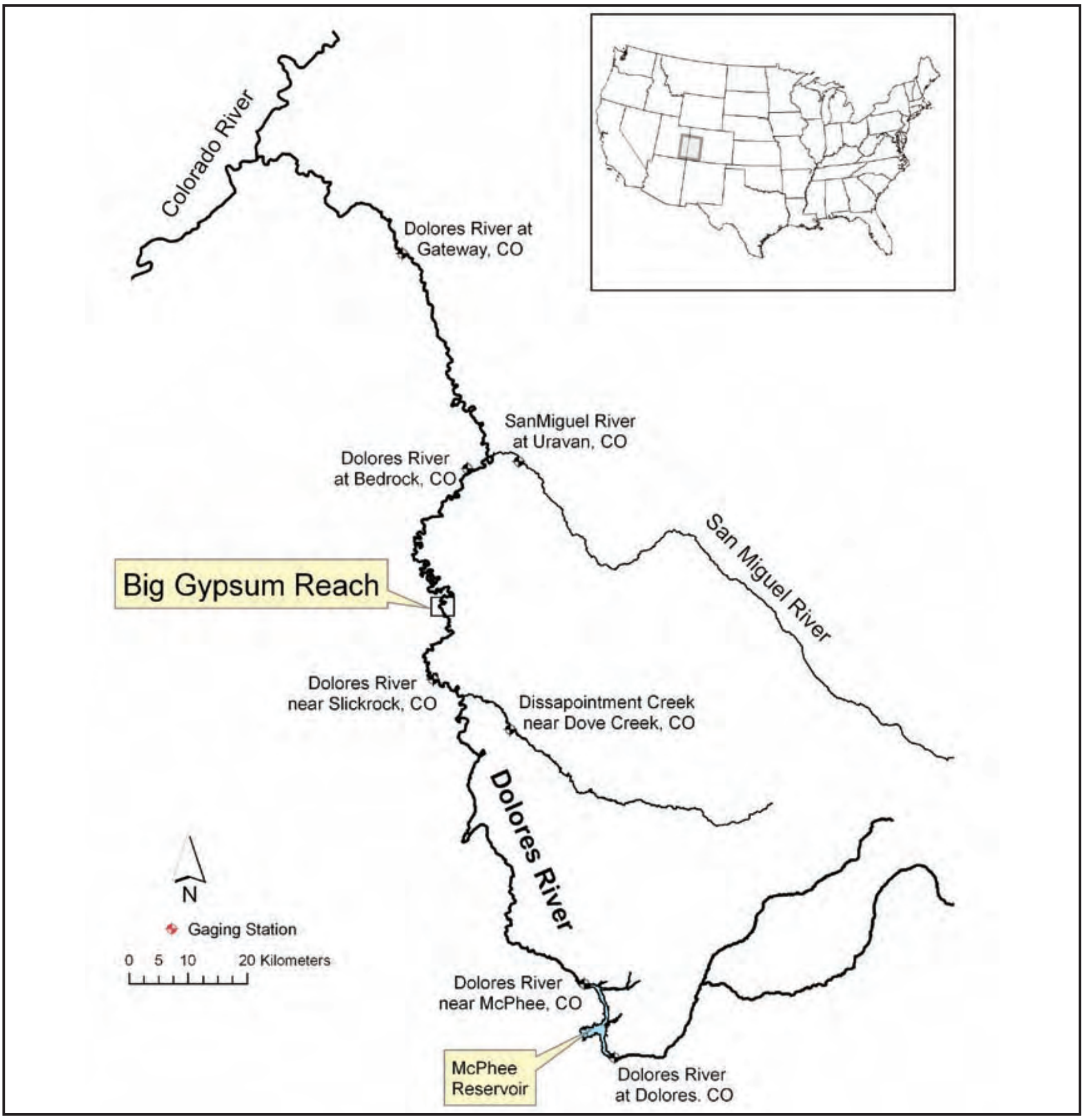

FIGURE 2. Location map for Big Gypsum Reach, Dolores River

FIGURE 3. McPhee Dam and Reservoir (from US Bureau of Reclamation, Western Colorado Area Office)

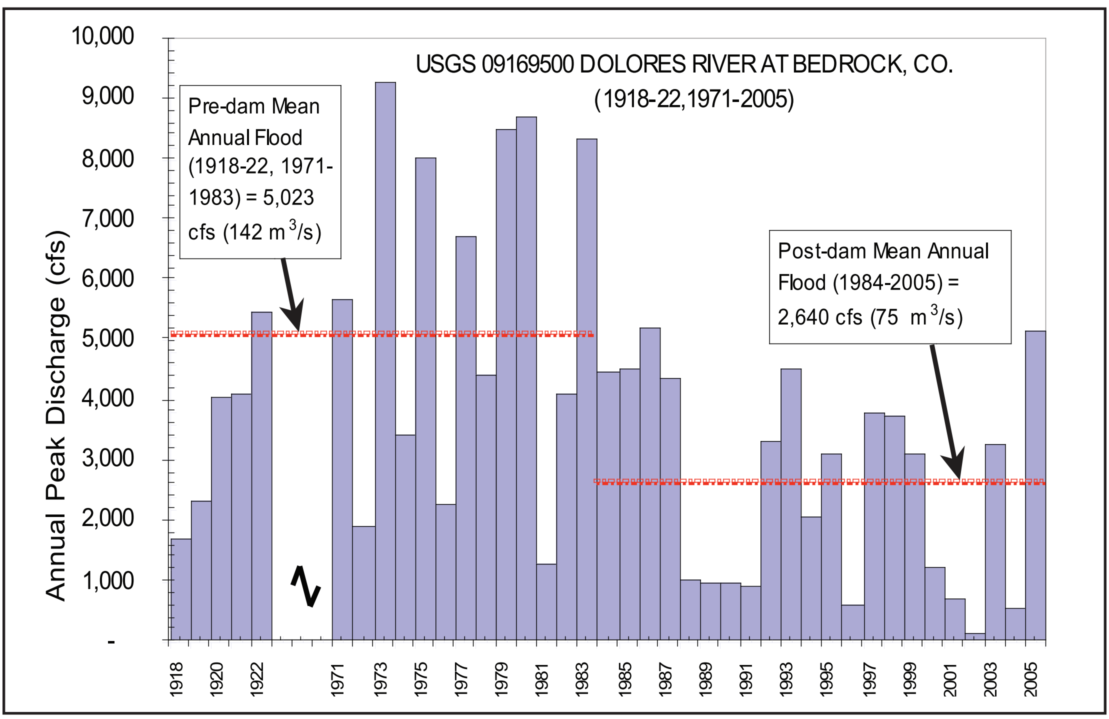

FIGURE 4. Annual Peak Flow At Bedrock, Dolores River, Colorado.

(1990) studied the pre-dam hydrology, estimated post-dam hydrology and proposed pre- and post-dam bankfull discharges (Table 1) and estimated that the bankfull discharge decreased by 1,000 cfs (28 m^3/s) from pre- to post-dam. Wilcox and Merritt (2005) performed an Indicators of Hydrologic Alteration (IHA) analysis on pre- and post-dam data from the Bedrock gage, which is about 150 km downstream from McPhee Dam. The annual maximum flows at the Bedrock gage decreased by approximately 40% and the duration of the high pulse decreased by 60% (Wilcox and Merritt, 2005).

Vandas et al. (1990) concluded that a flow of approximately 7,000 cfs (198 m^3/s) may be required to move most of the bed materials. Based on pre-dam data, Vandas et al. (1990) discerns that such peak flows occurred at a five-year recurrence interval at the Bedrock gage and that maintaining a flow of that magnitude (6,641 cfs or 188 m^3/s) for seven days is associated with a 10-year recurrence interval. Prior to McPhee dam, the median bed material moved about once every one to two years and the larger bed material moved about once every five to 10 years.

Table 1. Dolores River channel-forming discharge estimates from Vandas et al. (1990)

Channel-forming discharge estimates on the Dolores River	Discharge (cfs)
1.5-year recurrence interval peak flow at Bedrock (Pre-Dam 1918-22,1972-83)	3,068
Pre-dam bankfull flow below Gypsum Valley (estimated based on field data collected in 1989 and 1.5-year recurrence interval estimate)	2,300
Post-dam bankfull flow below Gypsum Valley estimated from expected 1.5 yr recurrence interval	1,300

Table 2. Pebble count and slope data below Disappointment Creek (from Vandas et al. 1990)

Station	D_{50}(mm)	D_{84}(mm)	Field Measured Slope
L1 riffle	74	181	0.0133
L3 riffle	79	181	0.005
L4 pool	21	84	0.0007
R1 riffle	59	147	0.02
R2 pool	36	97	0.0008
R2 riffle	59	147	0.0097
Riffle Average	68	164	0.012
Pool Average	29	91	0.00075
Average of all Stations	55	140	0.00825

Vandas et al. (1990) also estimated the discharge necessary to mobilize the bed. Vandas et al. (1990) performed cross section surveys in the Big Gypsum valley area. The channel geometry at bankfull for a representative cross section in this area had a top width of 39 m, depth of 1.2 m and average flow velocity of 1.6 m/s. The average median grain size in riffles was 68 mm and in pools was 29 mm (Vandas et al. 1990). Average slopes varied from 0.00075 in pools to 0.012 in riffles (Table 2).

The Big Gypsum reach is located in the lower, semi-arid portion of the Dolores River, 116 km downstream from McPhee Dam and 30 km downstream from the confluence with Disappointment Creek, a major source of sediment for the Dolores River (Figure 2). The lower Dolores River crosses Big Gypsum Valley, a northwest trending anticlinal valley. The Big Gypsum Reach is located at the downstream end of the area where the Dolores River crosses Big Gypsum Valley. Upstream and downstream of the valley crossing, the Dolores River flows through deep canyons. The Big Gypsum reach is fairly straight with a sinuosity of 1.56, with an average channel bed slope of 0.0015 (Figure 5).

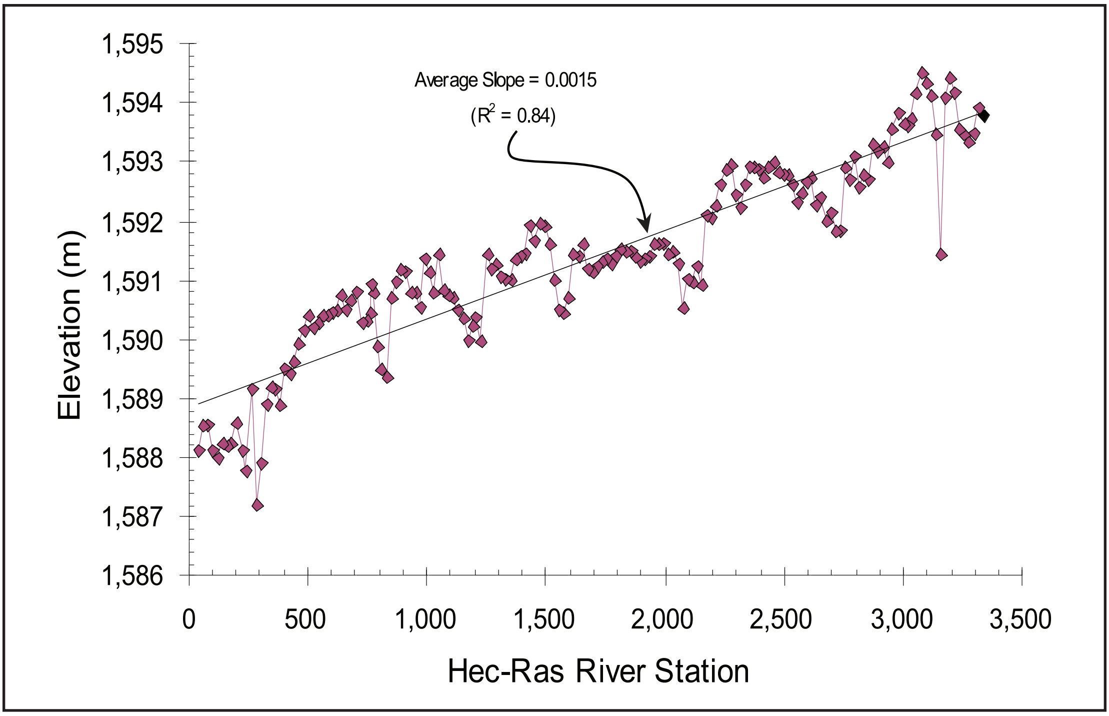

FIGURE 5. Thalweg Profile of Big Gypsum Reach, Dolores River, CO from CDOW RTK-GPS survey data

Yampa River, Colorado

Two study areas on the Yampa River representing different types of fish habitat were identified by CDOW for analysis: Lily Park and Sevens (Anderson and Stewart, 2004). The Lily Park study reach is the furthest downstream and is three km long (Figure 6). The Lily Park study reach begins just downstream of Cross Mountain Canyon and ends just above the mouth of the Little Snake River. The Sevens study reach begins upstream of Cross Mountain Canyon and is also three km long.

Lily Park

The Yampa River in the Lily Park study reach (Figure 7) flows through grazed and irrigated land and is bounded by steep, near vertical banks for a large portion of the reach. With a bed slope of 0.0021 (Figure 8), the bed material ranges in size up to cobble (Figure 9) and the sinuosity is 1.38. Grazing primarily occurs on the left bank and upstream portions of the right bank. Floodplain surfaces are small and discontinuous, with the exception of the large point bars associated the two meanders.

Sevens

The Sevens Reach (Figure 10) has a milder slope, 0.0005, (Figure 11) than the Lily Park reach and also flows through irrigated and grazed land (Figure 12). The right bank rises steeply to a bluff for a majority of the reach (Figure 13). Floodplain surfaces are small and discontinuous. The left bank is near vertical for a majority of the reach. We noted evidence of recent bank erosion along the left bank of the reach, for example in Figure 14 you can see a fence post that is falling into the river. In addition some survey pins were lost to erosion between their installation in the early 1990's and our visit in 2002. The bed material of the Sevens reach is smaller than the Lily Park reach (Figure 15) and the sinuosity is 1.26.

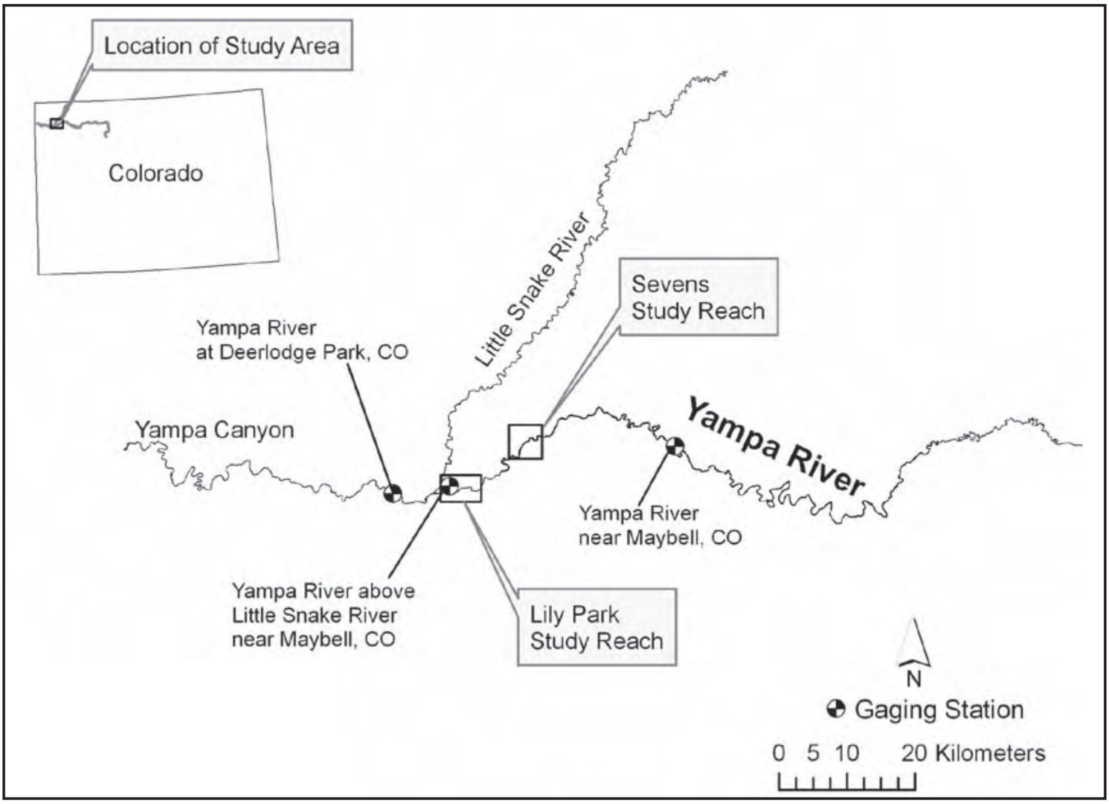

FIGURE 6. Location of Yampa River study reaches.

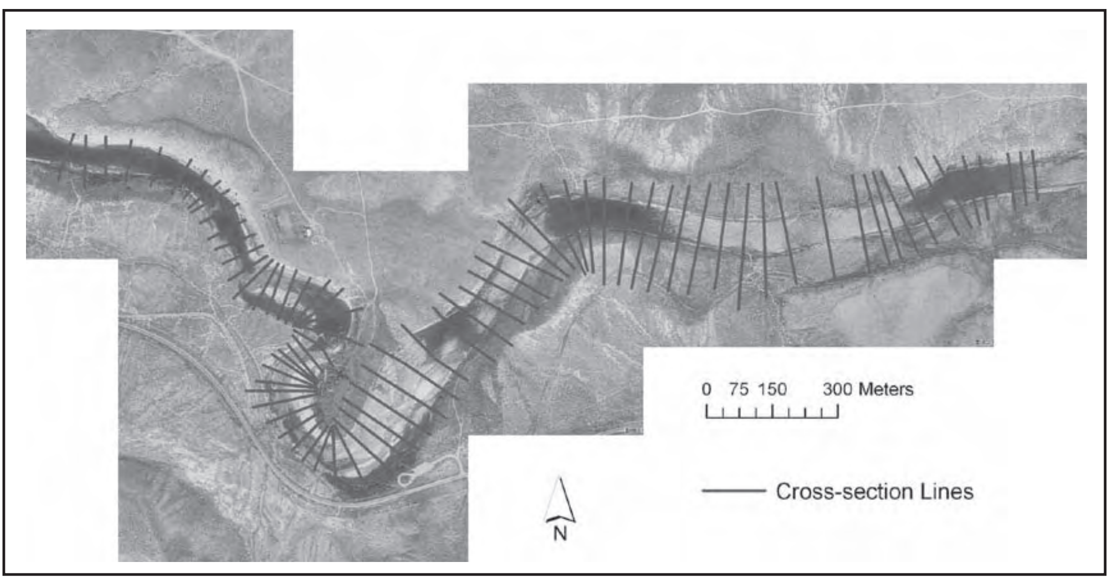

FIGURE 7. Lily Park study reach, Yampa River, CO. Background image: 1993 DOQQ from USGS, 1m resolution.

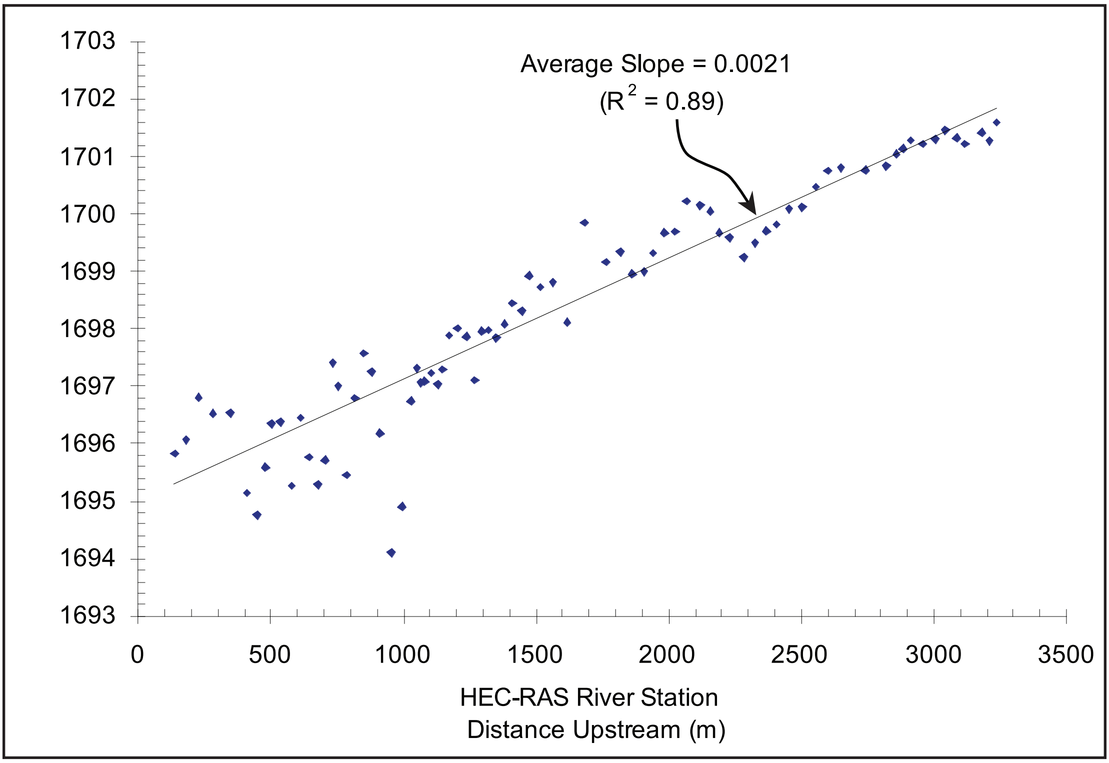

FIGURE 8. Thalweg profile of Lily Park Reach, Yampa River, CO from CDOW RTK-GPS survey data.

FIGURE 9. Point-bar surface on Lily Park Reach, Yampa River, CO

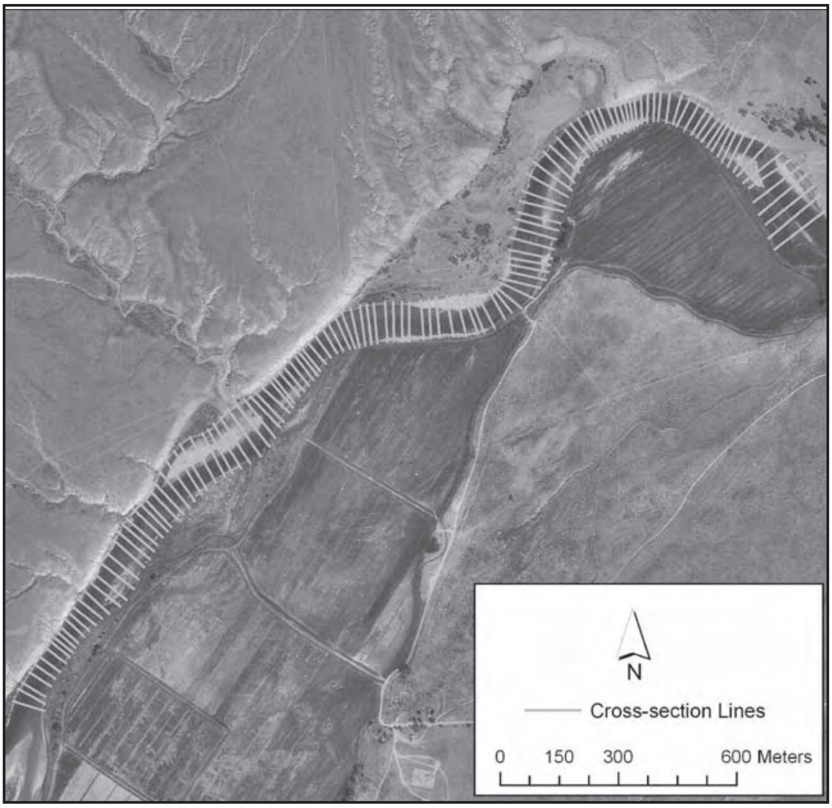

FIGURE 10. Sevens Reach, Yampa River, CO. Background image: 1993 DOQQ from USGS, 1m resolution.site.

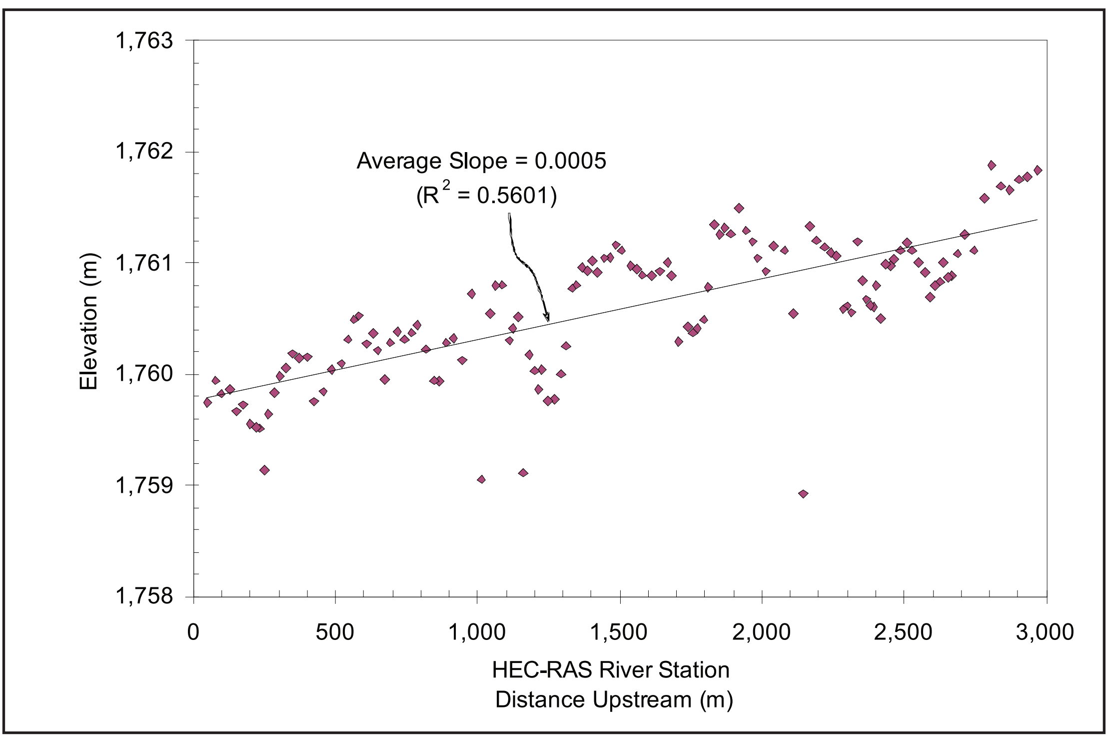

FIGURE 11. Thalweg profile Sevens Reach, Yampa River, CO from CDOW RTK-GPS survey data.

FIGURE 12. Grazing along the left bank of the Sevens Reach, Yampa River, CO. Note steepness of banks and evidence of slumping.

FIGURE 13. Upstream view of bluff along right bank of the Sevens Reach, Yampa River, CO.

FIGURE 14. View of Sevens reach looking upstream from left bank. Note fence post falling into the river from erosion of the left bank.

FIGURE 15. Typical bar material at Sevens Reach, Yampa River, CO.

METHODOLOGY

Bankfull Discharge

The bankfull discharge for each study reach was estimated using topographic data collected with survey-grade Real-Time Kinematic (RTK) GPS survey equipment combined with GIS mapping and HEC-RAS modeling to determine the discharge that begins to inundate the floodplains or that reaches the top of banks.

RTK-GPS Surveying

The RTK-GPS survey data were collected by the CDOW between 1999 and 2005 (Appendix A) with survey-grade equipment providing 15-mm accuracy (Anderson and Stewart, 2003). The CDOW performed extensive surveying of channel bathymetry using survey-grade RTK-GPS combined with sonar (accuracy = 1% of flow depth) at the three study sites from 1999 to 2003 (Anderson and Stewart, 2003). Channel banks, floodplains and some upland areas were surveyed using the RTK-GPS in 2003 on the Yampa River and in 2003 and 2005 on the Dolores River. The location and elevation of the waterline at various discharges were also surveyed using GPS for model calibration.

GIS Pre-processing

The three-dimensional GPS survey points were imported to a GIS where a triangulated irregular network (TIN) was created from the location and elevation of the survey points. Breaklines and additional points were added where necessary to make the TIN more representative of the topography.

Using HEC-GEO-RAS (v. 4.1) and ArcGIS (v. 9.0), cross-section cutlines, channel centerline, banklines and flowlines were created and exported for use in HEC-RAS (v. 3.1.3). On the Dolores River, the cross sections were created ~20m apart and were "dog-legged" so that the cross sections remained as nearly perpendicular to the channel as possible. In HEC-RAS, cross sections were interpolated every five meters. On the Lily Park and Sevens reaches cross sections were drawn varying distances apart to coincide with survey points that were surveyed in lines perpendicular to the channel. On the Lily Park reach the average distance between cross sections averaged 40 meters and on the Sevens reach averaged 30 meters. In HEC-RAS cross sections were interpolated every 10 meters.

The centerline followed the main flow channel when the flow divided and was drawn in the center of the channel. The banklines were drawn following the surveyed points for one of the lower-flow water surfaces and did not necessarily coincide with bankfull. The flowpaths are lines drawn outside of the banklines to indicate the direction of flow and distances between river stations.

HEC-RAS Modelling and Calibration

HEC-RAS was calibrated for each reach by running the model at a flow rate for which we had a measured water-surface line. The highest discharge for which we had data was used because a higher flow would provide greater accuracy in modeling bankfull discharge. Measured water surface elevations were compared to the calculated water surface elevations and the Manning's n was adjusted until the measured and calculated elevations were within 0.1 m of each other. For each reach, the average error was less than five cm.

For the Dolores River, HEC-RAS was calibrated for two high flows, 2,230 cfs (63 m^3/s) and 4,700 cfs (133 m^3/s). There were cross sections at the upstream and downstream ends of the reach where it was impossible to achieve an error of less than 0.1 m for every section for both flow rates. As a result, the calibration efforts were focused on identified floodplain areas (Figure 19). In the floodplain areas, the difference between the calculated and measured water surface elevations was less than 0.1m for every cross section (Figure 16).

The Lily Park study reach on the Yampa River was calibrated for a flow of 8,100 cfs. The error was less than 0.1 m for all cross sections and the average error was less than five cm (Figure 17).

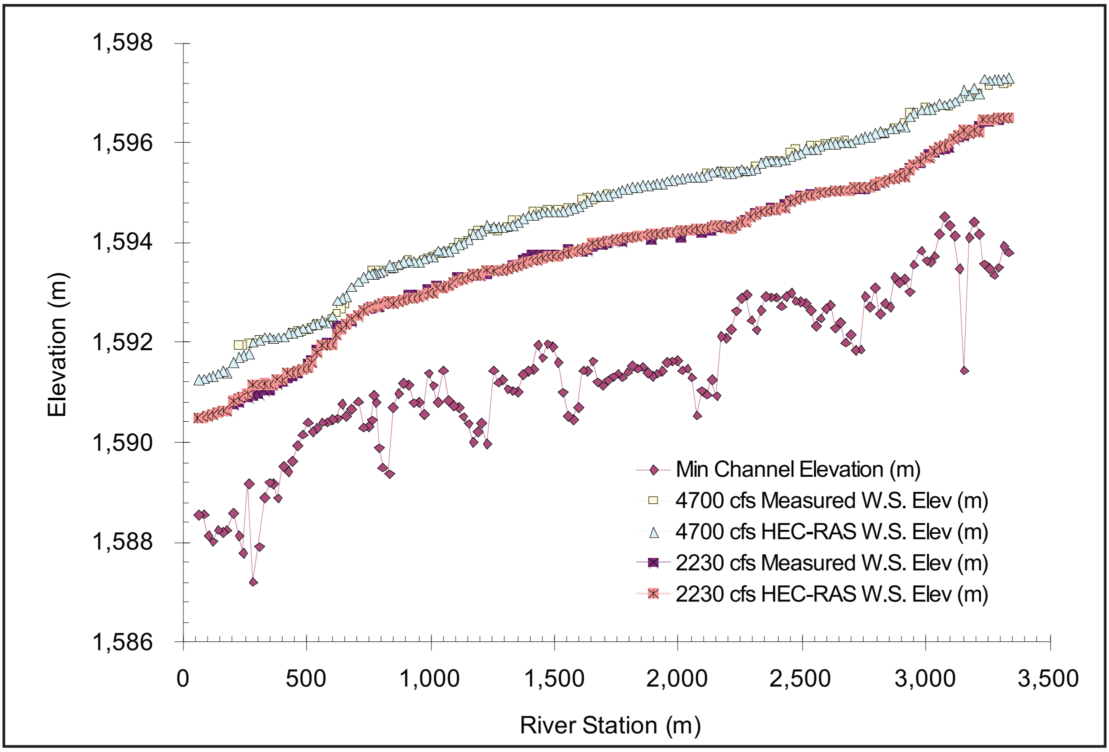

FIGURE 16. HEC-RAS Calibration Results Big Gypsum Reach, Dolores River ,CO.

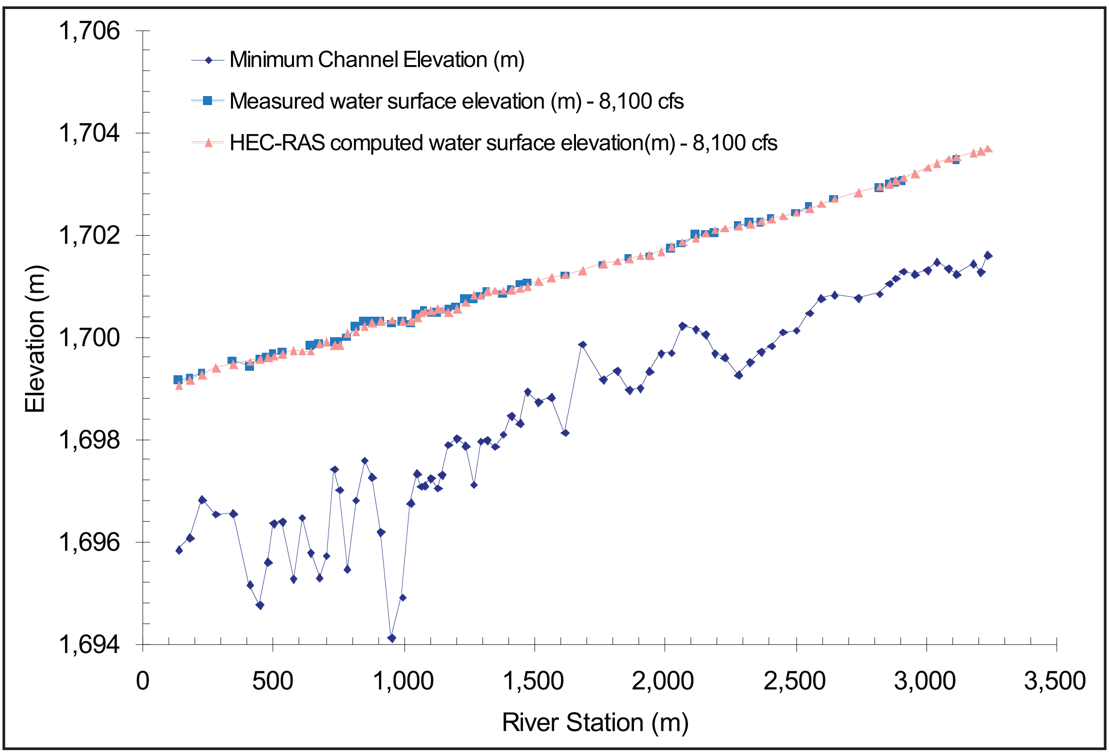

FIGURE 17. HEC-RAS Calibration Results Lily Park reach, Yampa River, CO.

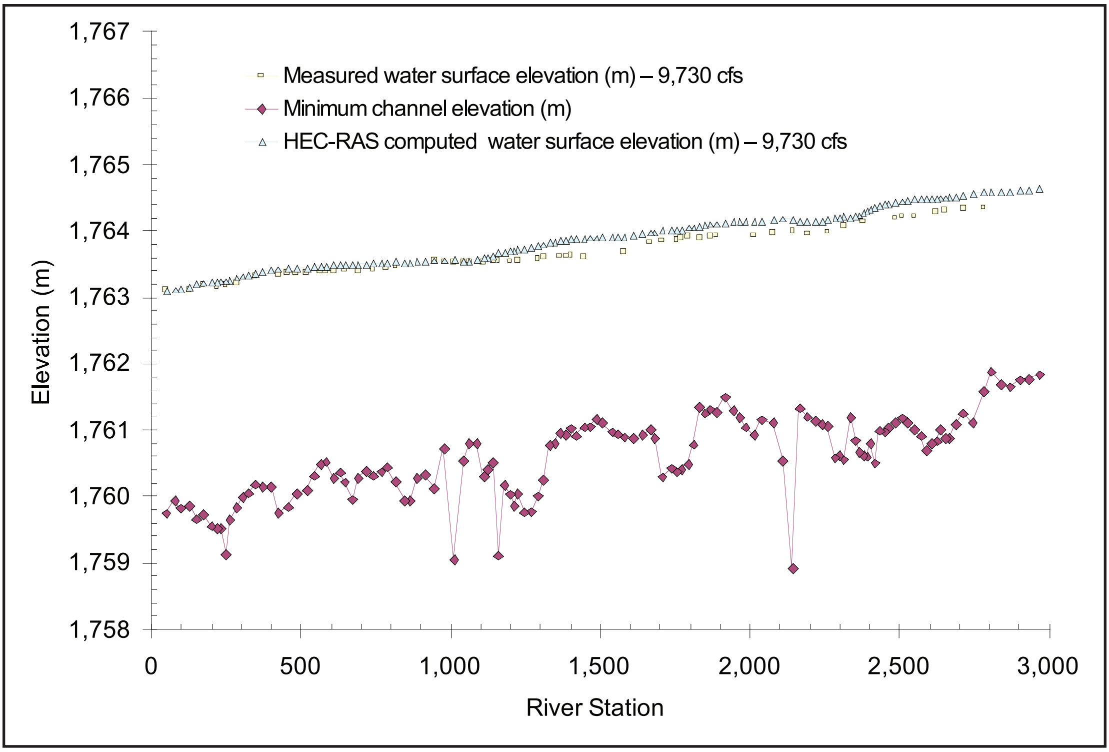

FIGURE 18. HEC-RAS validation - Sevens Reach, Yampa River, CO (9,730 cfs).

The HEC-RAS model of the Sevens Reach was calibrated for a flow of 880 cfs and validated for a flow of 9,730 cfs. The 9,730 cfs data points were not available at the time of calibration. The measured water surface elevation for 880 cfs differed by less than five cm from the HEC-RAS calculated water surface for all 28 cross sections where water surface elevation points were available. The average error for the calibration was 2.3 cm.

The average error for the validation with 9,730 cfs was 13 cm, with the upper portion of the reach having a greater error. All of the cross sections downstream of station 1,140 exhibited errors less than 10 cm. The model was calibrated for a low flow (880 cfs) and therefore it is not surprising that the water surface is overestimated at high flow when the influence of channel roughness decreases as flow depth increases.

Bankfull Determination

Once HEC-RAS was calibrated, a series of increasing flow rates were run through each reach in HEC-RAS. The flow rates that created bankfull conditions for at least 50% and 95% of the cross sections were identified. Bankfull conditions were defined as calculated water-surface elevations equal to or greater than flooplain surface or top-of-bank elevations. Some floodplain surfaces had been identified in the field and surveyed with GPS. Other floodplain surfaces were identified by a slope break in the bankline of the cross section or as flat areas in the TIN. The lowest flow rate that produced a water surface with an elevation above the slope break in the bankline was identified as bankfull flow for that cross section.

On the Dolores River, 39 cross sections were identified with evident floodplain surfaces (Figure 19) and the lowest discharge that began to flow over the floodplain surface was determined for each cross section. The flow rates that flowed over the floodplain surface for at least 50% and 95% of the cross sections were identified.

Bankfull discharge on the Lily Park reach was identified using survey point elevations to determine inundation. Forty-one

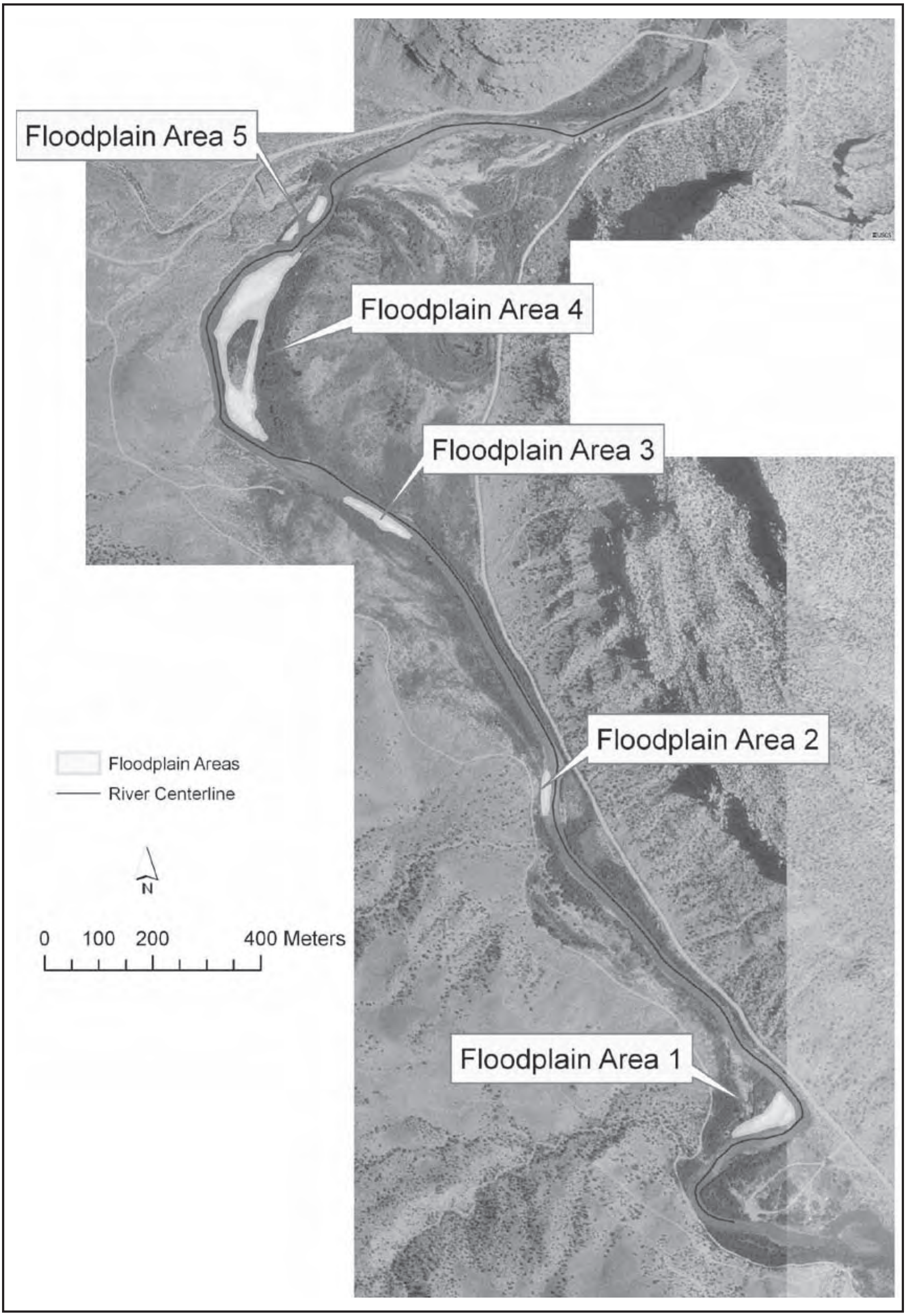

FIGURE 19. Location map of floodplain areas in the Big Gypsum Reach, Dolores River, CO.

cross sections had floodplain surfaces that were identified in the field during GPS surveying. These 41 cross sections were located at HEC-RAS stations 445-1024 (two floodplain areas, one on each bank) and stations 1813-2818 (thin strip of floodplain). The water-surface elevations computed by HEC-RAS were compared with surveyed elevations at those 41 cross sections. Figure 20 illustrates one floodplain area on the Lily Park reach. The stars symbolize points that were identified as floodplain in the field during the GPS surveying. The triangles are the surveyed waterline at 8,100 cfs (229 m^3/s). The floodplain points were surveyed prior to the waterline. Note that some of the floodplain points were inundated at 8,100 cfs.

Floodplain areas were not clearly evident on the Sevens reach, so top-of-bank points were used to determine bankfull discharge. The water surface elevations generated from each flow rate were compared to surveyed bank elevations. The flow rate that reached the top-of-bank for at least 50% of the cross sections was designated as bankfull.

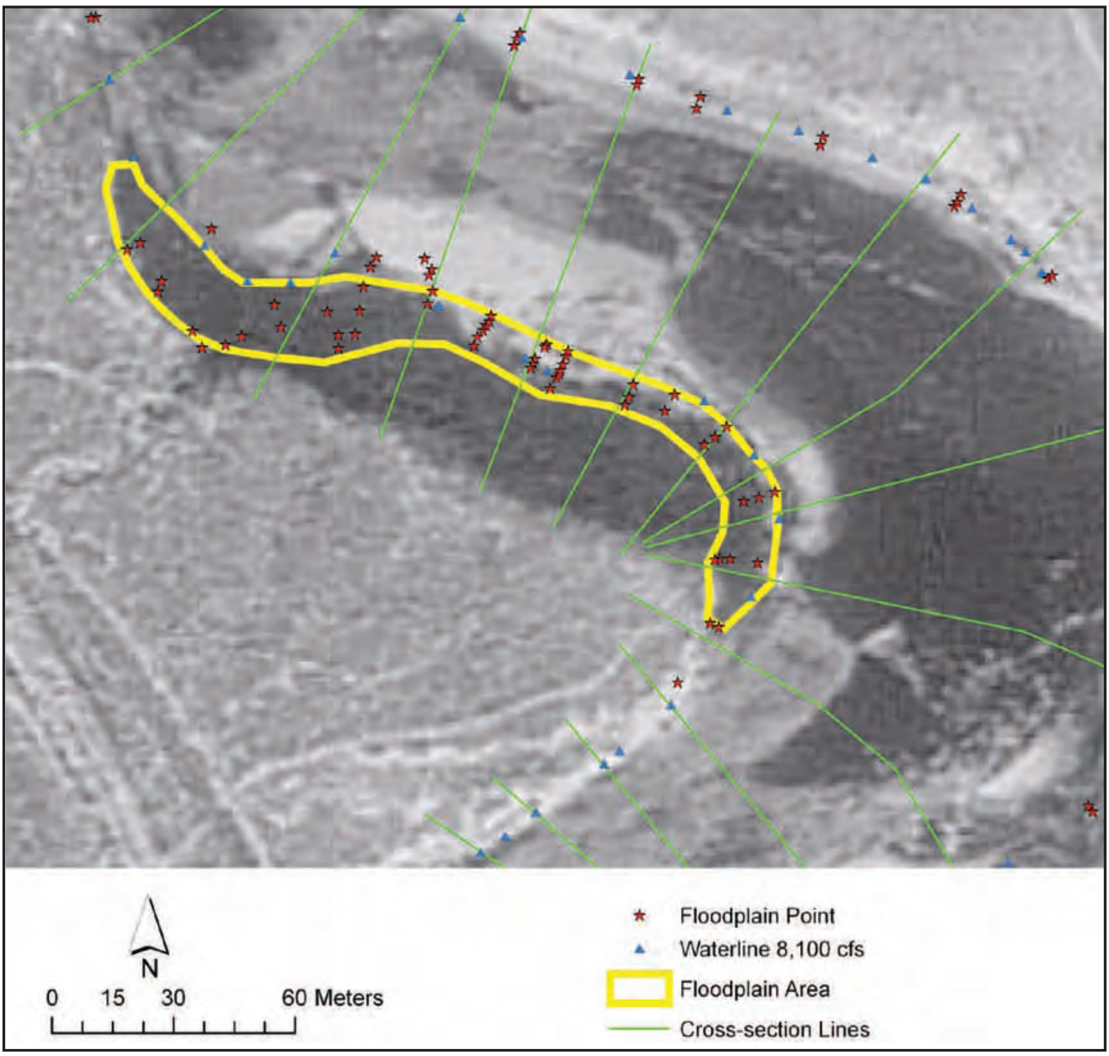

FIGURE 20. Floodplain area on the Lily Park Reach, Yampa River, CO. Floodplain and waterline points are from RTK-GPS survey. Background image: 1993 DOQQ from USGS, 1m resolution.

Effective Discharge

The effective discharge was calculated for the Yampa River, but not the Dolores River because no sediment data were available. The effective discharge is defined by Andrews (1980) as the increment of discharge that transports the largest fraction of the annual sediment load over a period of years. The effective discharge of the Yampa River was calculated at two stream gages: Yampa River near Maybell, CO and Yampa River above Little Snake River near Maybell, CO (Figure 6). The methodology from Biedenharn and Copeland (2000) and Biedenharn et al. (2001) was followed to create flow-frequency curves, sediment load rating curves and sediment load histograms. The effective discharge was determined from the peak of the sediment load histogram, which corresponds to the discharge that transports the greatest percentage of sediment.

The first step in determining the effective discharge is to create a flow-frequency curve from the daily mean discharge date for each gage. Flow-frequency curves were created for each gage following Biedenharn and Copeland's (2000) methodology. The flow-frequency curves were initially created with 25 bins, then the number of bins was reduced until all of the bins had at least one occurrence. The result was 24 bins, however, Andrews (1980) used 20 bins in his flow frequency distributions. In order to compare our results with Andrews' (1980) results, we derived flow-frequency distributions using 20 bins. Using a smaller number of bins is consistent with Biedenharn et al.'s (2001) methodology because a smaller number creates a smoother sediment load histogram. In addition, with 20 bins, the number of bins was large enough that the effective discharge did not fall in the first bin.

The next step was to create a sediment load rating curve and determine an equation, in the format $Qs = aQ^b$, that estimates sediment load, Qs for a given discharge, Q. Ideally the sediment load rating curve should be based on bed material transport, however, only suspended sediment data were available at the Maybell gage (1951-52, 1974-82). More detailed sediment data and rating curves were available for the Yampa River gage above Little Snake River near Maybell, CO gage (Elliott and Anders, 2004), which only operated from 1997-2003 (Table 3 – Sediment-transport equations). A suspended sediment rating curve was developed from the Maybell gage data by plotting water discharge versus sediment discharge for each sediment measurement and performing a linear regression (Figure 21, Table 3). The sediment rating curves at the two gages all have an exponent approximately equal to two.

Table 3. Sediment-transport equations for the Yampa River, CO.

Gaging Station	Type of Sediment Discharge	Regression Equation	R^2	n
Yampa River near Maybell, CO (1951-52, 1974-82)	Suspended	$Qs = 0.0006\,Q^{1.84}$	0.84	104
Yampa River above Little Snake River near Maybell, CO (1998-2002, from Elliott and Anders, 2002)	Total	$Qs = 0.06\,e10^{-4}Q^{2.33}$	0.85	25
	Suspended	$Qs = 5.81e10^{-5}Q^{2.13}$	0.87	26
	Bedload	$Qs = 1.88e10^{-7}Q^{2.33}$	0.80	25
	Sand and gravel	$Qs = 2.23e10^{-6}Q^{2.39}$	0.86	25

[Qs , sediment discharge in tons per day; Q, water discharge in cubic feet per second; R^2, coefficient of determination; n, number of samples]

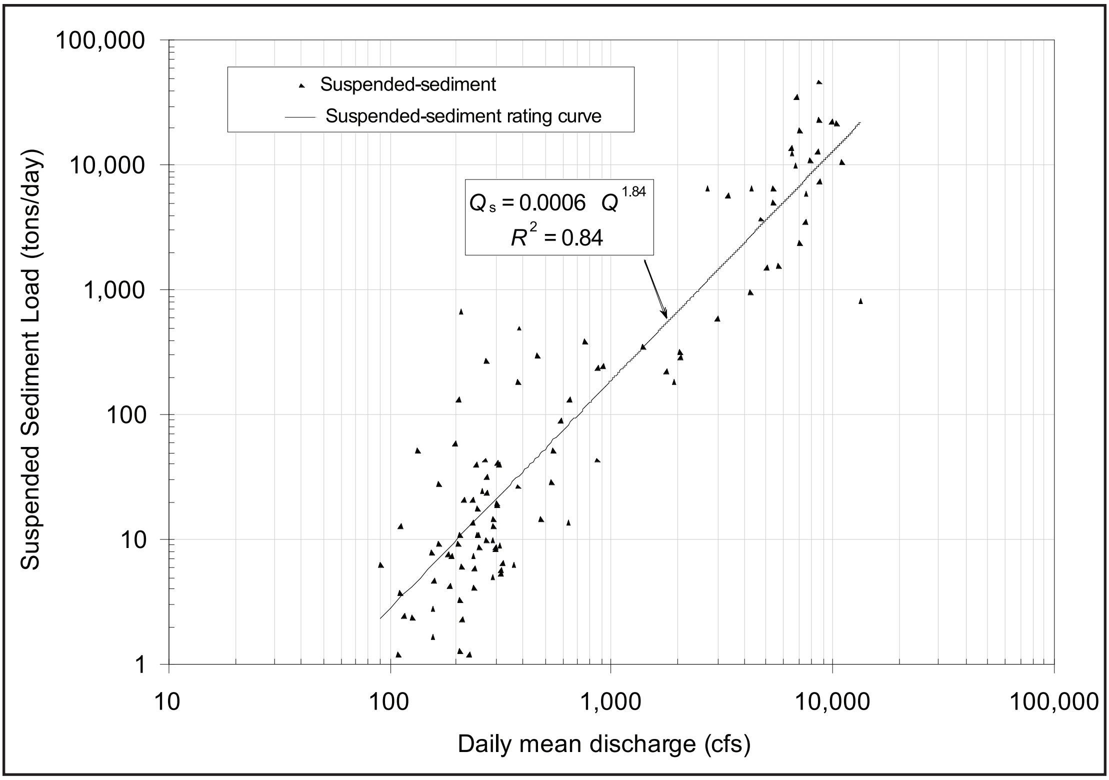

FIGURE 21. Relation of sediment load at Yampa River near Maybell, CO, 1951-52, 1974-82, to water discharge.

A sediment load histogram was created by multiplying the mean discharge within each class interval of the flow-frequency curve by the sediment load transported at that discharge computed by the sediment load rating curves. The effective discharge was determined as the mean discharge corresponding to the peak frequency. We also ensured that the first bin did not contain the maximum value of the effective discharge histogram. The effective discharges were compared between different sediment load rating curves and gaging stations.

Critical Shear Stress

Channel-forming discharge was also estimated by determining the discharge that creates a bed shear stress exceeding critical shear as estimated by the Shield's equation. Other studies have shown that the discharge that causes significant motion of the bed material is equivalent to the bankfull discharge (Andrews, 1984; Pitlick and Van Steeter, 1998). Determination of the discharge that mobilizes bed material can be accomplished by computing the critical shear stress for a given particle size, τ_c from the Shield's equation

$$\tau_c = \tau_c^*(\rho_s - \rho)gD$$

where τ_c^* is the critical dimensionless shear stress (or Shields parameter), ρ_s is the density of sediment, ρ is the density of water, g is the gravitational acceleration and D is the particle diameter. The average boundary shear stress, τ can be computed for different discharges using the following equation

$$\tau = \rho g R S_f$$

where R is the hydraulic radius and S_f is the energy gradient. The discharge that produces an average boundary shear stress that equals or exceeds the critical shear stress will produce motion of the bed material.

Selection of an appropriate value for τ_c^* is important and not straightforward. Andrews (1984) determined that on average for 24 gravel-bed river in the Rocky Mountain region of Colorado, the average value of τ_c^* at bankfull was 0.046. The Yampa River near Maybell, CO was one of the stations used in Andrews' (1984) study and the bankfull dimensionless shear stress for that gage was found to be 0.029. Pitlick and Van Steeter (1998) found that a critical dimensionless shear stress of 0.047 corresponded to the bankfull discharge on the Colorado River in western Colorado. Values for dimensionless shear stress of 0.03 and 0.047 were used in this study following the reasoning of Pitlick and Van Steeter (1998) and Elliott and Hammack (1999) where 0.03 corresponds to "marginal transport" and 0.047 to "significant motion". The resulting discharges provide a range of likely sediment entraining conditions.

Values for bed material size and bed shear stress were determined from previous studies and HEC-RAS modeling results respectively. The median bed material grain size was assumed to be equivalent to measurements from previous studies (Vandas et al., 1990 for the Dolores River and Andrews, 1984 for the Yampa River reaches). The critical shear stress that mobilizes the median grain size for each reach was then compared with the channel shear stress computed by HEC-RAS for each cross section for a range of flows. HEC-RAS computes the average boundary shear stress at each cross section for the main channel using the hydraulic radius of the main channel and the energy grade line slope for each cross section. The discharge that produced a channel shear stress greater than or equal to the critical shear stress at a minimum of 50% of the cross sections was considered the discharge that begins to mobilize the bed material.

Flood-Frequency Analysis

Flood-frequency curves were created using Cunanne's plotting position formula (Salas et al., 1998) and the annual peak discharge data from the Yampa River near Maybell, CO (USGS 09251000) and Dolores River at Bedrock (USGS 09169500) gaging stations. The 1.5-year and two-year discharges were estimated for each gage. On the Dolores River, pre-dam and post-dam flood frequency curves were created.

Geomorphic Analysis

Two methods of exploring the geomorphology of the reaches were employed: reach-averaged channel morphology from HEC-RAS modeling results and review of historic aerial photos (Appendices B and C). From the HEC-RAS modeling results for the three study reaches, the reach-averaged width, width/depth ratio, hydraulic depth, slope and channel cross-section area were computed for each reach for the channel-forming discharge. On the Yampa River, several historic sets of aerial photos were available. The photos were scanned if necessary and the active channel digitized from the georeferenced photos. The sinuosity and average channel width were measured from the photos. Also, observations of changes in the reaches were made. Historic aerial photos were not available for the Dolores River.

RESULTS

Bankfull Discharge

In the Big Gypsum reach of the Dolores River the bankfull flows at the selected cross sections ranged from 2,230 cfs to 3,800 cfs, with a median value of 2,600 cfs. A flow of 3,400 cfs was necessary to begin inundation of 95% of the floodplains of the 39 cross sections. On the Lily Park reach of the Yampa River, a flow rate of 11,000 cfs inundated more than 50% of the floodplain elevations at the 41 sections. For the Sevens Reach of the Yampa River 11,200 cfs reached the top-of-bank at a minimum of 50% of the cross sections and was determined to be the bankfull flow.

TABLE 4. Summary of channel-forming discharge results.

Reach and Time Period	Bankfull Discharge (cfs,% inundation)	Effective Discharge (cfs)	Marginal Transport Discharge (cfs)	Significant Motion Discharge (cfs)	2-year Discharge (cfs)
Big Gypsum Reach, Dolores River	2,600 (50%) 3,400 (95%)		3,200	10,000	
1918-22, 1971-2005					3,760
Pre-dam (1918-22, 1970-84)					4,280
Post-dam (1985-2005)					3,140
Lily Park Reach, Yampa River	11,000 (50%) 13,00 (95%)	8,100	5,500	11,500	10,400
Sevens Reach, Yampa River	11,200 (50%)	8,100	>20,500	>20,500	10,400

Effective Discharge

Effective discharge was computed for the Yampa River at two gages. The flow-frequency curves created from the entire daily mean discharge data record for the two Yampa River gaging stations are shown in Figure 22. Both were created with 20 equal-sized interval classes or bins. The range of discharges at the Maybell gage was larger than at the Little Snake River gage because the data record was longer (1916-2005). As a result the interval classes were larger and the distributions at the two gages were slightly different. The near Maybell gage also has a smoother flow-frequency distribution than the gage above Little Snake River.

Combining the flow frequency curves (Figure 22) with the sediment load rating curves (Table 3) for each gaging station resulted in sediment load histograms. The bed material of the Yampa River is predominantly of the sand and gravel size, so the sand and gravel rating curve was used for determination of the effective discharge. Because the rating curves for the different sediment sizes are so similar, the resulting effective discharge

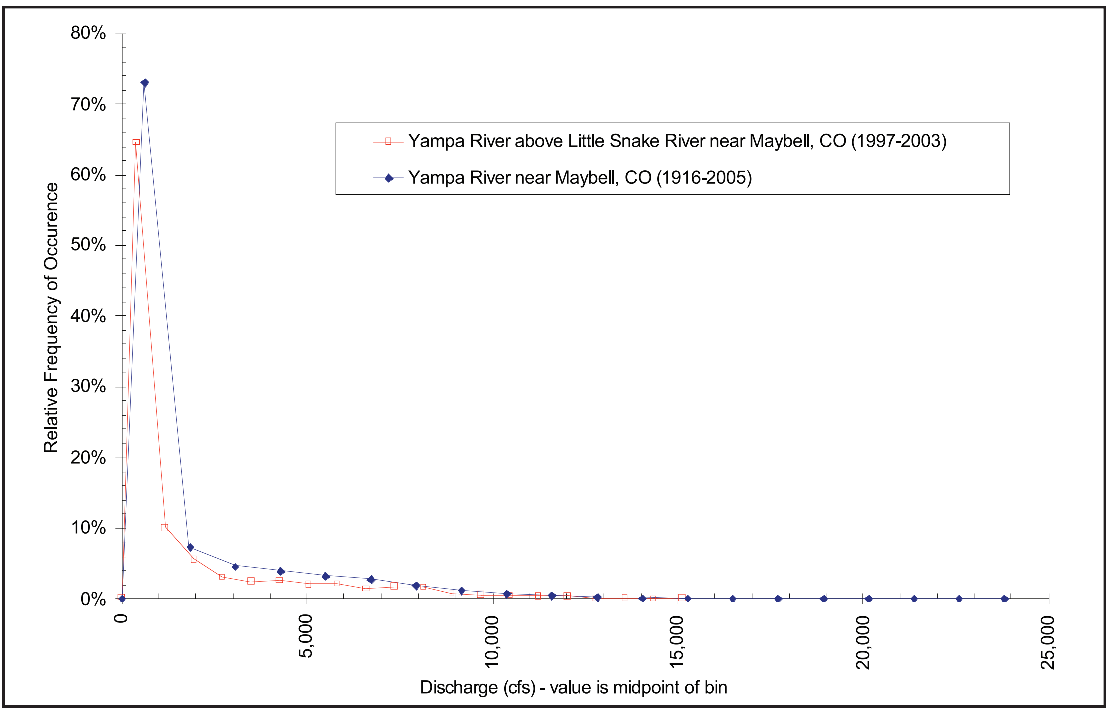

FIGURE 22. Frequency distributions for daily mean discharge.

did not vary substantially between the different rating curves given in Table 3.

The effective discharge for sand and gravel sized sediment at the Little Snake River gage was 8,138 cfs and at the Maybell gage was 7,930 cfs (Figure 23 and Figure 24). Andrews (1980) determined that the effective discharge for the Yampa River near Maybell, CO was 9,111 cfs (258 m^3/s).

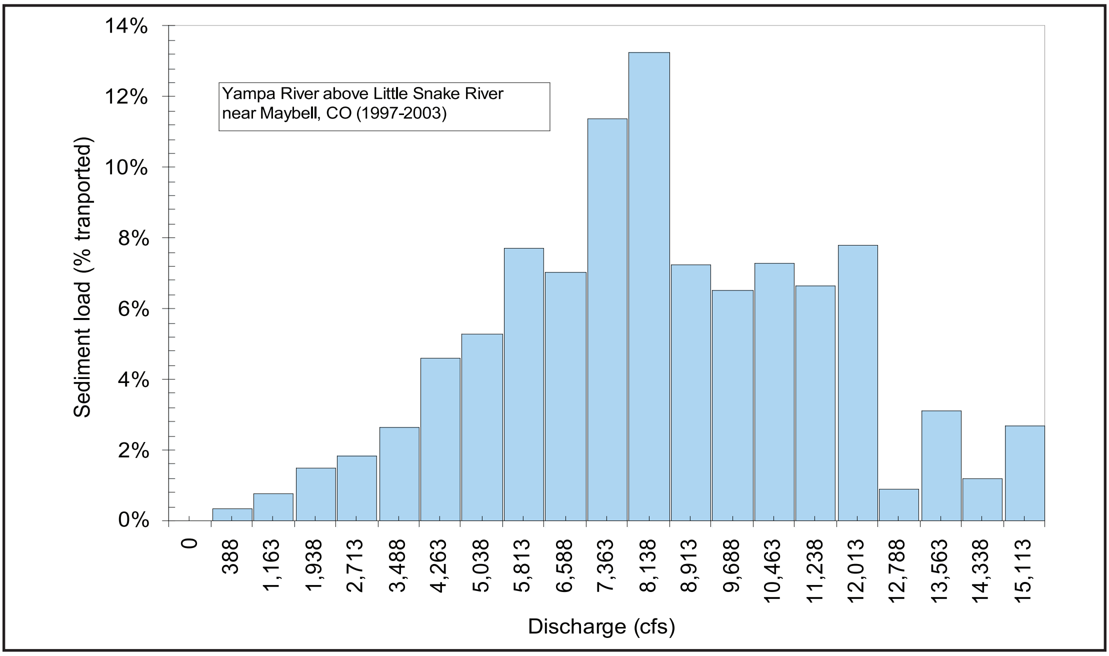

FIGURE 23. Sediment load histogram for Yampa River above Little Snake River near Maybell, CO (1997-2003) for sand and gravel sized sediment.

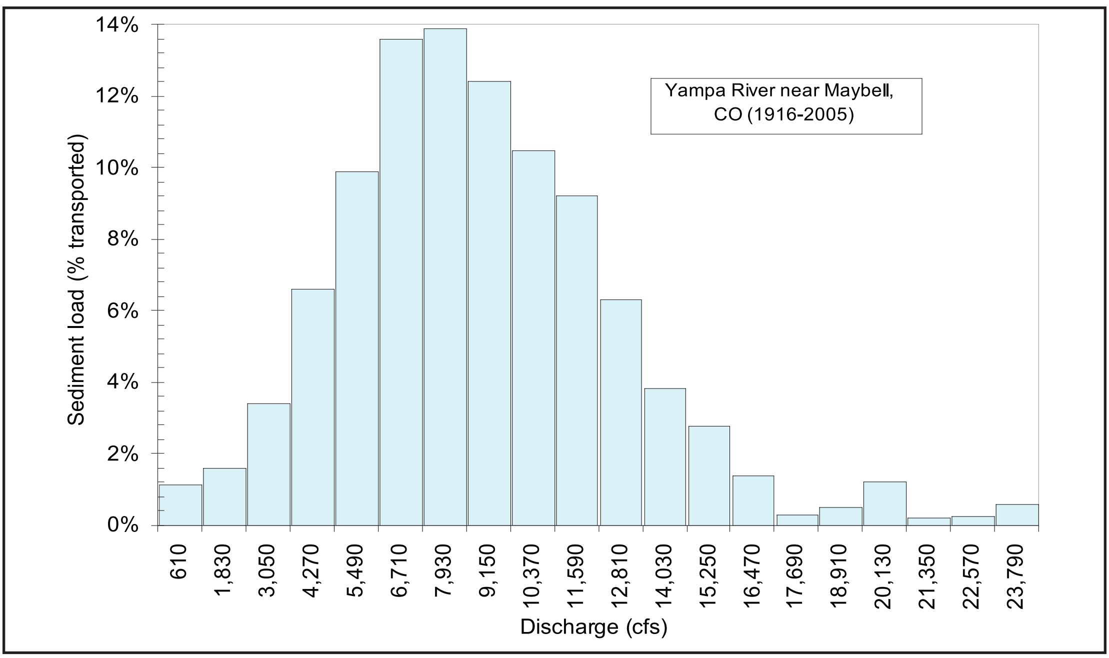

FIGURE 24. Sand and gravel load histogram for Yampa River near Maybell, CO (1916-2005) for sand and gravel sized sediment.

Critical Shear Stress

The discharges necessary to achieve critical shear stress for marginal transport $\tau_c^* = 0.03$) and significant motion ($\tau_c^* = 0.047$) of the median bed material size at a minimum of 50% of the cross sections were computed for the three study reaches (Table 5). The critical shear values computed from the Shields equation to mobilize the bed material ranged from 16.5 N/m^2 to 41 N/m^2, which are reasonable values for threshold of motion for very coarse gravel to small cobble-size material (Julien, 1995).

Flood Frequency Analysis

The 1.5-year and two-year recurrence interval flows were extracted from the flood-frequency curves developed for the Dolores River at Bedrock, CO and the Yampa River near Maybell, CO stream gages (Table 6, Figure 25, Figure 26 and Figure 27). The two-year recurrence interval flow decreased by 27% from the pre-dam to post-dam time period on the Dolores River. At the Yampa River near Maybell gage, the two-year discharge is 10,400 cfs (294 m^3/s) and the 1.5-year discharge is 8,870 cfs (251 m3/s) based on the entire data record of 1916-2005.

TABLE 5. Results of shear stress analysis for Yampa River and Dolores River.

Reach	D_{50}(m)	Shear Stress (N/m^2) for Marginal Transport of D_{50}, $\tau_c^* = 0.03$	Discharge (cfs) for Marginal Transport of D_{50}, $\tau_c^* = 0.03$	Shear Stress (N/m^2) for Significant Motion of D_{50}, $\tau_c^* = 0.047$	Discharge for Significant Motion of D_{50}, $\tau_c^* = 0.047$
Lily Park	0.034	16.51	5,500	25.87	11,500
Sevens	0.034	16.51	>20,500	25.87	>20,500
Big Gypsum	0.054	26.22	3,200	41.08	10,000

TABLE 6. Results of flood-frequency curve analysis for the Dolores River at Bedrock, CO (1918-22, 1971-2005) and the Yampa River near Maybell, CO (1916-2005).

Gaging Station	Time Period	1.5-year Recurrence Interval Flow	2-year Recurrence Interval Flow
Dolores River at Bedrock, CO	Entire Period 1918-22, 1971-2005	2,340 cfs	3,760 cfs
	Pre-Dam 1918-22, 1971-84	4,040 cfs	4,450 cfs
	Post-Dam 1985-2005	1,010 cfs	3,135 cfs
Yampa River near Maybell, CO	1916-2005	8,870 cfs	11,400 cfs

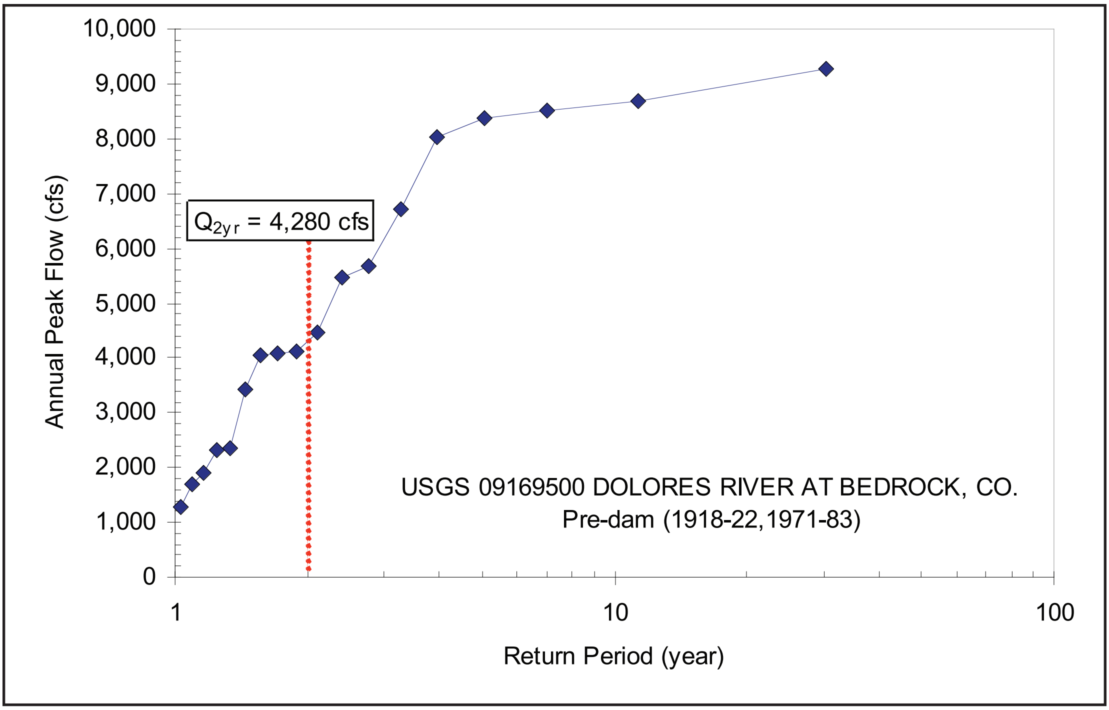

FIGURE 25. Pre-dam flood frequency curve Dolores River at Bedrock, CO.

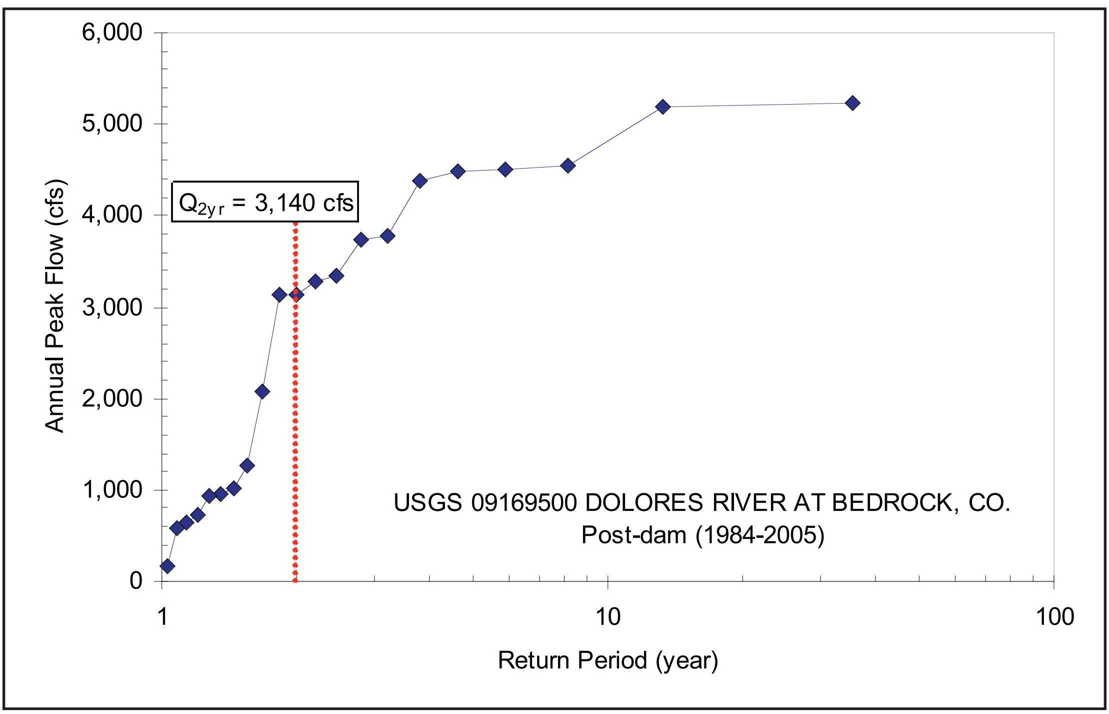

FIGURE 26. Post-dam flood frequency curve Dolores River at Bedrock, CO.

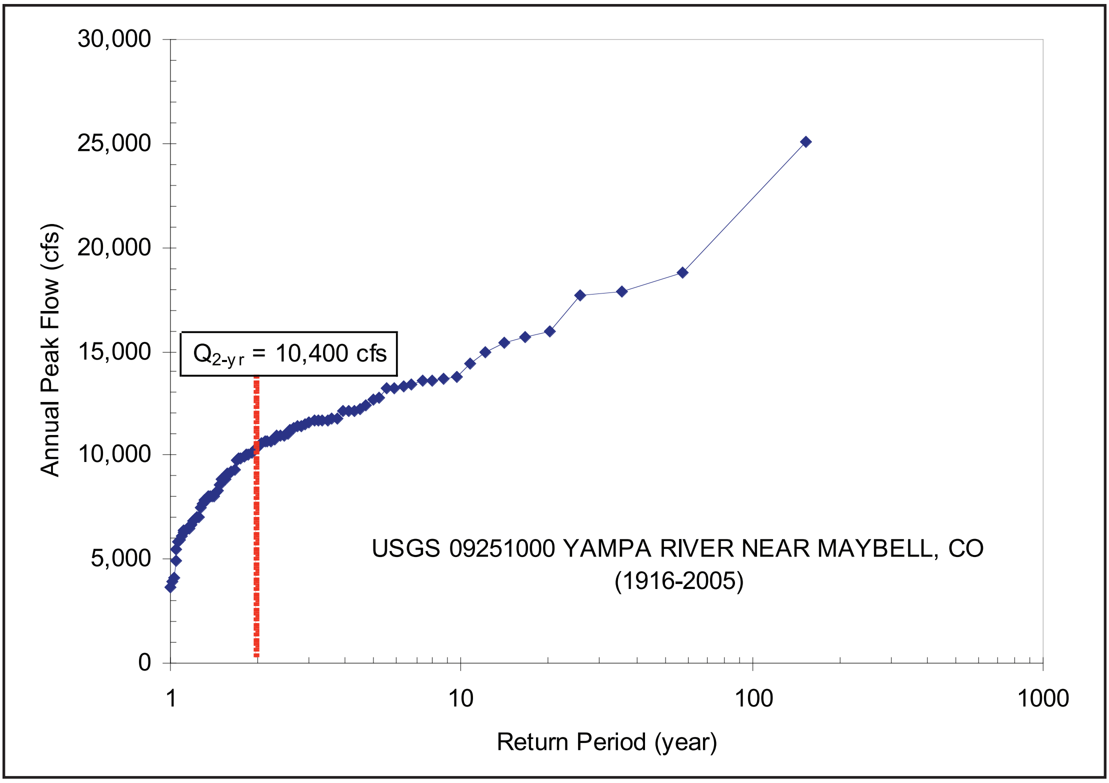

FIGURE 27. Flood frequency curve for Yampa River near Maybell, CO.

Geomorphic Analysis

The morphology of each reach was summarized using the results of the HEC-RAS model run at bankfull discharge. The bankfull width of the Big Gypsum reach on the Dolores River was 38 m and the on the Yampa River was 93 and 98 meters on the Lily Park and Sevens reaches respectively (Table 7). The Big Gypsum reach has the steepest average energy grade slope (0.0016) and the Sevens reach has the mildest energy grade slope (0.00044). Plots of changes in these variables along each reach are presented in Appendix D.

Qualitative analysis of the historic aerial photos revealed changes in the banklines of both the Lily Park and Sevens reaches. The meander neck in the Lily Park reach decreased by about 39 meters between 1953 and 1999 (Figure 28). While surveying during high flows near bankfull (9,730 cfs, 276 m^3/s) in 2003 (Figure 29), we noticed the near vertical bank "calving" off into the water on the right bank upstream of the meander. The change in channel alignment is also visible in the movement of the channel centerlines (Figure 28). The sinuosity of the Lily Park reach remained fairly constant

TABLE 7. Summary of bankfull discharge reach-averaged HEC-RAS modeling results.

Bankfull Reach-Averaged Value	Big Gypsum Reach Dolores River	Lily Park Reach Yampa River	Sevens Reach Yampa River
Bankfull Width (m)	38.1	93.0	98.1
Bankfull Depth (m)	2.1	2.1	3.0
Energy Grade Slope	0.0016	0.0012	0.00044

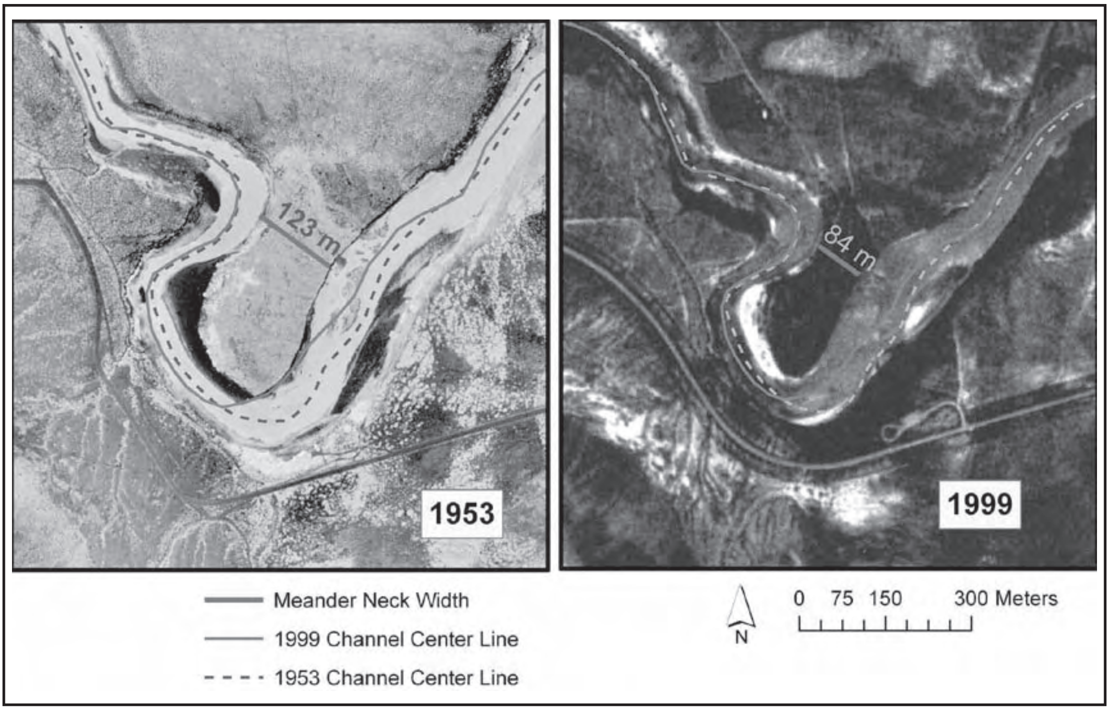

FIGURE 28. Reduction in meander neck width on the Lily Park reach, Yampa River, CO. In 1953 the neck was about 123 meters wide and in 1999 it was about 84 meters wide. Direction of flow is from right to left.

varying from 1.39 in 1937 to 1.41 in 1999. The average channel width increased by 20% from 66 m to 79 m from 1953 to 1993.

Changes in the Sevens reach include channel widening and bank erosion. For almost the entire length of the reach, the left bank eroded between 1953 and 1998. Between 1953 and 1993 the left bank eroded about 20 meters across from and downstream of the confluence with a small ephemeral tributary on the right bank (Figure 30). The right or outer bank eroded about 30 meters in the downstream portion of a meander (FigureFigure 31). The sinuosity of the Sevens reach varied from 1.23 to 1.25 from 1952 to 1999. The average channel width increased by 10% from 78 to 86 meters from 1953 to 1988, which was the most recent year that we had a complete set of aerial photos of good enough resolution to measure channel width for the entire reach.

FIGURE 29. Surveying water line at 9,730 cfs at Lily Park Reach, Yampa River, CO (5/13/03)

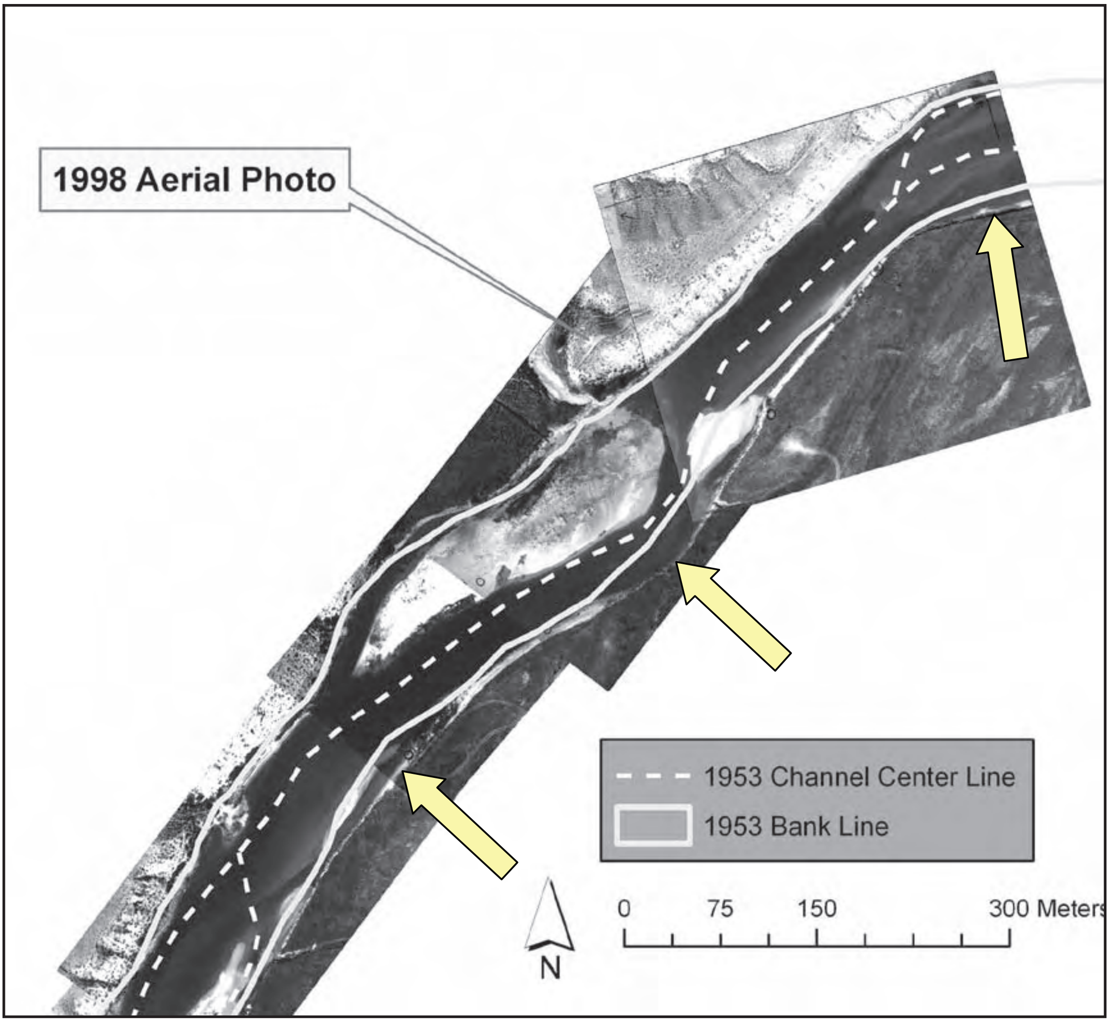

FIGURE 30. Bank erosion (~20 m from 1953 to 1998) on the left bank of the Sevens Reach, Yampa River, CO. Arrows indicate regions of bank erosion on the left bank. Direction of flow is from upper right to lower left.

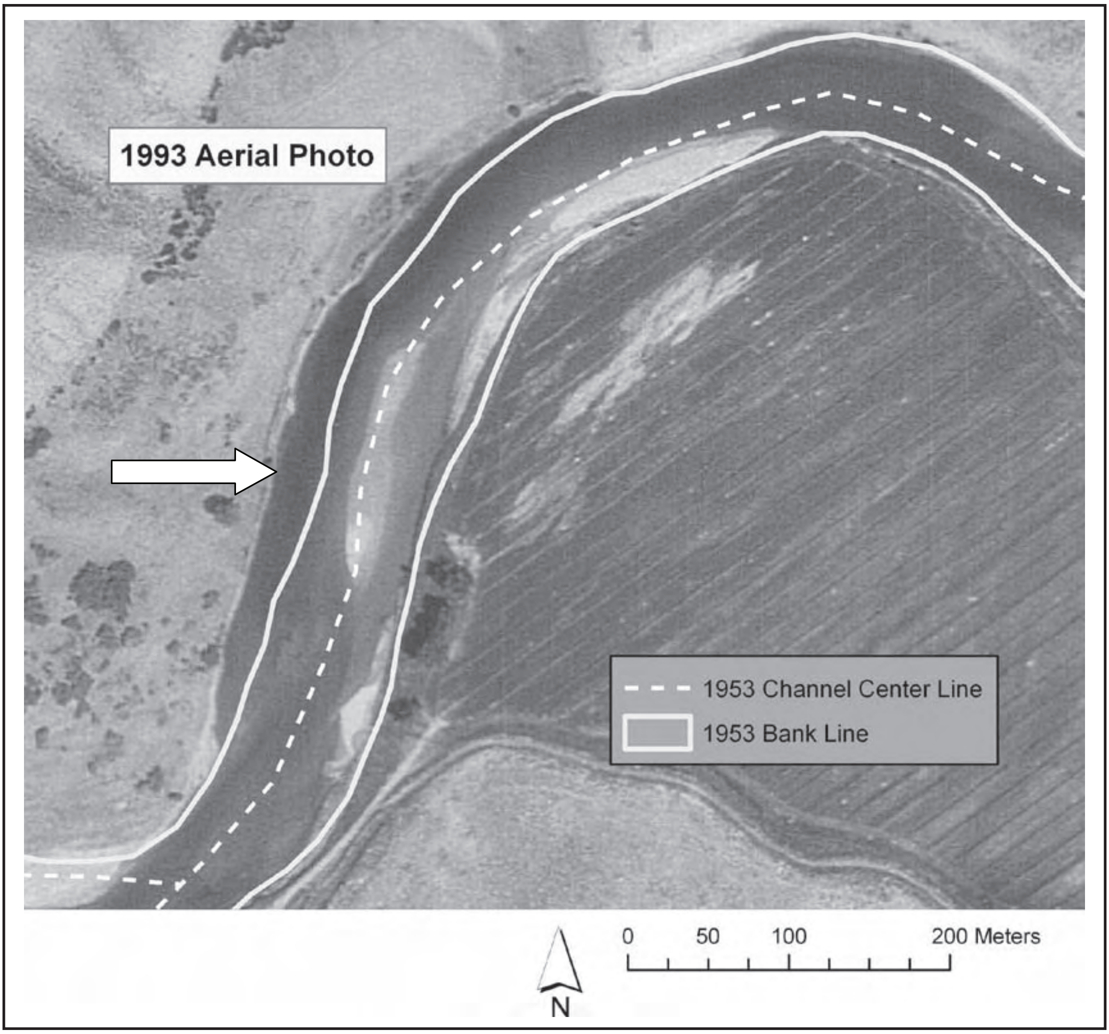

FIGURE 31. Meander migration (~30 m from 1953 to 1993) on the Sevens Reach, Yampa River, CO. Arrow indicates area of greatest bank erosion. Direction of flow is from right to left.

DISCUSSION

The flows determined to be channel-forming in this study on the Dolores River are in the range of 2,600 to 10,000 cfs (Table 4 and Table 8). Marginal transport of the bed and significant inundation of the floodplains should occur at about a two-year frequency given the post-dam flow regime. Field observations by the authors during a high spring runoff in 2005 revealed that a flow of 4,700 cfs inundated some of the floodplain areas, but not all. The high estimate of 10,000 cfs was the discharge necessary for significant motion of the bed material. This estimate could be refined with future surveys of the bed material, cross section geometry and channel slope. Vandas et al. (1990) suggested that a flow of 7,000 cfs was necessary to significantly mobilize the bed material.

Identifying areas that are current floodplains on the Dolores River was particularly challenging because of vegetation encroachment on the channel since construction of McPhee Dam. The post-dam diminished peak flows have allowed substantial tamarisk, russian olive and willow stands to take hold in areas that would have previously been flooded more regularly. The thick vegetation made surveying of the riparian areas particularly challenging. More thorough surveying of the floodplains could increase the accuracy of the bankfull discharge estimates.

The channel has likely undergone other morphology modifications since construction of McPhee Dam, which would result in a change in the bankfull discharge. The two-year discharge decreased by 27% following dam construction and the 1.5-year flow decreased by 73%. It is possible that the channel is still adjusting to the new post-dam discharge and sediment regime.

Channel-forming discharge estimates on the Yampa River from this study vary from 7,000 cfs to greater than 20,500 cfs (Table 5), though the high estimate should be viewed with skepticism because of the lack of accurate bed material data for the Sevens reach. Field observations in 2005 confirmed that the Yampa River was "lapping at the top of the bank" at 12,000 cfs (Lori Martin, CDOW, Personal Communication, 2005) suggesting that the bankfull discharge values estimated in this study (11,000 cfs to 13,000 cfs) are accurate.

The bankfull discharge estimate for both the Lily Park and Sevens reaches are higher than Andrews' (1980) estimate suggesting that changes in the channel configuration have occurred because a higher flow is now necessary to reach bankfull. In addition, the return period of the bankfull flow increased from 1.6 years from Andrews (1980) to 2.5 to 2.9 years in the current study. From analysis of the historic aerial photos, both study reaches on the Yampa River have undergone as much as 20% widening since 1953. An increase in channel area from bank erosion and widening could result in an increase of the magnitude of the flow necessary to reach bankfull, which would be a less frequent discharge. The reasons for widening are unclear, though impacts of grazing on the channel banks were evident during our field visits.

TABLE 8. Comparison of channel-forming discharge estimates for the Dolores River from current study with those from Vandas et al. (1990). The pre- and post-dam recurrence intervals were derived from the flood frequency curves developed from the Dolores River at Bedrock Gage data presented in Figure 26.

Channel-Forming Discharge Estimate (Current Study)	Discharge (cfs)	Post-dam Recurrence Interval (years)	Pre-dam Recurrence Interval (years)	Channel-Forming Discharge Estimate (Vandas et al., 1990)	Discharge (cfs)	Post-dam Recurrence Interval (years)	Pre-dam Recurrence Interval (years)
Bankfull Discharge							
Big Gypsum Reach (50% floodplain inundation)	2,600	1.8	1.36	Bankfull Discharge	2,300	1.7	1.2
Big Gypsum Reach (95% floodplain inundation)	3,400	2.5	1.44				
1.5-yr Recurrence Interval				1.5-yr Recurrence Interval			
Pre-dam - Bedrock Gage (1918-22, 1970-84)	3 ,712	2.8	1.5	Pre-dam	3,068	1.8	1.4
Post-dam - Bedrock Gage (1985-2005)	1 ,010	1.5	<1.0	Post-dam	1,300	1.6	1.0
2-yr Recurrence Interval							
Pre-dam - Bedrock Gage (1918-22, 1970-84)	4 ,280	3.7	2.0				
Post-dam - Bedrock Gage (1985-2005)	3 ,140	2.0	1.4				
Critical Shear Stress				Critical Shear Stress			
Marginal transport - Big Gypsum Reach	3 ,200	2.1	1.4	Marginal Transport	2,500	1.7	1.4
Significant Motion - Big Gypsum Reach	10,000	>35	>30	Significant Motion	7,000	>35	3.4

Table 9. Comparison of channel-forming discharge estimates for the Yampa River from this study with those from Andrews (1980, 1984). Recurrence intervals were determined from the flood-frequency curve developed from the Yampa River near Maybell gage data (Figure 27).

Channel-Forming Discharge Estimate (Current Study)	Discharge (cfs) (a) Maybell Gage, (b) Lily Park, (c) Sevens	Recurrence Interval (years)	Channel-Forming Discharge from Andrews (1980, 1984)	Discharge (cfs)	Recurrence Interval (years)
Bankfull Discharge			Bankfull Discharge at Maybell Gage		
50% floodplain inundation	11,000 (b)	2.5		9,006	1.6
	11,200 (c)	2.6			
95% floodplain inundation	13,000 (b)	5.4			
2-yr Recurrence Interval	10,400 (a)	2.0			
Effective Discharge	8,100 (a)	1.4	Effective discharge at Maybell Gage	9,111	1.6
Critical Shear Stress					
Marginal transport	5,500 (b)	1.1			
Significant Motion	11,500 (b)	2.9			

CONCLUSION

The channel-forming discharge and channel morphology were examined at three sites on the lower Yampa and Dolores Rivers. Studies describing channel-forming discharge by Andrews (1980) and Vandas et al. (1990) showed that on the Yampa River channel-forming discharge was in the range of 9,000 to 9,100 cfs (255 to 258 m3/s) and on the Dolores River from 2,300 cfs (65 m^3/s) to as high as 7,000 cfs (198 m3/s) to achieve significant motion of the bed material. The objectives of this study were to estimate the channel forming discharge for the two rivers and to compare current results with results of past studies.

On the Dolores River, the flow that begins to inundate at least 50% of the floodplain areas and the flow that begins to mobilize the bed material are in the range of 2,600 to 3,400 cfs (74 to 96 m^3/s). The flow regime and resulting channel morphology of the Dolores River have been affected by McPhee dam, which reduced the 1.5-year discharge by 73%, the two-year discharge by 27% and the mean annual flood by nearly 50%. The range of flows determined to be channel-forming occurred at about a 1.4-year frequency before construction of the dam. The recurrence interval for channel-forming flows has increased to 1.8 to 2.5 years since construction of the dam, which is a 28% to 79% decrease in frequency of occurrence. The expected result would be an adjustment in channel morphology, with bed material being mobilized less frequently, reduction in channel width and depth and encroachment of riparian vegetation on the channel.

On the Yampa River, the flow that begins to inundate at least 50% of the floodplain areas and the flow that significantly mobilizes the bed material are in the range of 11,000 to 11,500 cfs (311 to 326 m^3/s) and 2.5 to 2.9 year return periods, which are about 20% higher than Andrews' (1980) bankfull estimate. The effective discharge was estimated to be 8,100 cfs (229 m^3/s) on the Yampa River, which is lower than previous estimates by Andrews (1980). Based on an analysis of historic aerial photos of the Yampa River, the channel has widened as much as 20% and undergone bank erosion of as much as 20 to 30 meters. It is possible that channel widening has resulted in a bankfull discharge that is larger and occurs less frequently. Bed material surveys would increase the reliability of the estimates of the flow rate necessary to mobilize the bed material, which would provide a better estimate of the channel-forming discharge.

The methodology described in this study for bankfull discharge determination using GPS data, GIS mapping and HEC-RAS modeling is labor intensive, but if the survey data are available the method provides an accurate means of estimating bankfull discharge. Better identification of floodplain surfaces and additional surveying of areas adjacent to the channel would increase the ease and accuracy of the bankfull determination.

LITERATURE CITED

Anderson R. M. and G. Stewart. 2003. Riverine fish-flow investigations: Relationships between flow and habitat availability for warm-water riverine fish communities. *Colorado Division of Wildlife. Federal Aid Project F-289-R6*. Job Pro. Report, Fort Collins 96 pp.

Anderson R. M. and G. Stewart. 2006. Riverine fish-flow investigation, Final Report: Impacts of stream flow alterations on the native fish assemblage and their habitat availability as determined by 2D modeling and the use of fish population data to support instream flow recommendations for the sections of the Yampa, Colorado, Gunnison and Dolores Rivers in Colorado. *Colorado Division of Wildlife Special Report 80*. Fort Collins, CO.

Andrews, E.D., 1980. "Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming", *Journal of Hydrology*, v. 46, pp. 311-330.

Andrews, E. D. 1983. "Entrainment of gravel from naturally sorted riverbed material". *Geological Society of America Bulletin* v. 94, pp. 1225-1231.

Andrews, E.D., 1984. "Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado", *Geological Society of America Bulletin*, v. 95, pp. 371-378.

Biedenharn, D.S. and Copeland, R.R., 2000. *Effective Discharge Calculation*, US Army Corps of Engineers, ERDC/CHL CHETN-VII-4.

Biedenharn, D.S., Thorne, C.R., Soar, P.J., Hey, R.D. and Watson, C.C., 2001. "Effective Discharge Calculation Guide", *International Journal of Sediment Research*, v. 16, n. 4, pp. 445-459.

Biedenharn, D.S., Thorne, C.R., Soar, P.J., Hey, R.D. and Watson, C.C., 1999. "A Practical Guide to Effective Discharge Calculation", in *Demonstration Erosion Control Design Manual*, eds. Watson, C.C., Biedenharn, D.S. and Thorne, C.R., U.S. Army Engineer Research and Development Center, Vicksburg, MS, pp. 239-274.

Carling, P. A., 1988. "The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds". *Earth Surface Processes and Landforms*. v. 13, pp. 355-67.

Elliott, J.G. and Anders, S.P., 2004. *Summary of Sediment Data from the Yampa River and Upper Green River Basins, Colorado and Utah*, 1993-2002, USGS Scientific Investigations Report 2004-5242.

Elliott, J. G. and Hammack, L. A., 1999. *Geomorphic and Sedimentologic Characteristics of Alluvial Reaches in the Black Canyon of the Gunnison National Monument, Colorado*. U.S. Geological Survey, Water-Resources Investigations Report 99-4082, Denver, CO.

Emmett, W.W. and Wolman, M.G., 2001. "Effective discharge and gravel-bed rivers", *Earth Surface Processes and Landforms*, v. 26, pp. 1369-1380.

Iorns, W. V., Hembree, C. H. and Oakland, G. L., 1965. *Water Resources of the Upper Colorado River Basin, Technical Report.* U.S. Geological Survey, Professional Paper 441.

Julien, Pierre Y., 1995. *Erosion and sedimentation*. Cambridge University Press, NY, NY.

Leopold, L. B. and Wolman, G. M., 1957. *River Channel Patterns: Braided, Meandering and Straight*, USGS Professional Paper 282-B, Washington, D.C.

Milhous, R. T. 1982. "Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers". In *Gravel-bed rivers: fluvial processes, engineering and management.* Eds. Hey, R. D.; Bathhurst, J. C. and Thorne, C. R., John Wiley & Sons, Chichester, UK, pp. 819-842.

Nash, D. B., 1994. "Effective sediment-transporting discharge from a magnitude-frequency analysis". *Journal of Geology*. v. 102, pp. 79-95.

Pickup, G. and Warner, R. F., 1976. "Effects of hydrologic regime on magnitude and frequency of dominant discharge". *Journal of Hydrology*. v. 29, pp. 51-75.

Pitlick, J. and Van Steeter, M.M., 1998. "Geomorphology and endangered fish habitats of the upper Colorado River 2. Linking sediment transport to habitat maintenance", *Water Resources Research*, v. 34, n. 2, pp. 303-316.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. and Stromberg, J. C., 1997. "The Natural Flow Regime". *BioScience*. v. 47, n. 11, pp. 769-784.

Salas, J. D., Smith, R. A., Tabios, G. Q. III and Jeo, J-H. 1998. *Statistical computer techniques in water resources and environmental engineering*, Colorado State University, Fort Collins, CO.

U.S. Department of Interior Bureau of Reclamation (USBR), 2006. Upper Colorado Regional Office, Western Colorado Area Office, Grand Junction, CO.

Vandas, S., Whittaker, D., Murphy, D., Prichard, D., MacDonnell, L., Shelby, B., Muller, D., Fogg, J. and Van Havern, B., 1990. *Dolores River Instream Flow Assessment, Project Report*. US Department of the Interior, Bureau of Land Management.

Wilcox, A. and Merritt, D.M., 2005. "Effects of modified flow regimes on the Dolores River", *Riparian Response to Altered Flow Regimes*, Proceedings of the Colorado Riparian Association, 18th annual conference, October 5-7, 2005, Durango, CO, pp. 69-83.

Williams, G.P., 1978. "Bank-full discharge of rivers", *Water Resources Research*, v. 14, n.8, pp. 1141-1154.

Wolman, M.G. and Miller, J.P., 1960. "Magnitude and frequency of forces in geomorphic processes", *Journal of Geology*, v. 68, pp. 54-74.