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Relationships between tributary catchments, valley-bottom width, debris-fan area, and mainstem gradient on the Colorado Plateau: A case study in Desolation and Gray Canyons on the Green River

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RELATIONSHIPS BETWEEN TRIBUTARY CATCHMENTS, VALLEY-BOTTOM WIDTH, DEBRIS-FAN AREA, AND MAINSTEM GRADIENT ON THE COLORADO PLATEAU: A CASE STUDY IN DESOLATION AND GRAY CANYONS ON THE GREEN RIVER

by

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ABSTRACT

Relationships between tributary catchments, valley-bottom width,

debris-fan area, and mainstem gradient on the Colorado

Plateau: A case study in Desolation and

Gray Canyons on the Green River

by

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Department: Geology

The alluvial forms of the rivers that drain the Colorado Plateau are a product of the water and sediment load that tributaries deliver to the trunk streams. Where the Green and Colorado Rivers cross structural barriers, narrow canyons have been incised. In the steep terrain adjacent to many of these canyons debris flows occur in the catchment basins of tributaries and deliver coarse sediment to the mainstem river corridor. Over time, debris flow deposits have aggraded in trunk stream valleys and created landforms known as debris fans. The sizes of these debris fans are related to the accommodation space available for fan formation. Lithologic variation in the layer-cake stratigraphy of the Colorado Plateau has led to varying valley widths. Tributary catchment, debris fan, depositional site, and mainstem river characteristics are examined over the 156-kilometer reach of the Green River through Desolation and Gray Canyons.

Desolation and Gray Canyons provide some of the widest valley widths and resultant debris fan areas on the Colorado Plateau.

(129 pages)

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CONTENTS

Page

ABSTRACT....ii

ACKNOWLEDGMENTS....iv

LIST OF TABLES....vii

LIST OF FIGURES....viii

CHAPTER

I. INTRODUCTION.... 1

References Cited....3

II. TRIBUTARY DEBRIS FANS, CATCHMENT CHARACTERISTICS AND MAIN-STEM RIVER INTERACTION ON THE GREEN RIVER IN DESOLATION AND GRAY CANYONS, EAST-CENTRAL,UTAH....4

Abstract....4
Introduction....5
Previous research....6
Setting....13
Methods....19
Results....24
Discussion and Conclusions....64
References Cited....66

III. RELATIONSHIPS BETWEEN TRIBUTARY CATCHMENT AREA, VALLEY-BOTTOM WIDTH, DEBRIS-FAN AREA, AND MAINSTEM GRADIENT ON THE Colorado Plateau....72

Abstract.... 72
Introduction.... 73
Geologic setting and background....74
Methods.... 77

Page
Results..79
Discussion and Conclusions..84
References Cited..85

IV. CONCLUSIONS..88

APPENDICES..90

APPENDIX A: Catalog of geomorphically signficant tributaries..................91
APPENDIX B: Catchment data for geomorphically significant tributaries........95
APPENDIX C: Valley-bottomcharacteristics..99
APPENDIX D: Debris fan characteristics...103
APPENDIX E: Green River characteristics at debris fan locations................107
APPENDIX F: Unit descriptions for mapping 111
APPENDIX G: Channel activity index..115
APPENDIX H: Climate station data...116
APPENDIX I: Air photo information...117
APPENDIX J: Grain size data..118
APPENDIX K: Rock-mass strength data..119

PLATES

PLATE 1: Map of the Green River through Desolation Canyon............in packet
PLATE 2: Map of the Green River through Gray Canyon.................. ..in packet

LIST OF TABLES

Table Page

1. Drainage-basin data for selected debris fans.. 30

2. Mapped deposits in the Green River valley...39

3. Debris-fan data for study sites...40

4. Channel altering debris flow events in Desolation and Gray Canyons.............41

5. Reach designations in Desolation and Gray Canyons.....................................58

6. Reaches and reach-averaged attributes of debris fan affected canyon reaches of the Green and Colorado Rivers...78

LIST OF FIGURES

Figure Page

1. Map of study area indicating detailed study sites indicated 14

2. Longitudinal profile of the Green River through the study area 16

3. Stratigraphic column of Tavaputs Plateau and Book Cliffs region 18

4. Histogram of drainage areas of tributaries in the study area 27

5. Map of tributary drainage basins that contribute sediment to debris fans and alluvial fans in the Green River's valley 28

6. Variation in tributary drainage basin area 29

7. Longitudinal profiles of selected drainages 32

8. Variation in valley-bottom width 33

9. Rock-mass strength and valley width relationship 34

10. Typical canyon cross sections for different rock types 35

11. Longitudinal variation in channel width in the study area 36

12. Example of mapping around river mile 56 38

13. Variation in debris-fan area in Desolation and Gray Canyons 41

14. Photos and descriptions of debris fans 42

15. Power function relationships between drainage basin area and debris fan area in Desolation and Gray Canyons 45

16. Reach-averaged relation between drainage area and debris fan-area 48

17. Types of debris fans and degrees of linkage to the mainstem Green River 49

18. Channel entrenchment for detailed study sites 50

19. Trends in type of debris fan-river linkage 54

20. Gravel bar area by river mile in the study area 55

Page
21. Relationship between reach-averaged Green River slope and debris fan characteristics in Desolation and Gray Canyons.... 56

22. Box and whisker statistical plots of variation in reach characteristics.............. 59

23. Representative examples of mapping in each of the four main reaches in the study region.... 60

24. Map of Colorado Plateau region and the canyon reaches of the Green and Colorado Rivers analyzed in this study.... 75

25. Box and whisker statistical plot of variation in the data set of valley width and debris fan area.... 80

26. Relationship between debris-fan area and drainage-basin area.......................82

27. Correlation between reach-averaged debris-fan area and mainstem river slope...83

Plate 1: Map of the Green River through Desolation Canyon........................ in packet

Plate 2: Map of the Green River through Gray Canyon................................ in packet

CHAPTER I

INTRODUCTION

The Colorado Plateau region of the United States is known for its spectacular landforms. In this semi-arid and sparsely vegetated region, a thick sequence of relatively flat-lying sedimentary rocks are exposed. The geomorphology of the region is greatly influenced by geology; escarpments, such as the Vermillion Cliffs and Book Cliffs, have formed due to differential erosion where resistant sandstones overlie softer shales. Laccolithic mountain ranges, such as the Henry Mountains and La Sal Mountains stand high above surrounding lowlands riddled with canyons and narrow gorges.

The region supports few perennial drainages compared to wetter regions. The Colorado River system drains at least 90 percent of the area of the Colorado Plateau (Patton et al., 1991). The Colorado River and its major tributaries, the Green River and the San Juan River, all have headwaters high in the Rocky Mountain province adjacent to the Colorado Plateau where the majority of their streamflow originates. However, most of the sediment in these systems originates from more local sources, with fine-grained sediment primarily supplied from tributaries such as the Price, Escalante, and Paria Rivers. These and many other similar tributaries that drain low semiarid regions supply considerable sediment, especially where less-resistant shale and mudstone lithologies such as the Wasatch, Mancos, Morrison, Chinle, and Moenkopi formations outcrop (Andrews, 1990). Coarse sediment is delivered to the system where coarse alluvial deposits lie adjacent to the modern stream or where hillslope processes in regions with steep slopes connect tributaries with the mainstem river through the process of debris-flow.

steep slopes connect tributaries with the mainstem river through the process of debris-flow.

Debris flows occur and aggrade in the mainstem river valley as debris fans on the Green and Yampa Rivers in the eastern Uinta Mountains (Graf, 1979; Hammack and Wohl, 1996; Grams and Schmidt, 1999, 2002), and in the Green River's canyons through the Tavaputs Plateau in central Utah (Schmidt and Rubin, 1995). On the Colorado River, debris flows occur and create debris fans in Westwater and Cataract Canyons in Utah, and Glen and Grand canyons in northern Arizona (Webb et al., 1988, Melis et al., 1995).

This report is divided into two main body chapters. This introduction provides a background and context for the study. Chapter II addresses the characteristics of tributary catchments, debris fans, their depositional valleys, and effects on the mainstem channel for 162 debris fans on the Green River through Desolation and Gray Canyons in east-central Utah. This is the first work focusing on tributary debris fans and their catchments on this reach of the Green River where considerably wider valley settings and a higher frequency of large debris fans occur compared to other canyons on the plateau. Field investigation, photogeologic mapping, and digital elevation model analysis were used to characterize the tributary catchments, debris fans, river valley, and mainstem Green River channel. Plates of geomorphic mapping of this 135-km segment of the Green River and tables of data collected can be found in the appendix to this report.

Chapter III provides a wider perspective and context on the factors controlling debris fan size on various reaches of the Green and Colorado Rivers. The data set presented in Chapter II has been added to a larger data set of debris fan size and valley widths compiled from existing data for other canyons on the Colorado Plateau. This provides the first regional synthesis of debris-fan size on the Colorado Plateau focusing on Lodore, Desolation, Gray, and Grand Canyons.

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CHAPTER II

TRIBUTARY DEBRIS FANS, CATCHMENT CHARACTERISTICS, AND MAINSTEM INTERACTION ON THE GREEN RIVER IN DESOLATION AND GRAY CANYONS, EAST-CENTRAL UTAH

ABSTRACT

Hillslope and channel linkages are described through debris flow processes in tributaries to the Green River through Desolation and Gray Canyons. In the 135-km study reach tributaries frequently deliver coarse sediment to the canyon bound mainstem valley and create coarse debris fans that often obstruct the river resulting in rapids. Tributary catchment, debris fan, depositional site, and mainstem river channel characteristics are described for this reach of the Green River. This study area provides wider valley widths and larger debris fans than other comparable Colorado Plateau canyons with debris fans. Debris fan size is controlled by accomodation space availible in valley bottoms, not drainage basin area as has been demonstrated for debris and alluvial fans deposited in unconstrained valleys. Valley bottom width is influenced by changes in geology where variation in lithology provides variation in erosional resistance. Models of fan reworking and fan-river linkage were developed to further relate mainstem slope with debris fan frequency. Fan river linkage is defined by a connectivity between tributary processes and the mainstem river through an incised channel, and the presence of reworked gravel bars associated with debris fans. Debris fan frequency rather than area explains the steep gradient of the Green River in fan-eddy dominated reaches.

Furthermore, where debris fans are incised with channels coarse sediment is delivered directly to the river debris fans create a steeper mainstem gradient. Reaches with debris fans and frequent gravel bars are responsible for the steep gradient of the Green River through Desolation and Gray Canyons.

Introduction

Hillslopes and channels are linked at the base of slopes and at tributary mouths. At these points, hillslope processes deliver hillslope-derived sediment to the channel, resulting in adjustments in the main channel and downstream. Sediment transfer from hillslopes to channels is a stochastic process that varies with climate, geology, and topography. A continuum of types of linkages exists from small-scale hillslope rills, to mass failures that block or constrain streamflow in a valley, to perennial tributaries that deliver a coarse tributary load to a master stream and thereby reset the longitudinal pattern of downstream fining (Rice, 1994). One type of linkage occurs where debris flows from steep tributaries enter the valley of a master stream. At these junctions, the hydrologic and geologic processes of the tributary drainage that give rise to debris flows become linked with the processes of the master stream influencing its water and sediment flux. At the linkage point, tributary and mainstem processes combine to define the mainstem's geomorphic organization.

The purpose of this paper is to describe the linkages that occur as tributary catchments join the master stream of a canyon on the Colorado Plateau. The study reach is Desolation and Gray Canyons on the Green River in east-central Utah. In Desolation and Gray Canyons, variation in catchment and geologic characteristics in tributaries and variation in geologic characteristics in the master valley cause longitudinal patterns in the geomorphic organization of the Green River. In this system, catchment-scale processes interact with the geologic control of valley width to create distinctive attributes of mainstem channel form. I explore the relationship between debris fans and the Green River at several scales, focusing on the tributary catchments, debris fans, characteristics of the river valley, and their effects on the mainstem Green River channel.

Previous research

Catchment processes: debris-flow initiation and frequency

Debris flows are an important sediment delivery process that connects hillslopes to fluvial channels in a wide variety of climatic settings in high relief regions such as the arid southwestern United States (Blackwelder, 1928; Hooke, 1967), the Appalachian Mountains (Miller, 1990), the Pacific Northwest (Pierson, 1982; Benda, 1990; Grant and Swanson, 1995), the Idaho Batholith (Meyer et al., 2001), and the Colorado Plateau (Cooley et al., 1977; Webb et al., 1988; Cannon et al., 2001). Steep slopes, fine-grained source material, and a means of saturation are important factors related to debris-flow initiation (Costa, 1984). Initiation sites on hillslopes often have slopes between 25-40° (Johnson and Rodine, 1984). Abundant source material in the form of thick colluvial soils, weathered bedrock, and colluvium-filled hollows are necessary for debris-flow initiation (Johnson and Rodine, 1984). Source-material saturation occurs through high intensity rainfall events, rain-on-snow events, or ground-water infiltration (Caine, 1980; Costa, 1984).

In Grand Canyon National Park on the Colorado Plateau, four mechanisms of debris-flow initiation have been identified to occur: 1) failure of weathered bedrock; 2) the "firehose effect"; 3) colluvial wedge failure; and 4) combinations of these processes (Griffiths et al., 1996, 1997). The "firehose effect" occurs where a stream of water from an upslope area saturates a pile of colluvium is stored at the base of cliffs, initiating a debris flow (Johnson and Rodine, 1984). Many debris flows in Grand Canyon, especially those occurring after intense rainfall events, occur from a combination of these trigger mechanisms (Griffiths et al., 1996). Precipitation is an important factor for debris-flow initiation in Grand Canyon. Debris flows have occurred in Grand Canyon with rainfall events with intensities greater than 20 mm/hr, with event totals ranging between 25 – 50 mm (Melis et al., 1995). Debris-flow generating storms in Grand Canyon have been both localized and regional, including summer monsoon thunderstorms, dissipating tropical cyclones, and winter frontal storms (Melis et al., 1995). Rain-on-snow events on high-elevation areas near the canyon rim are believed to increase runoff over cliffs in winter and spring (Melis et al., 1995).

Debris-flow frequency is highly variable and depends on local geology, climate, and disturbance history. Disturbed landscapes, such as areas affected by fire, human development, or volcanic eruptions tend to have a higher frequency of debris flows than undisturbed lands (Pierson, 1982; Wohl and Pearthree, 1991; Meyer et al., 1995). In Grand Canyon, the overall recurrence interval between debris flows varies between 30-50 years, and there is a higher rate for eastern Grand Canyon tributaries of 10-15 years (Webb et al., 1996).

Debris fans and their depositional settings

Fan-shaped landforms that are primarily built by debris flows are often termed debris-flow fans or debris fans (Schumm et al., 1987; Whipple and Dunne, 1992). Like alluvial fans, debris fans are deposited where a channel undergoes a transition from confinement in an upland drainage basin to a wider valley where deposition can occur, such as a mountain front or where a tributary enters a master valley. Sediment is deposited at this point, because supply exceeds transport capacity (Harvey, 1990). Debris fans occur in a range of physiographic, geologic, and climatic settings, and these settings give rise to a wide variety of debris fan sizes, shapes, and slopes (Leece, 1990; Harvey, 1990; Blair and McPherson 1994; Mills, 2000).

Pioneering research describing relationships between watershed characteristics and debris fan form was conducted by Bull (1964), who demonstrated power function relations between tributary catchment area and fan area, as well as catchment slope and fan slope. Bull also showed that relief, lithology, and climate created distinctive watershed processes that led to distinctive debris flow characteristics. Such relations apply to fans that form along mountain fronts in large structural basins where there are few constraints to fan size (Bull, 1964; Harvey, 1990; Leece, 1990; Blair and McPherson, 1994). These fans tend to be very large, with radii on the order of several kilometers.

Debris flows occur and build fans in other physiographic settings, however, and fan size can be more limited where debris flows enter narrow valleys. Debris fans that form in intramontane valley settings occur at tributary valley junctions (Kostaschuck et al., 1986; Harvey, 1990; Kochel, 1990; Sorrisio-Valvo et al., 1998; Milana and Ruzycki, 1999; Taylor, 1999; Mills, 2000). Intramontane valley fans have been well studied in the

Appalachians where narrow valleys control their size and shape (Kochel and Johnson, 1984; Kochel, 1990; Mills, 2000; Taylor, 1999). Mills (2000) recognized that many tributary junction fans in the Appalachians are not fully accommodated in a master stream valley but a m occupy the lower part of the tributary valley as well. He called these intrabasinal fans (Mills, 2000).

Debris flows provide ixture of clay to boulder-sized sediment and build debris fans in the mainstem valley, constricting the Colorado and Green Rivers and creating most of their rapids. These debris fans range widely in size and shape. Hereford et al. (1996) described debris flows in Grand Canyon as: 1) fan forming, resulting in large, broad, and flat fan surfaces, and 2) channelized, which are smaller in area and dissect the broad fan surfaces and form fans at the mouths of the channels (Hereford et al., 1996). In the eastern Uinta Mountains, Martin (2000) determined all historic debris flows were channelized.

Debris fans on the Colorado and Green Rivers are deposited in valleys much wider than the depositional settings of the Appalachians, but much narrower than the structural basins of the Basin and Range. Thus, relations between watershed characeristics and fan size are potentially confounded by the width of the master valley, and fan size is not a simple function of drainage basin area. One objective of our research is to define this relationship. Martin (2000) found the size of debris fans to be dependent on the lithology and structure of mainstem and tributary canyons. Larger debris fans occur at the mouths of tributaries located along large faults in a wide section of the mainstem canyon in Lodore Canyon (Martin, 2000).

Studies of debris-fan/mainstem river interaction: the linkage point

Debris fans deposited in valleys often experience post-depositional modification by higher order streams (Kochel, 1990). Fan-truncation and lateral erosion have been documented in many settings, including the Shenandoah Valley in the Appalachians (Kochel; 1990; Whittecar and Ryter, 1992; Mills, 2000), the Bow River Valley in Alberta (Kostaschuck et al., 1986), and Yellowstone National Park (Meyer et al., 1995). Complex inset relationships can result from fan and stream interaction over time leading to fan-cut stream terraces. Narrow valleys in the Appalachians often experience lateral fan erosion and truncation leading to interfingered master-stream and debris fan deposits (Mills, 2000). Debris flow deposits affect the distribution of sediment in channels and valley floors in the Oregon Coast Range (Benda, 1990). Grant and Swanson (1995) defined a model in which debris fans have varying effects on channels related to the valley width of depositional sites. Benda (1990) found 65% of meanders in third and fourth order streams to be associated with debris fans.

Landform and process scale are key factors in determining the relative amounts of fan preservation and reworking. A small stream in a wide valley may meander around a large fan with minor post-depositional modification or change in mainstem slope (Germanoski and Barclay, 2000). Conversely, the longitudinal profile of a small stream that flows in a narrow valley may be controlled by the spatial distribution of debris flow deposits. The ratio of depositional valley width to master stream width, as well as fan width to valley width, are important factors in determining the effectiveness of master stream reworking.

Perhaps the process of main-stem and debris-fan interaction on a large river is most striking on the Colorado River in Grand Canyon. Tributary debris fans constrict the river and create large rapids over its 445-km course from Lees Ferry, downstream from Glen Canyon Dam, to the Grand Wash Cliffs (Powell, 1875; Dolan et al., 1978; Webb et al., 1988). John Wesley Powell was the first geologist to encounter these rapids and observe that large rapids occurred at tributary mouths, although he did not recognize debris flows as the process responsible for the transport of large boulders to the Colorado River (Powell, 1875; Melis et al., 1995). Large debris-flow events occurred in several locations in Grand Canyon in the winter of 1966, and Cooley et al. (1977) were the first to document debris flows as a process responsible for debris fan aggradation and rapid formation. The correlation between tributary debris-flow processes and the formation and reworking of rapids in Grand Canyon was not well understood until over a century after Powell's first observations (Howard and Dolan, 1981; Kieffer, 1985; Webb et al., 1988).

Howard and Dolan (1981) related the canyon's rock type and structure to tributary and rapid location, and argued that geology ultimately controls the locations of fine-grained sediment deposition in eddies upstream and downstream from rapids. Debris fans have been shown to influence the Colorado River in Grand Canyon over the length of a fan-eddy complex (Schmidt and Rubin, 1995). This sequence of deposits consists of an upstream backwater of ponded flow and fine-grained terraces and eddy deposits, a rapid of turbulent flow and coarse material located at the point where the fan constricts the river, a downstream region of recirculating flow and fine-grained sediment deposition, and a downstream gravel bar consisting of reworked debris flow material.

In the canyons of the eastern Uinta Mountains, Grams and Schmidt (1999, 2002) argued that the number of debris fans controls river gradient; steeper reaches havemore debris fans. Grams and Schmidt (1999) found that 76% of the rapids in Lodore, Whirlpool, and Split Mountain Canyons to be constricted by tributary fans, and the remaining 24% to be constricted by expansion gravel bars downstream from debris fans. Debris-fans do not control geomorphic organization in all bedrock canyons of the major rivers draining the Colorado Plateau, however. On the Green River, the confluences of large, low-gradient tributaries such as the Yampa, Duchesne, and White Rivers have little influence on mainstem gradients (Harden, 1983). Debris fans do not exhibit strong control in Labyrinth and Stillwater Canyons on the Green River (Harden, 1983; Schmidt and Rubin, 1995), because tributaries in these reaches do not support debris flows. These tributaries drain the Green River desert, which do not produce significant runoff nor coarse sediment.

Desolation and Gray Canyons

The first scientific expedition to explore the Green River through Desolation and Gray Canyons and encounter its rapids was led by John Wesley Powell in 1869 (Powell, 1975). A survey crew from the United States Geological Survey, including hydraulic engineer R. R. Wooley, and geologist J. B. Reeside, floated the Green River from Green River, WY, to Green River, UT, in 1922 (Wooley, 1922; Reeside, 1923). The principal products of the 1922 trip were 5-ft contour water surface survey maps of the plan and profile of the Green River with 20-ft contours of the adjacent canyon topography (U. S. Geological Survey, 1924). These maps still provide the most accurate available longitudinal profile of the Green River. A second scientific river expedition in 1940 by the Bureau of Reclamation, led by geologist M. Merriman, collected detailed data on potential dam sites in the canyons between Ouray, UT, and Green River, UT. Both Wooley (1922) and Merriman (1940) observed that rapids with coarse debris generally occurred at tributary junctions.

Orchard and Schmidt (1998) mapped deposits in the river corridor, repeated historical photos, and surveyed 22 cross sections in four 8-km study reaches of Desolation and Gray Canyons. This research was done in order to provide geomorphic assessment of habitat for humpback chub (*Gila cypha*), one of the endangered endemic fishes of the Colorado River basin. Reach scale surficial geolgic mapping focused on active channel and debris fan deposits adjacent to the river finding that debris fans occupy as much as 58 percent of the spatial area of the alluvial valley (Orchard and Schmidt, 1998). Graf (1979) determined that tributary locations corresponded with rapid locations in Desolation and Gray Canyons. This study explores the nature of these prominent features of Desolation and Gray Canyons, their catchment basins, depositional sites, and interaction with the Green River.

Setting

Geographic Setting

The study area is the 135-km long segment of the Green River between Sand Wash and Swasey's Rapid (Figure 1), known as Desolation and Gray Canyons. The climate is semi arid, and the region is sparsely vegetated (see appendix H for details). There is some inconsistency in identification of the upstream end of Desolation Canyon.

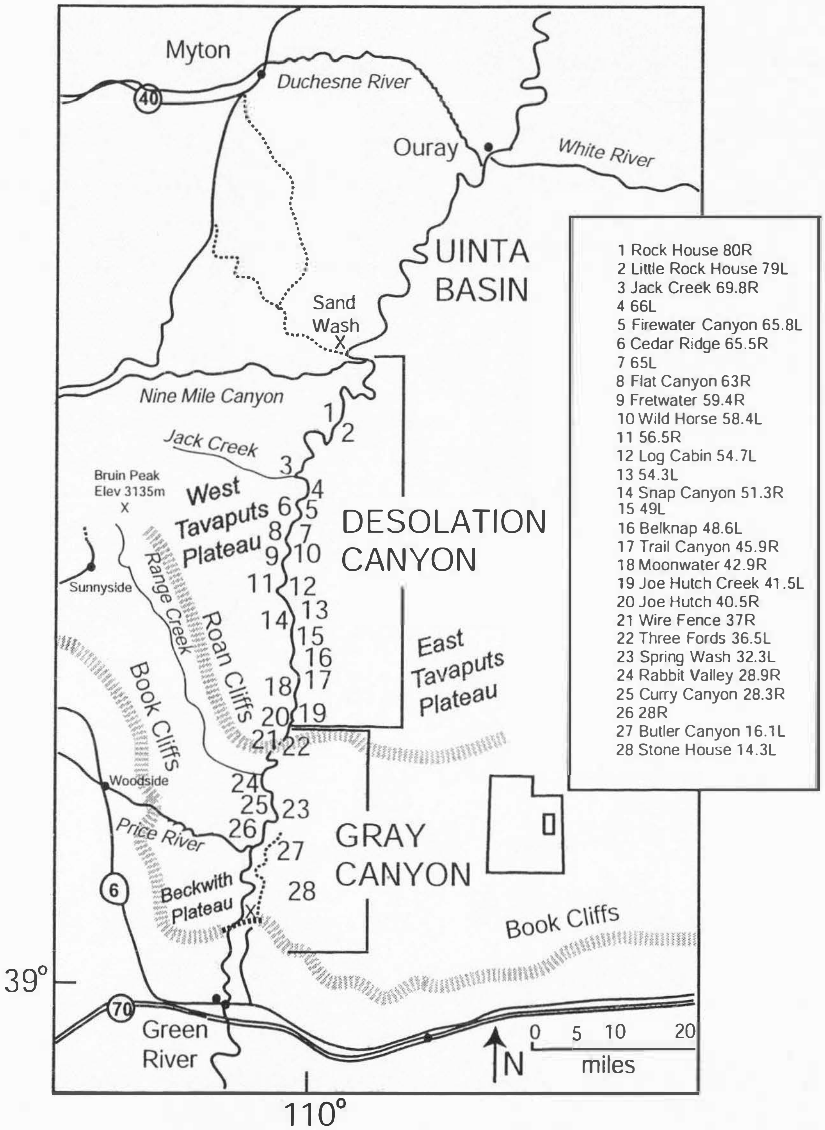

Figure 1. Map of study area with detailed study sites indicated. Fan locations indicated are site number, name, and locations, defined as river mile upstream from mile 0 located at the railroad bridge in Green River, UT.

For instance, Powell (1875) and the U.S.G.S. (1924) maps of the Green River designated Jack Creek to be the beginning of Desolation Canyon. However, Reeside (1923) designated Desolation Canyon as the reach between Nine Mile Canyon and the Roan Cliffs, and Merriman (1940) refer to the section from Ouray to the Roan Cliffs as Desolation Canyon. Belknap and Evans (1974) and Rampton (1992), both popular recreational river guides, referred to the section from Sand Wash to the Roan Cliffs as Desolation Canyon. For purposes of this study, Desolation Canyon begins at Sand Wash, and Gray Canyon begins at Wire Fence Rapid, 96 km downstream from Sand Wash (Figure 1). River elevation at Sand Wash is 1405 m and is 1250 m at Swasey's Rapid at the downstream end of Gray Canyon (Figure 2). Thus, the average slope of the Green River through the study reach is 0.00116 m/m. Locations in this report are given in river kilometers and miles upstream of Green River, UT, because that is the location scheme in common use on the Green River (USGS, 1924; Belknap and Evans, 1974; Rampton, 1992). Distances and all other measures are in the SI system.

Geologic setting

The couse of the river in Desolation and Gray Canyons is through the Cretaceous and Tertiary rocks of the Tavaputs Plateau. The river flows against the prevailing regional dip of the rocks, and elevations of the Tavaputs Plateau typically increase to the south until the Tertiary rocks are truncated by the Roan Cliffs (Figure 2). This is the approximate location where the river leaves Desolation Canyon and enters Gray Canyon near river kilometer 59.2 (river mile 37). Elevations at the drainage divide on the Tavaputs Plateau are more than 3000 m; approximately 1500 m above the Green River.

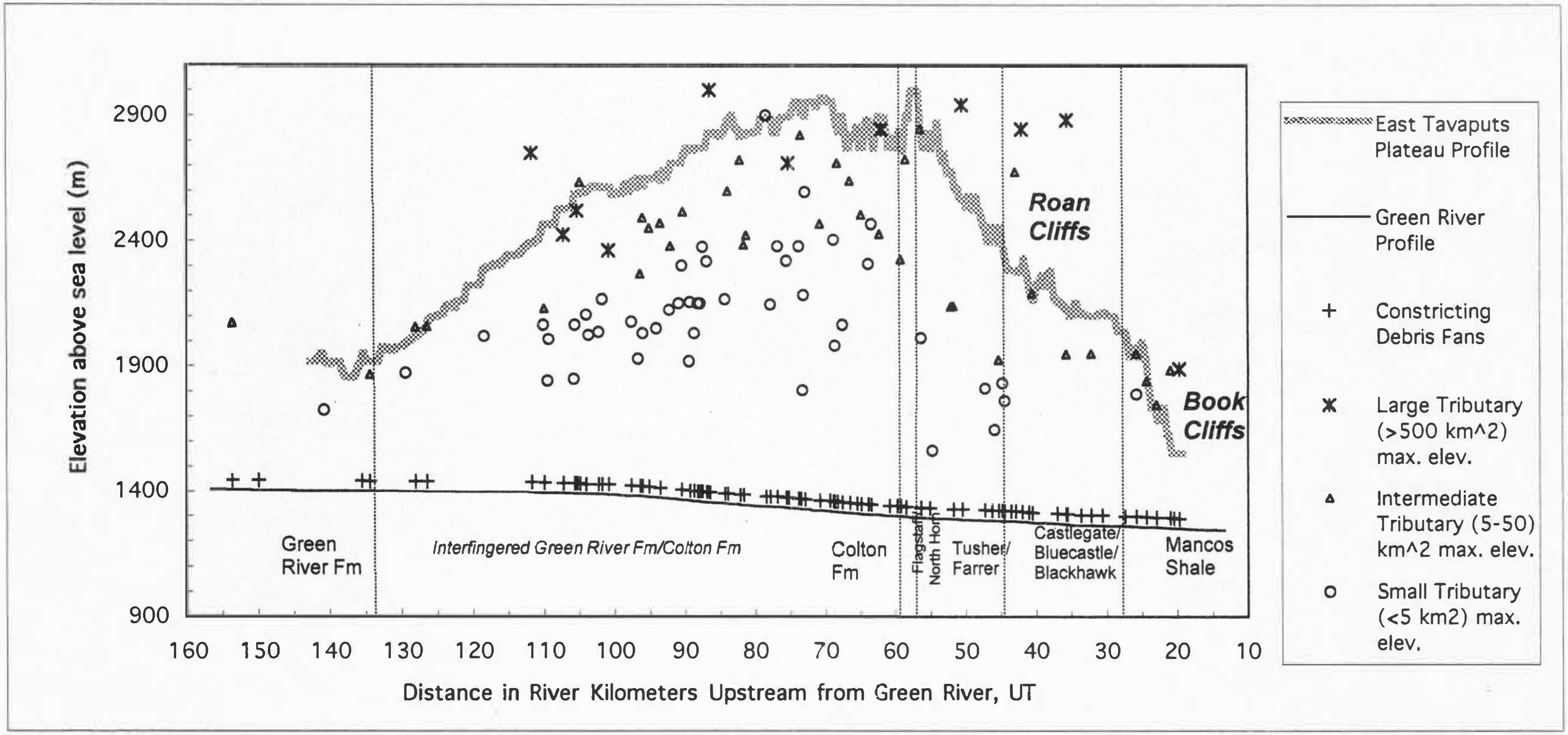

Figure 2. Longitudinal profile of Green River through the study area with elevation data from Wooley (1930). Profile of the east Tavaputs Plateau computed by extracting a cross section from a 10-m DEM. Maximum elevation of tributary basins, locations of major debris fans, and river-level geology are also shown. Vertical exaggeration is 50x.

Incision of the Tavaputs Plateau has led to high relief in the drainages that are tributary to the Green River.

The Cretaceous Mancos shale outcrops at the base of the Book Cliffs, and as one moves upstream, one moves upsection (Figure 3). Rocks have a regional northward tilt into the Uinta Basin. In Gray Canyon, the river flows through the Cretaceous Mesa Verde Group, consisting of the Blackhawk Formation, Castlegate Sandstone, Bluecastle Tongue, and the Tuscher and Farrer Formations, an alternating sequence of sandstones, limestones, and shales (Witkind et al., 1978). The less resistant rocks of the North Horn Formation, a fluvial conglomerate, and the Flagstaff Formation, a lacustrine limestone, occur above the Mesa Verde Group (Witkind et al., 1978).

The Tertiary Green River Formation in Desolation Canyon is made up of sequences of siltstones, sandstones, and mudstones deposited in an extensive lake system that once occupied the Uinta Basin, north from Sand Wash (Reeside, 1923, Rowley et al., 1979). A large north-draining fluvial system brought coarser material into the lake margins (Dickinson et al., 1986). The Colton member of the Wasatch Formation was deposited in this fluvial environment. The Colton is a relatively resistant and variable unit consisting mostly of sandstones and conglomerates, with some interbedded shales. The basal unit of the Colton Formation in the region of the Roan Cliffs is shale-rich. Sandy facies of the Green River Formation were deposited in shallower water on the lake margins to the north and are dominant in the upstream sections of Desolation Canyon. As one travels south and downstream, the Colton becomes more prevalent (Reeside, 1923; Merriman, 1940). In most of Desolation Canyon, the Colton Formation and the

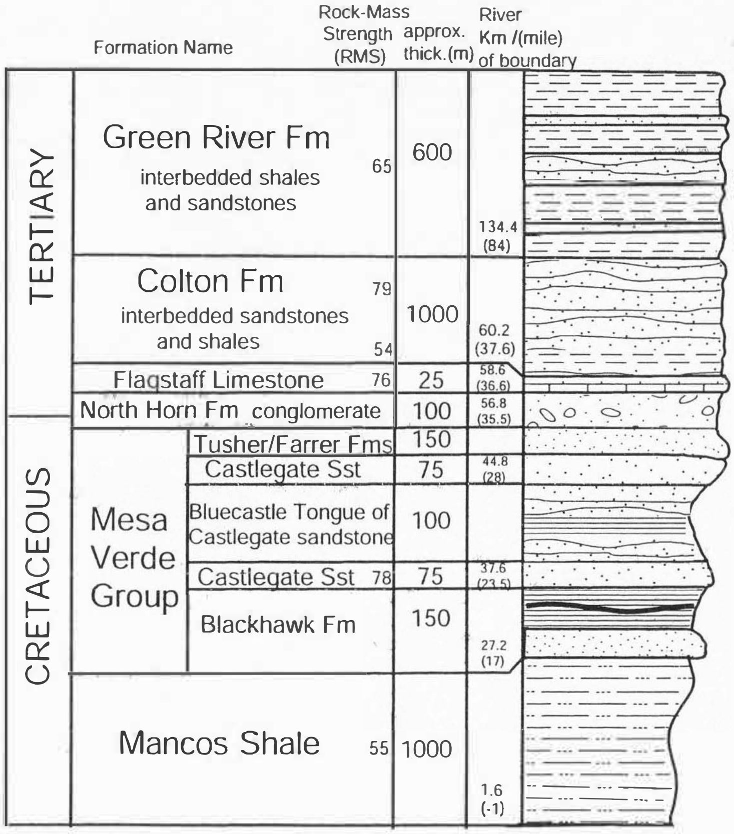

Figure 3. Stratigraphic column of Tavaputs Plateau and Book Cliffs region with approximate thicknesses, Rock-mass strength values, and river kilometers of outcrop along the Green River in Desolation and Gray Canyons. (complied from Dickinson et al., 1986, Hintze, 1988, Belknap and Evans, 1974, and Rampton, 1992)

sandy facies of the Green River Formation are extensively interfingered (Belknap and Evans, 1974; Dickinson et al., 1986).

Methods

Mapping

Various methods were used to characterize and examine the debris fans of Desolation and Gray Canyons, their catchment basins, depositional sites, and attributes of the Green River. The catchment basins were primarily examined through the analysis of 10-meter digital elevation models in a geographic information system. Debris fan and Green River channel and valley characteristics were examined using a map database created for this study. Field investigation was used to aid and verify mapping, and in the collection of detailed surveys of the debris fans.

A surficial geologic map of 134-km of the Green River valley was created for this study and entered into a geographic information system (Plates 1 and 2). The map base was established using digital elevation map data derived from 10-meter scale USGS digital elevation models of the field area. Contour maps were created and overlain on digital orthophoto quadrangles taken in July 1987 at a discharge of 255 m^3/s . Mylar overlays on 1:5000 stereo aerial photograph pairs taken of the field area on October 5, 1993, at a discharge of 55 m^3/s were used to map 75 debris fans and adjacent Green River deposits in the field. River deposits visible in the aerial photographs but submerged on the map base were mapped as submerged deposits. Map unit polygons were digitized and entered into the GIS. Map units include debris fans and their related channels, as well as mainstem gravel bars, sandbars, and fine-grained river terraces, talus and other colluvial units in the Green River valley were also mapped. All air photo series used in mapping are listed in appendix I.

Cataloging of significant tributaries

Tributaries that intersect the bedrock valley of the Green River were catalogued to create a database of debris-fan and drainage basin attributes. Criteria similar to those defined by Melis et al. (1995) for tributaries in Grand Canyon were used to determine "geomorphically significant tributaries." Geomorphically significant tributaries are those drainages that have a potential to produce debris flows or significant amounts of streamflow sediment where they intersect the valley of the mainstem Green River. These tributaries generally have drainage areas larger than 0.01 km^2, stream channels that are designated on USGS topographic maps as perennial or ephemeral, clearly terminate at the mainstem river in a single channel, or contribute to the formation of obvious debris fans or rapids (Melis et al., 1995). A list of all the geomorphically significant tributaries in Desolation and Gray Canyons is included in appendix A.

Catchment analysis

Analysis of the tributary drainages in the study area was performed using merged 10-m digital elevation models. Stream networks were generated using flow direction and flow accumulation commands in Arc Grid. Once drainages were delineated, areas were derived for all 164 tributaries in the study area. Basin relief and basin length/width ratio were measured for 96 representative drainages, comprising about 60% of all geomorphically significant tributaries. Longitudinal profiles of these 96 drainages were created by overlaying a clipped trunk stream coverage on an elevation grid. The resultant longitudinal distances and elevations were exported to a spreadsheet to derive channel relief and gradient. Drainage basin channel gradient was calculated as basin relief divided by drainage basin length. An additional metric to characterize the percent of steep terrain in a catchment near the river corridor was measured using Arc View and Arc Info. A threshold distance of 1000 meters from the channel was used based on debris flow initiation data available for Grand Canyon National Park (Melis et al., 1995). A threshold slope value of slopes >35% was used to characterize steep terrain. These data sets were combined to determine the percent of a tributary drainage with slopes greater than 35% within 1000 meters of the Green River. Catchment characteristics of Desolation and Gray Canyon's geomorphically significant tributaries are found in Appendix B.

Valley characteristics

Rock type in Desolation and Gray Canyons was determined from geologic maps and river guides (Reeside, 1923; Witkind et al., 1978; Belknap and Evans, 1974). Bedrock hardness was determined semi- quantitatively using a measure of rock mass strength (RMS) according to the methods of Selby (1993). Measurements of RMS collected by Roberson and Pederson (2001) for the major bedrock units in Desolation and Gray Canyons were used in this study. Supplemental RMS data was collected for the rock units exposed in the Mesa Verde Formation and Mancos Shale using a Schmidt Hammer and various indices of rock weathering according to the methods of Selby (1993). Valley bottom characteristics for geomorphically significant tributaries are listed in appendix C.

Mainstem Green River valley-bottom width was determined by measuring the width between bedrock walls on the GIS database in Arc View. Widths measured at the upstream and downstream limits of each fan as well as the fan midpoint were averaged to determine valley width at each tributary junction. Tributary valley widths were also measured in Arc View where they intersect the mainstem valley.

Detailed fan characteristics

Detailed data to characterize debris fans were collected during river expeditions to the field area. These trips were conducted when the discharge of the Green River was between 40-250 m^3/s; a majority of these trips were conducted at discharges less than 42.5 m^3/s, which facilitated mapping of river deposits.

Surveys of fan topography were conducted on 28 fans using a Topcon geodetic total station. Where fans are incised by a channel, topographic cross-sections were surveyed at the fan apex, near the fan midpoint, and fan mouth, and at the 42.5 m^3/s water surface line. These measurements were used to determine: 1) the elevation of the fan apex, or the highest elevation point on the fan surface within the bedrock valley of the Green River, 2) the degree of channel incision, measured from the fan surface to the base of the channel at the apex, midpoint and mouth, 3) the height of a debris-fans cutbanks above mainstem river level, and 4) the respective slopes of the fan surface and fan-channel. All measurements are relative to the 42.5 m^3/s water level, a common late-summer low water level discharge of the Green River in Desolation and Gray Canyons. Debris fan characteristics and measurements are included in appendix D.

Grain size of these 28 debris fans was also characterized. The intermediate axis diameter for 100 particles was measured on the reworked portion of a debris fan exposed at 42.5 m^3/s on transects parallel to the river channel. Measurements were made every 0.25 m and where large boulders occurred only one measurement was made. The b-axis of the 10 largest boulders on the reworked portion of debris-fans exposed above 42.5 m^3/s was also measured. Gravel counts to characterize the grain sizes of reworked downstream gravel bars were also performed using the methods of Wolman (1954). Grain size data is reported in appendix J.

Attributes of fans and rapids

The locations of tributary junctions with the Green River were assigned river miles to the nearest 0.1 mi based on the river mile distance upstream from Green River, UT (Belknap and Evans, 1974, Rampton, 1992). Names of tributaries and rapids were determined from river guides and the 9 USGS 7.5-minute topographic maps of the river corridor in the study reach.

Many fan and river attributes were collected for each fan in the database using methods similar to Melis et al. (1995) and Martin (2000). Most of the attributes collected from the map database were established directly from the 1987 digital orthophotos. Therefore, channel width measurements and rapid lengths were collected for a fairly high discharge of 255 m^3/s. Plan-view fan area was determined from the GIS map database. Locations where debris fans from multiple drainage basins coalesce in the Green River valley were mapped in the field to determine subtle differences in the slopes and boundaries of these fans. Fan shape was characterized by measuring the ratio between the maximum length of the fan parallel to the river channel and the width of the fan perpendicular to the river.

Green River channel widths upstream and downstream from the most constricted portion of the debris fan were made and averaged to determine average channel width at the river discharge of 255 m^3/s at each debris fan in the study reach. Constriction of the Green River at each debris fan was calculated using these channel width values using the methods of Webb et al. (1996). Webb et al. (1996) use Cw:

$$Cw = [1 - 2Wr/(Wu+Wd)] \times 100 \qquad (1)$$

where Cw is constriction width, Wr the channel width at the rapid, Wu the constriction width in the upstream backwater, and Wd the channel width in downstream of the debris fan. Fan and rapid attributes for each fan eddy complex are listed in appendix E.

Results

I. Characteristics of tributary drainages to the Green River

There are 164 geomorphically-significant tributaries that join the Green River in the 135-km long study area. The frequency of 1.2 geomorphically-significant tributaries per river kilometer is comparable to the frequency of such tributaries in Grand Canyon (Schmidt et al., 2002). The geologic and topographic characteristics of these tributary basins ultimately determine the effect that catchment processes of the Tavaputs Plateau have on the Green River.

Two tributaries the Price River and Minnie Maud Creek have no evidence of debris flows reaching the Green River, and their drainage areas are largest and gradients the lowest. The Price River has a drainage area of 3,988 km^2 and heads on the Wasatch Plateau, 150-km northwest from its confluence with the Green River. The Price River has a mean annual discharge of 4.87 m^3/s, as gaged near its confluence with the Green River at Woodside, UT (US Geological Survey gaging station 09314500), and its valley separates the Beckwith Plateau from the Book Cliffs itself. Only 7.5% of the terrain in Price River's drainage within 1000 meters of the Green River contains steep slopes (greater than 35%). The Price River has a bed of sand and gravel and a slope of 0.00398 m/m at its confluence with the Green River. Although there is no debris fan at its mouth, a gravel bar occurs immediately downstream from its confluence with the Green River.

Minnie Maud Creek flows in Nine Mile Canyon and drains the northern part of the West Tavaputs Plateau. It has a basin area of 1156 km^2, and its perennial flow is ungaged. Minnie Maud Creek's gradient near the mouth of 0.00758 m/m is nearly twice as steep as the Price River. Minnie Maud Creek's catchment within 1000 meters of the Green River, like the Price contains a relatively small percentage of steep slopes (7.8%). This creek forms a large alluvial fan where it enters the valley of the Green River, and the surface of this fan has several fine-grained alluvial terraces established across its surface. There is no evidence of debris flows having occurred near the mouth of this stream.

The other 162 tributaries draining the Eastern and Western Tavaputs Plateaus produce debris flows that can reach the Green River. The largest drainage of these tributaries is Range Creek at 369 km^2, and the smallest drainage is 0.09 km^2. We defined large basins as those draining areas between 50 and 500 km^2, intermediate basins as those with areas between 5 and 50 km^2, and small basins as those whose basin are less than 5 km^2 (Figure 4). The geographic arrangement of these basins consists of the intermediate and small basins nested within an exterior framework determined by the large basins, as well as the Price River and Minnie Maude Creek (Figure 5). Therefore, the mouths of tributaries draining large basins are separated by longer distances along the Green River than are the distances between tributaries draining small basins (Figure 6). Large percentages of the terrain within 1000 meters of the Green River in tributaries that support debris flows includes steep slopes (Table 1).

Large tributary basins typically have the highest total relief, the lowest basin-average gradient of the main channel, and the lowest gradient of the channel at the confluence of the Green River (Table 1; additional drainage basin data available in the appendix). Total drainage lengths for large basins are between 15 and 40 km from the Green River. Total relief in large basins is between 640 and 1650 m above the Green River and exceeds that of smaller basins. The slopes of tributary channels draining the large basins are between 0.012 and 0.046 m/m at their mouth.

The long distance between the headwaters of these large basins and the Green River and the low slope of these channels where they enter the Green River Valley are such that debris flows initiated in the far headwaters of these basins typically do not reach the Green River. Field inspection, however, indicates that each of these tributaries have had some debris flows that have reached the Green River. No systematic investigation was taken to determine debris-flow initiation sites, but most of these basins include high gradient terrain relatively near the Green River, which is the most likely source of debris flows that might reach the Green River (Table 1). Field evidence also suggests that

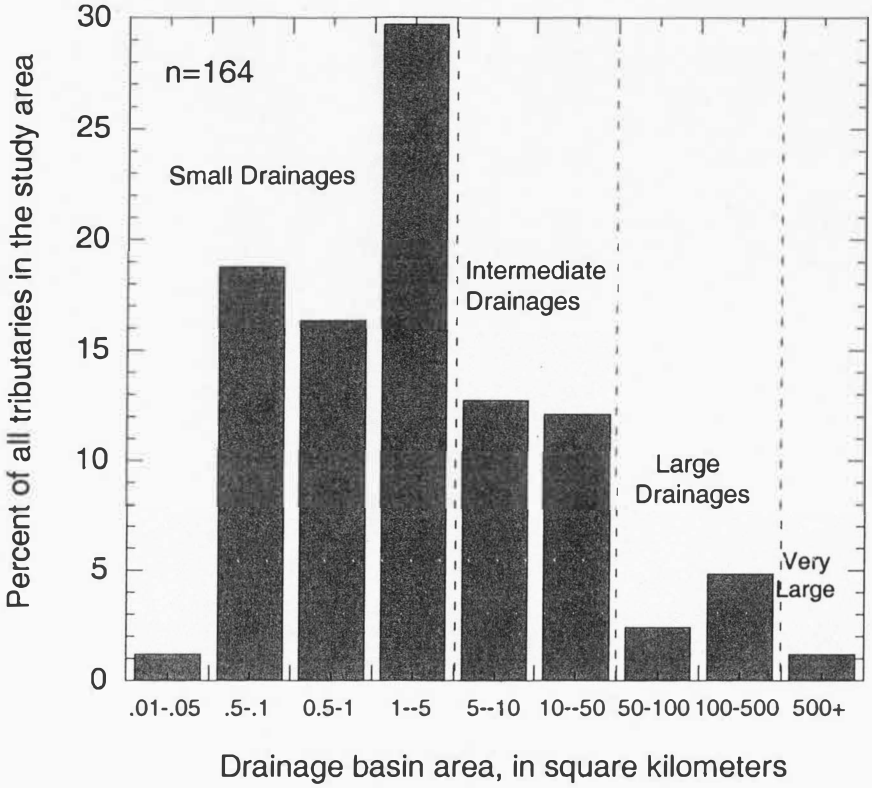

Figure 4. Histogram of drainage areas of tributaries in the study area. The mean basin size is 40.18 km^2. The median basin area is 1.69 km^2.

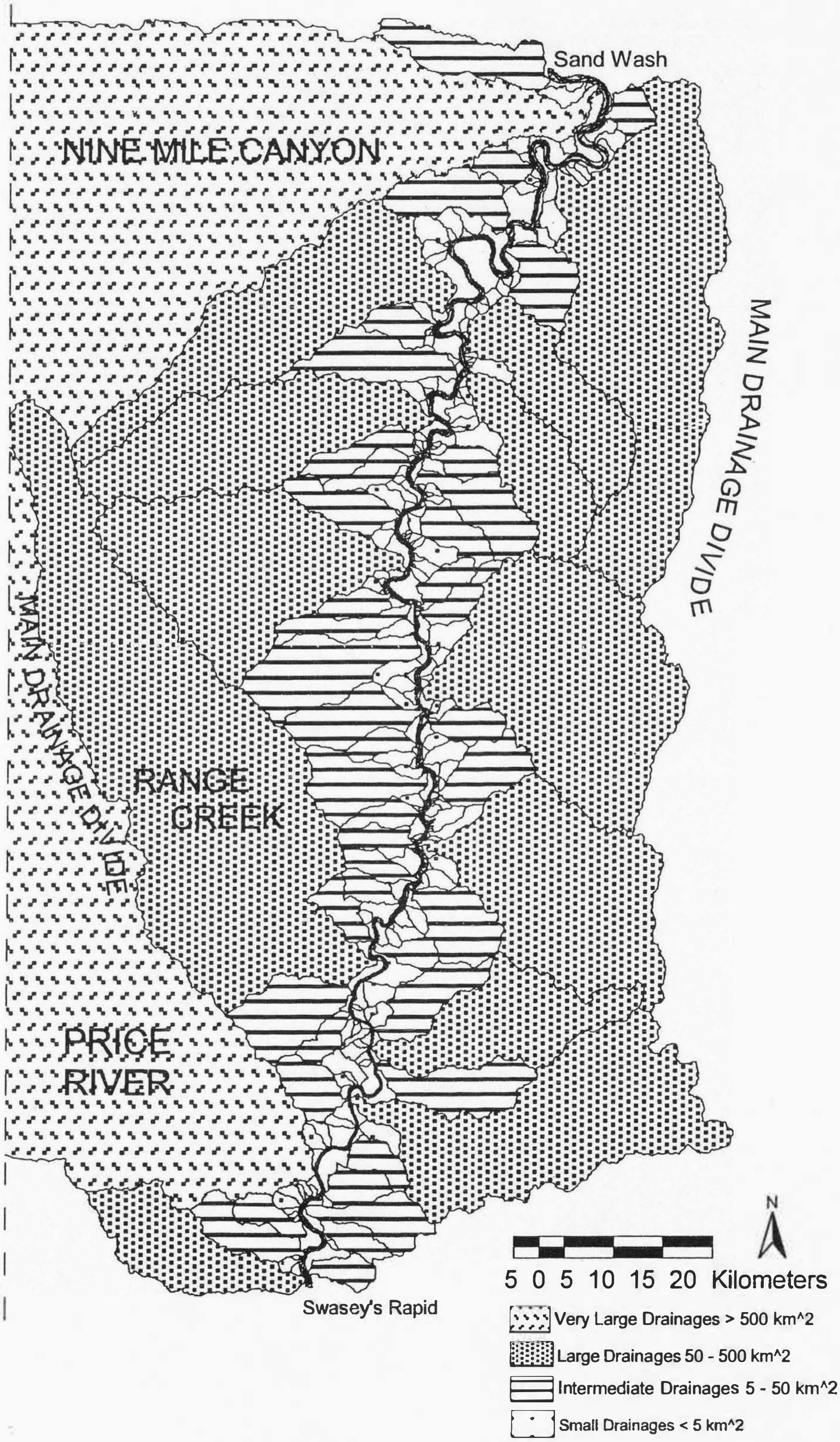

Figure 5. Map of tributary drainage basins that contribute sediment to debris fans and alluvial fans in the Green River's valley. The basins of Price River and Nine Mile Canyon extend west from the map area.

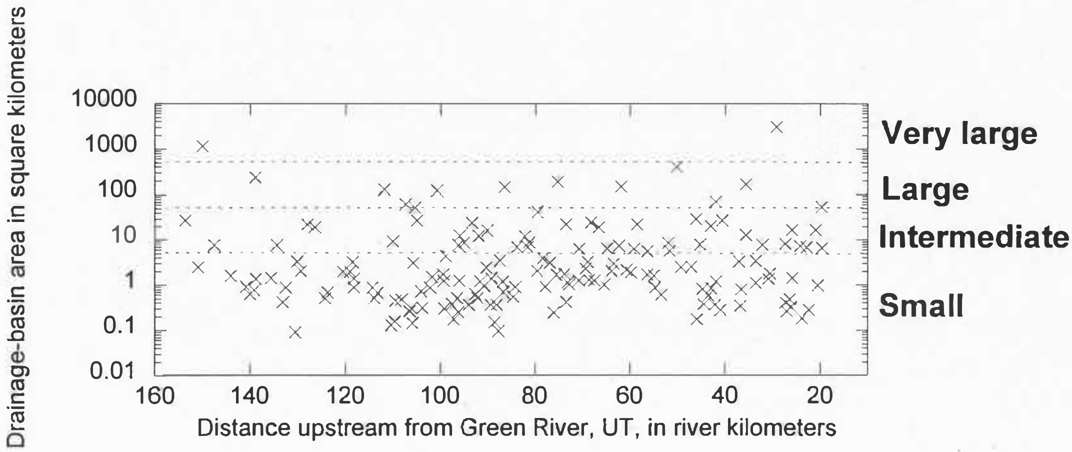

Figure 6. Variation in tributary drainage area.

flows that might reach the Green River (Table 1). Field evidence also suggests that debris-flow sediment from sites close to the river are more likely to contribute to debris fans. For example in Desolation Canyon, Jack Creek is a low-gradient, high-order tributary with steep terrain adjacent to the river. Low-order drainages that drain this steep terrain form small debris fans in the Jack Creek valley that contribute sediment to the main Jack Creek debris fan. Such small high gradient sub-drainages are likely to support debris flows that enter the Jack Creek channel and ultimately reach the Green River than distant headwaters.

Intermediate-sized basins have other basin characteristics in between those of large and small size basins (Table 1). These basins are geographically nested within the space between the large basin divides and the Green River (Figure 5). Total relief of these basins is between 460 and 1500 m. Channel slopes at their mouths range between 0.019 and 0.066 m. These drainages include named tributaries such as Cedar Ridge Canyon, Wire Fence Canyon, and Three Fords Canyon. The majority of these tributaries

TABLE 1

Drainage-basin data for selected debris fans

Drainage Name and River Mile[1]	Drainage Basin Area (km^2)	Drainage channel gradient	Basin Relief (m)	Basin Length (km)	Basin Shape (l/w)	Percent of steep slopes near river[2]
Very Large Drainages > 1000 km^2						
Price River	3988	0.00398	1738	131.2	2.7	7.5%
Nine Mile Canyon	1156	0.00758	1413	78.4	2.8	7.8%
Large Drainages 50-500 km^2						
Range Creek	369. 0	0.022	1845	44.6	3.0	7.9%
Jack Creek 69.8R	121.9	0.035	1354	24.0	3.3	47%
Flat Canyon 63 R	118.4	0.049	971	12.3	3.3	39%
Firewater Canyon 65.8L	50.6	0.053	1128	14.6	2.6	44%
Mean of size class	*143.0*	*0.0493*	*1318*	*19.4*	*2.4*	*34%*
Intermediate Drainages 5-50 km^2						
Rabbit Valley 28.9R	28.7	0.052	656	8.6	1.4	19%
Cedar Ridge Canyon 65.5R	26.2	0.055	1241	12.3	3.3	39%
Wild Horse Canyon 58.4L	23.2	0.084	1092	9.2	2.2	41%
Trail Canyon 45.9R	22.6	0.106	1490	9.2	2.8	36%
Three Fords Canyon 35.5L	22.4	0.092	1423	6.9	1.3	10%
Rock House Canyon 80R	22.1	0.037	653	8.6	2	25%
Joe Hutch Creek 41.5L	19.2	0.134	1320	7.1	1.6	39%
Little Rock House Canyon 79L	18.9	0.058	658	15.3	3.1	23%
Butler Canyon 16.1L	16.5	0.046	691	9	2.1	27%
Snap Canyon 51.3R	11.8	0.096	1372	9.6	5.7	51%
Fretwater 59.4R	8.4	0.142	1066	6.1	2.2	36%
Stone House 14.3L	7.0	0.099	496	3.2	1.1	14%
Joe Hutch Canyon 40.5R	6.6	0.139	1191	5.6	2.5	22%
Wire Fence Canyon 37R	6.4	0.109	1025	5.6	2.6	1%
Mean of size class	*14.1*	*0.098*	*977*	*6.9*	*2.4*	*30%*
Small Drainages < 5km^2						
Spring Wash Canyon 32.3L	5.7	0.098	848	4.6	2	8%
Unamed drainage 49L	3.8	0.243	1345	2.9	1.5	48%
Log Cabin 34.7L	3.4	0.287	1012	3.2	2.3	54%
Unamed drainage 66L	3.0	0.304	673	3.2	2.5	53%
Unamed Drainage 56.5R	2.4	0.201	931	2.9	2.3	49%
Moonwater Canyon 42.9R	1.2	0.173	663	2	2.9	23%
Unamed drainage 54.3L	1.1	0.320	979	2	1.8	39%
Belknap Falls 48.6L	0.9	0.304	808	1.5	1.1	54%
Unamed drainage 28R	0.7	0.297	551	2.1	2.7	11%
Unamed drainage 65L	0.7	0.310	717	1.5	2.6	56%
Curry Canyon 28.3R	0.09	0.095	642	4.6	2.3	8%
Mean of size class	*1.2*	*0.260*	*730*	*2.0*	*2.1*	*37%*

[1] River mile upstream from the railroad bridge at Green River, UT; [2] Percent of catchment area within 1000 meters of river with slopes greater than 30 percent.

have a total drainage length less than 10 km, and debris flows initiating anywhere in the basin have the potential to reach the river.

Small drainages occupy hillslope hollows, and their headwaters often do not extend to the canyon rim. Most small drainages are unnamed, however, named rapids such as Belknap Rapids, Log Cabin Rapids, and Moonwater Rapids lie at the base of small drainages. Tributaries draining these basins enter the Green River with steep gradients between 0.175 and 0.49 m/m. Debris flows initiated in these basins are likely to reach the Green River.

Although there is a general tendency of tributaries to have lower gradients if they drain larger basins, the profiles of some tributaries are determined by geologic conditions. Some tributary profiles are stepped and do not display a smooth profile (Figure 7). Cliff-forming sandstone units that control the width of the Green River alluvial valley, as discussed below cause a knickpoint at the mouths of some tributaries. Thus, the lower portions of some low gradient streams may include short channel reaches whose steep gradients may support debris flow transport.

II. Characteristics of the Green River Valley

The alluvial valley of the Green River in Desolation and Gray Canyons occupies 45.2 km^2, in the 135-km long study area and consists of the Green River and its channel margin alluvial deposits, and alluvium and colluvium from tributaries. The average width of the Green River alluvial valley is 335 m, although overall variation is between 100 and 850 m in the study area (Figure 8). The characteristics and distribution of the deposits that occur within the valley are described in the next section.

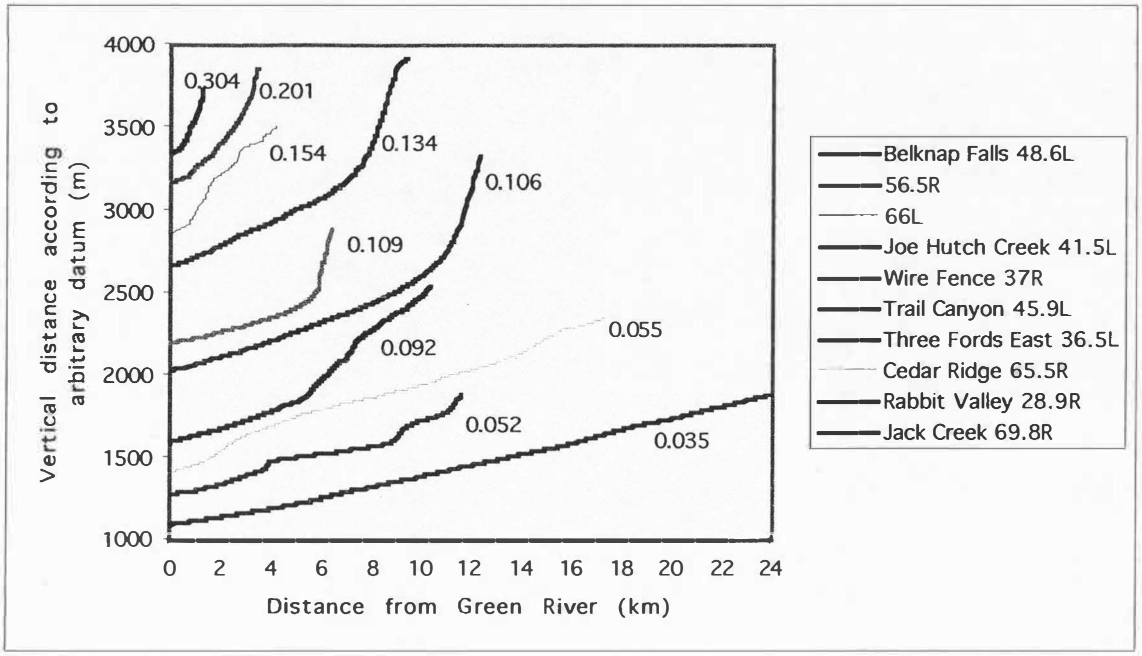

Figure 7. Longitudinal profiles of representative drainages in Desolation and Gray Canyons.

The ultimate control on valley width is the hardness of the rocks and their erodibility as controlled by faults or joints. In general, the alluvial valley of the Green River is wider where formations with lower mass-strengths occur at river level (Figure 9). Well-cemented sandstones in the Mesa Verde Formation have the highest rock mass strength. The weakest rock measured is a shale in the lowest section of the Colton Formation (Figure 3, data available in appendix K).

Bedrock geology also affects the cross-sectional profile of the canyon. Rock-type controls valley-bottom width and canyon form (Figure 10). Near-vertical canyon walls are characteristic of harder rocks such as those occurring between river kilometers 48 to 32 (Figure 10). A wider valley profile occurs where the Roan Cliffs cross the river near kilometers 64 through 51 (Figure 8). This reach of river is characterized by a wide valley inset within the main canyon. In Gray Canyon, the Mancos Shale is exposed at river level, and is capped by more resistant formations of the Mesa Verde Formation. Therefore, the valley in lower Gray Canyon is wide with near-vertical canyon walls in the high terrain above the river.

Channel width of the modern Green River does reflect major changes in the width of the alluvial valley. Channel width fluctuates between 50 m and 320 m with an average width of 120 m. The river channel is narrowest at debris fan constrictions and widest in backwaters above and expansion zones below debris fans (Figure 11). The widest channel widths occur upstream and downstream from debris fan constrictions between river kilometers 72 to 56. Channel widths are consistently less than 180 m between river

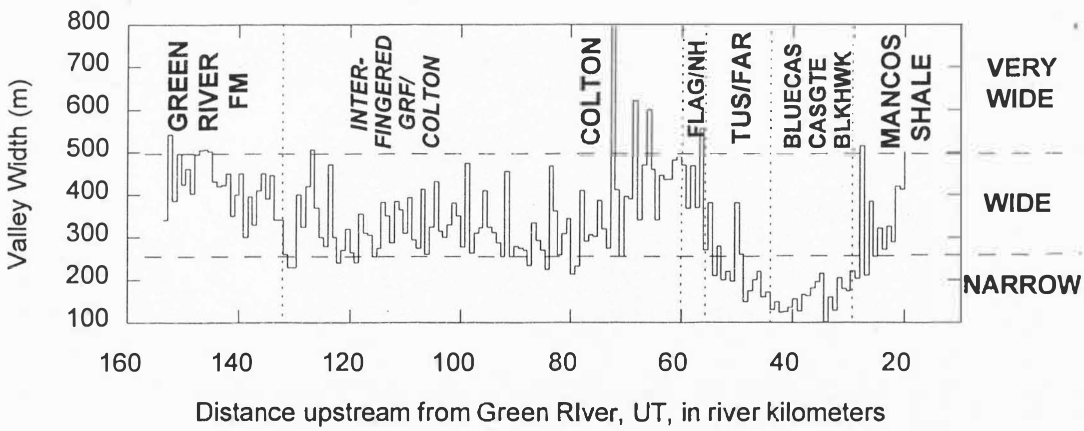

Figure 8. Variation in valley-bottom width measured every 0.5 miles along the trunk stream in the study region. Changes in bedrock lithology and narrow, wide, and very wide valley width thresholds indicated. GRF is the Green River Formation, Flag/NH is the Flagstaff Limestone and North Horn Conglomerate, TUS/FAR is the Tusher Formation and Farrer Formation, Bluecas is the Bluecastle Tongue of the CastlegateSandstone,and Blkhwk is the Blackhawk Formation.

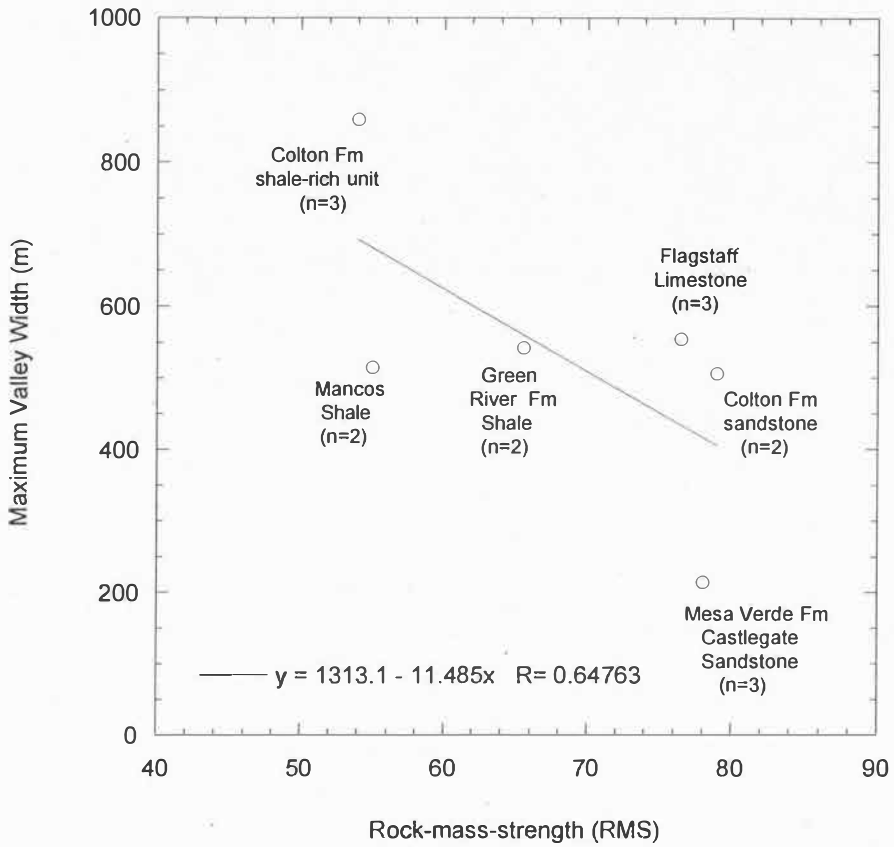

Figure 9. Rock-Mass strength and valley width relationship for rock units exposed in Desolation and Gray Canyons. Data for rock units in Desolation Canyon from Roberson and Pederson (2001) Gray Canyon RMS values (Castlegate Sandstone and Mancos Shale) Raw data in appendix K.

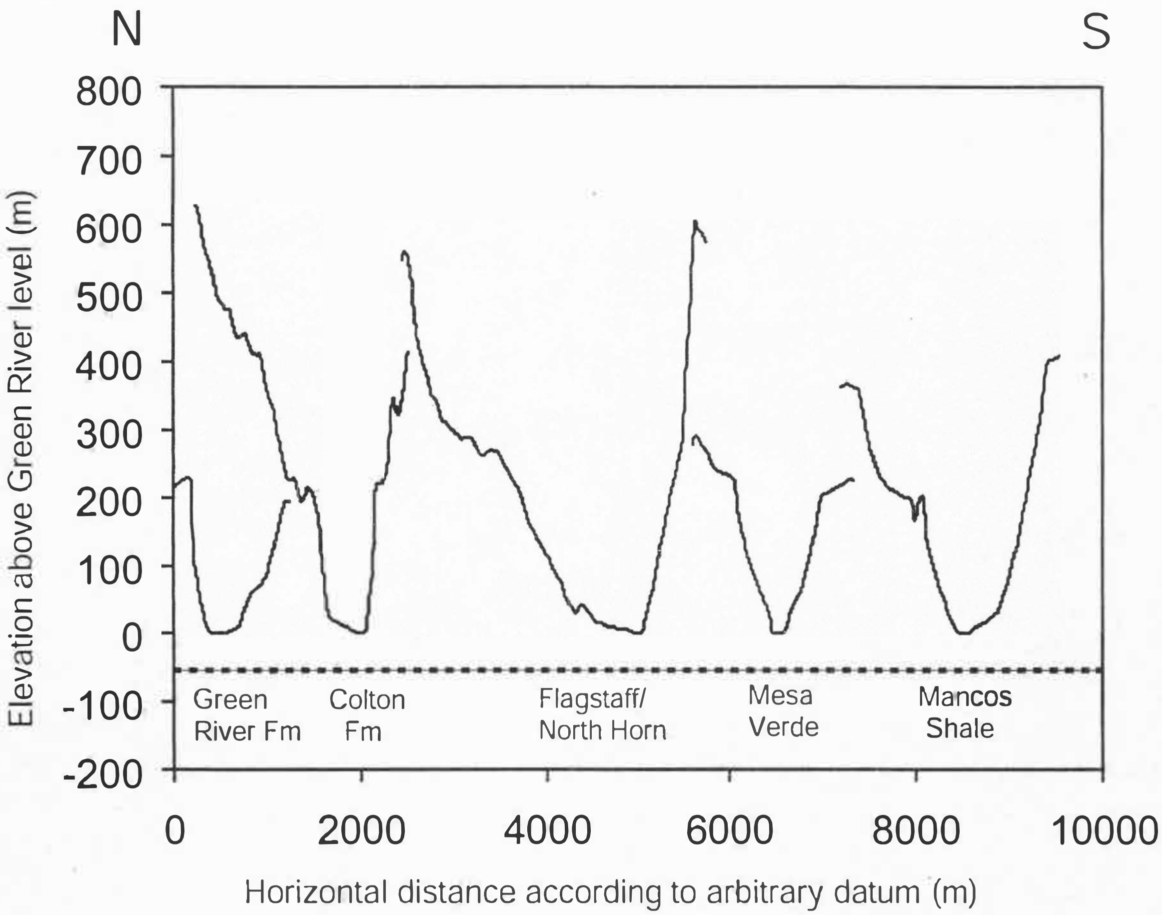

Figure 10. Typical canyon cross-sections for different rock units exposed in the study region.

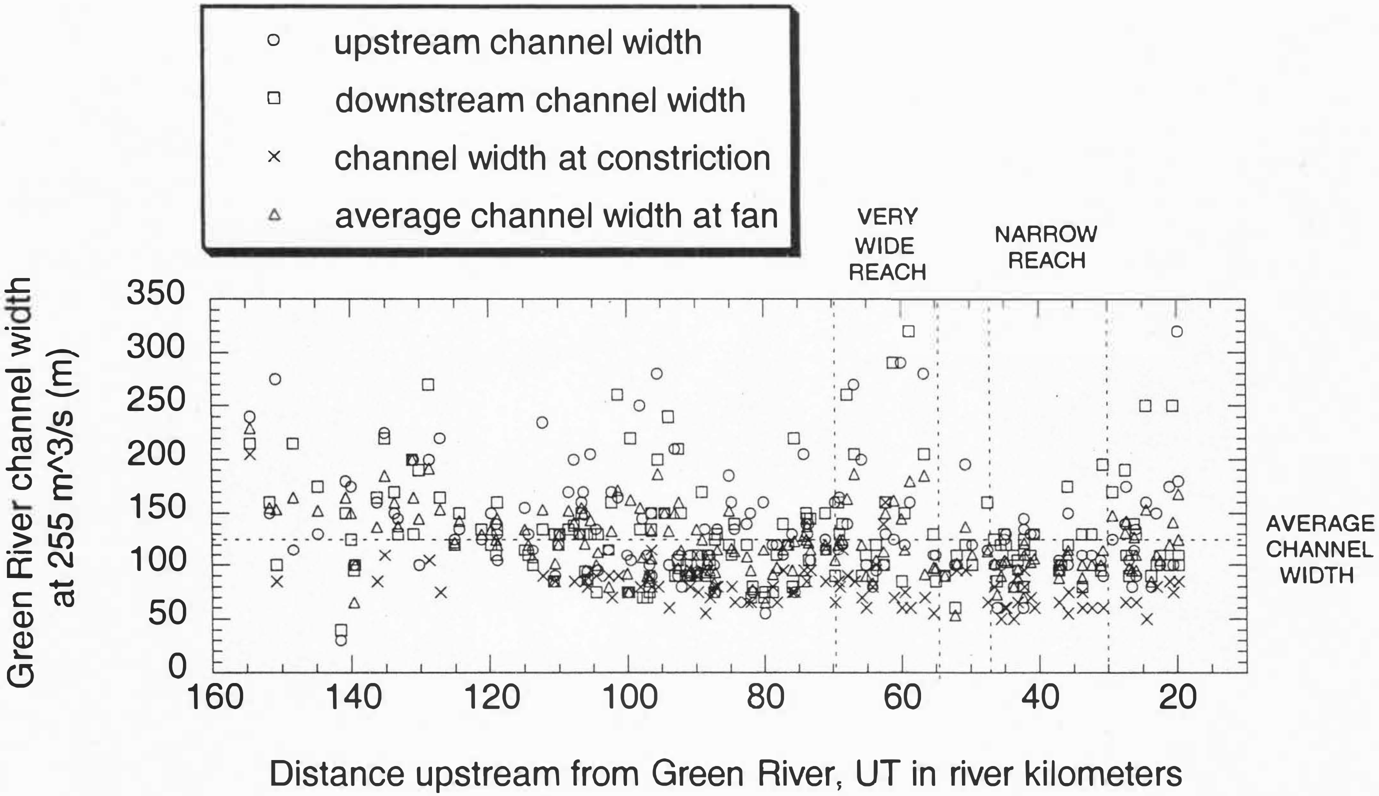

Figure 11. Variation in channel width in the study area. Measurements were made at a river level of 255 cms on 1987 USGS digital orthophoto base layers. Channel width was measured upstream of debris fans, at the point of maximum constriction, and downstream of constrictions. Average channel widths at constrictions are also indicated.

kilometers 56 and 24 in the narrowest reach of the river.

III. Photogeologic mapping of th esurficial geology of the Green River alluvial valley

The alluvial valley of the Green River was mapped within bedrock walls at a scale of 1:12,000. The valley is filled with Green River alluvium, tributary alluvium, hillslope colluvium, and aeolian dunes (Figure 12). Full unit descriptions are found in appendix F of this report. Plates of mapping of the entire field area are also included. The total mapped area is 45.2 km^2 (Table 2).

Mapped Green River alluvial deposits include gravel bars and sandbars in the active channel, channel margin deposits, and terraces. The river and its alluvial deposits occupy two-thirds of the entire map area, about 30.4 km^2 (Table 2). Approximately a third of this total includes Green River terraces, which were subdivided into high terrace, intermediate terrace, and floodplain subunits. The active channel, and adjacent gravel bars, sand bars, and channel margin deposits occupy a total of 37.2% of the mapped area.

Colluvial units were differentiated into debris fans, talus, and small colluvial fans. Debris fans occupy a total area of 11.7 km^2, or 25.9% of the valley in Desolation and Gray Canyons. Debris fans were sub-divided into debris fan surfaces and channels. Where bouldery deposits occur at debris fan mouths a bouldery channel sub-unit is indicated. Other colluvial deposits including talus and small colluvial fans make up 6.8% of the mapped area. Aeolian sand dunes lie on top of debris fan and terrace surfaces and occupy 1.3% of the total area of the valley.

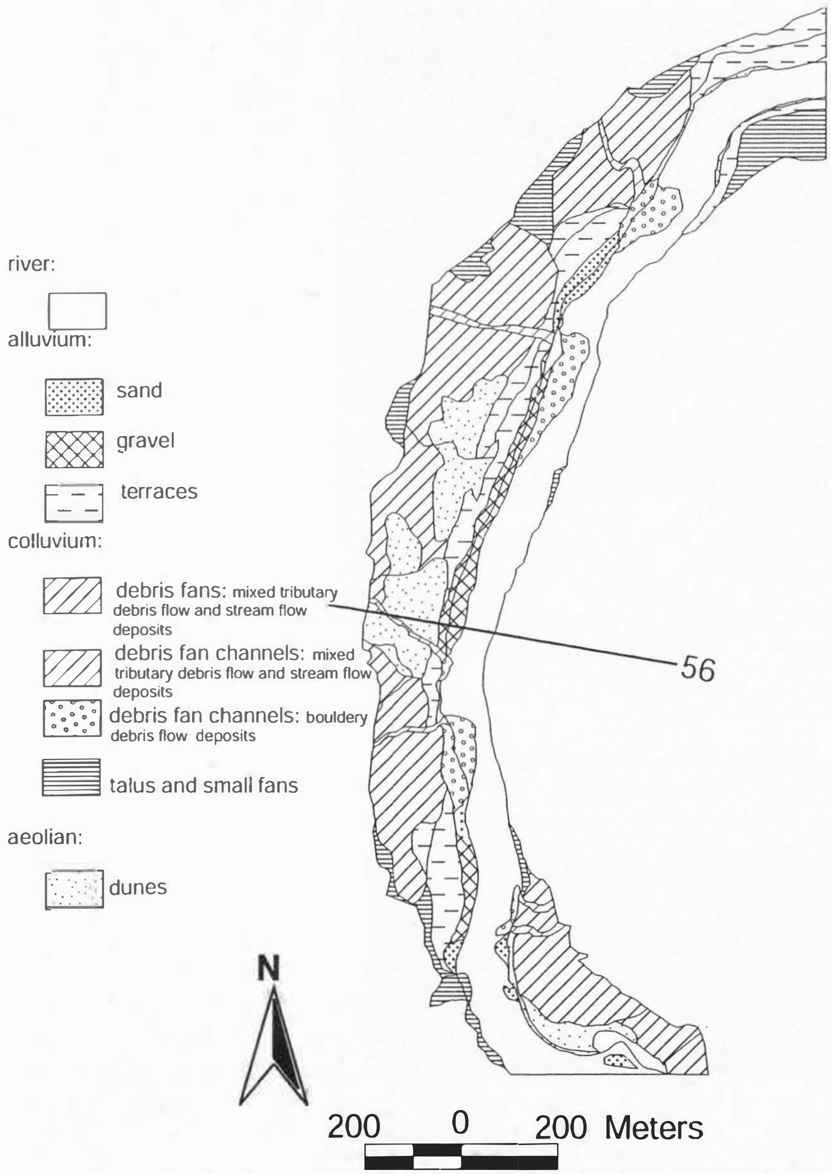

Figure 12. Example of mapping around river mile 56 and Steer Ridge Rapid within the bedrock valley of the Green River. Full unit descriptions are included in the appendix.

TABLE 2

Mapped Deposits in the Green River valley

Deposit	**Map Unit**	**area (km^2)**	**Percent of total deposits**
river		15.6	34.0
alluvium		14.79	33.0
	bars	0.46	1.0
		0.96	2.2
	channel margin deposits	0.43	0.9
	terraces	12.9	28.5
colluvium		14.75	33.0
	debris fans	11.7	25.9
	talus	0.82	1.8
	small colluvial fans	2.24	5.0
aeolian	dunes	0.60	1.3
total:		45.2	

IV. Fan characteristics

Debris fans comprise 26% of the valley's unconsolidated deposits, and fans of varying sizes occur throughout the study area (Table 3). The two largest debris fans in the study area both occur near river mile 40; the largest of these is nearly 500,000 m^2 in area (Figure 13). Small debris fans occur in wide and narrow valley settings.

Debris-fan areas in Desolation and Gray Canyons are larger than fans in Lodore Canyon or Grand Canyon. The average plan-view area of debris fans in the study area is 70,000 m^2. The largest fans in Grand Canyon are about 200,000 m^2 in area, and they average 12,000 m^2 (Webb et al., 1996; Melis, 1997). In Lodore Canyon debris fan areas are as large 110,000 m^2 and their median size is 17,000 m^2 (Martin, 2000).

Most debris flows of record have occurred in August or September. Storm histories and intensities were difficult to determine due to a lack of climate stations in the region. Debris flows large enough to alter rapids in the mainstem channel of the Green

TABLE 3

Debris fan data

Fan Name and River Mile[1]	Fan Area m²	Fan l/w	Fan Max Height[2]	Fan Slope	Channel Slope	AVERAGE Entrench-ment[3]	Cutbank height [2]
Joe Hut chCreek 41.5L	476,450	2.86	32.6	0.082	0.030	4.06	8.4
Trail Canyon 45.9R	218,535	0.77	19.4	0.099	0.077	5.26	8.1
Three Fords Canyon 36.5L	187,405	1.75	20.1	0.177	0.100	3.1	4.9
Moonwater Canyon 42.9R	173,430	1.32	26.5	0.199	0.081	3.0	8.3
Rock House Canyon 80R	165,174	2.09	14.8	0.054	0.049	1.55	5.2
Firewater Canyon 65.8L	134,378	0.61	17.7	0.059	0.061	3.07	3.4
Jack Creek 69.8R	130,504	2.67	10.7	0.036	0.024	2.43	4
Fretwater 59.4R	116,702	2.73	26.8	0.065	0.058	3.16	10.6
Joe Hutch Canyon 40.5R	113,897	2.22	18.6	0.062	0.051	2.56	6.7
Little Rock House Canyon 79L	113,201	2.57	14.7	0.078	0.070	2.57	7.4
Snap Canyon 51.3R	104,813	1.73	20.2	0.103	0.053	5.61	8.8
Unamed tributary 49L	101,440	2.02	21.8	0.193	0.163	5.63	10.6
Wire Fence Canyon 37R	99,547	1.98	33.1	0.114	0.087	2.62	2.6
Flat Canyon 63R	94,181	1.82	8.8	0.070	0.062	1.65	1.3
Unamed tributary 66L	84,333	0.52	24.5	0.304	No ch.	-	7.1
Log Cabin 54.7L	77,452	2.52	23.6	0.127	0.134	6.06	10.2
Wild Horse Canyon 58.4L	74,629	1.8	18	0.116	0.070	3.39	4.7
Cedar Ridge Canyon 65.5R	69,950	0.52	14.5	0.105	0.118	3.65	9.8
Unamed Canyon 54.3L	59,280	1.42	-	0.116	0.083	7.08	-
Stone House 14,3L	56,297	1.54	6.5	0.083	0.060	2.98	6.4
Unamed Canyon 65L	54,440	1.8	26.8	0.183	0.225	2.7	6.1
Unamed Canyon 56.5R	48,187	2.16	18.5	0.111	0.120	6.09	10.7
Belknap Rapid 48.6L	38,715	1.24	23.5	0.344	0.107	7.66	9.8
Spring Wash Canyon 32.3L	36,696	4.11	6.8	0.035	0.038	2.13	1.6
Curry Canyon 28.3R	16,611	1.6	8	0.100	No ch.	-	-
Butler Canyon 16.1L	15,798	1.55	9.3	0.025	0.021	3.38	6.8
Rabbit Valley 28.9R	15.528	1.53	5.9	0.018	0.185	1.08	3.7
Unamed Canyon 28R	8,110	1.1	7.8	0.282	No ch.	-	-

[1] River mile upstream from the railroad bridge at Green River, UT; [2] Height measurements refer to height above the Green River channel at low flow (42.5 m³/s); [3] Entrenchment depths measured from fan surface to channel bottom

River occurred in at least 6 tributaries during the past 25 years (Table 4). Field evidence in the form of fresh-looking levees and lobes deposited in debris flow channels and damaged vegetation suggests small recent debris flows have been deposited in the past few years on several debris fans (14d; see Appendices D and G for details).

Most debris fans in the study area consist of an extensive inactive debris fan surface with a relatively small area of active channel that covers about 7.5% of the fan surface. This percentage is less than the 17% reported by Hereford et al. (1996) for Grand Canyon debris fans. Inactive fan surfaces have extensively varnished and

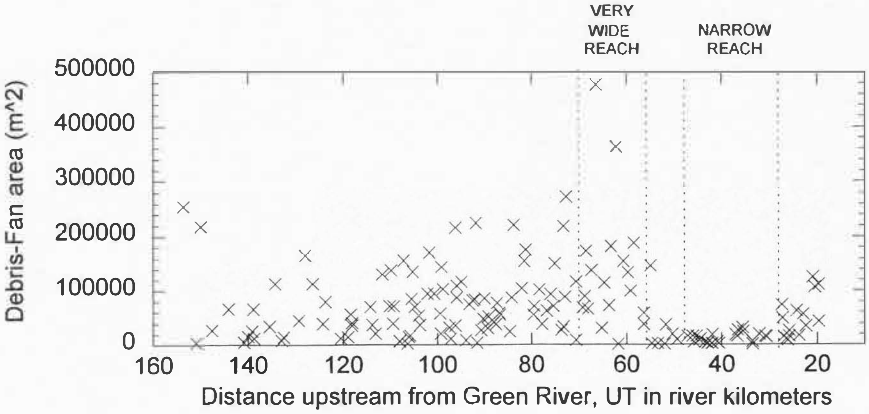

Figure 13. Longitudinal variation in debris-fan area in Desolation and Gray Canyons.

TABLE 4

Channel altering debris flow events in Desolation and Gray Canyons

Date	Location	Event	Source/evidence
8/1987	Belknap Falls (48.6L)	Debris flow event, created new rapid	Rampton, 1992
Late 1980's	Cedar Ridge Canyon (65.5R)	Large channelized debris flow; Backed up Green River, deposited bouders in channel	Joan Bacon, river runner, pers. comm.
8/1994	Moonwater Canyon (42.9R)	Debris flow added boulders to channel large	Brad Higdon, BLM ranger
1994	Joe Hutch Canyon (40.5R)	Debris flow added boulders to channel	Paul Grams, photos
1974 8/1987	Wire Fence Canyon (37R)	1974 event altered rapid 8/87 Debris flow event backed up Green River, flowed across fan	Joan Bacon, river runner pers. comm; Brad Higdon, Dennis Willis, Mike Hart, (BLM); BLM photos
1987	Three Fords Canyon (36.5L)	Aerial photo evidence suggests an event deposited boulders in channel in fall 1987	Rampton, 1992; photos

weathered surface boulders, aeolian dunes, and dense pinyon-juniper forest communities (Figure 14a). These surfaces have abandoned channels and boulder levees. Active channels are typically incised into the fan surface, and all debris flows reported during the past 20 years have occurred in incised channels. Active incised channels expose fresh gravel, contain woody debris, and may have perennial vegetation within them (Figure 14b). Inactive incised channels have gently sloping banks, varnished large boulders in

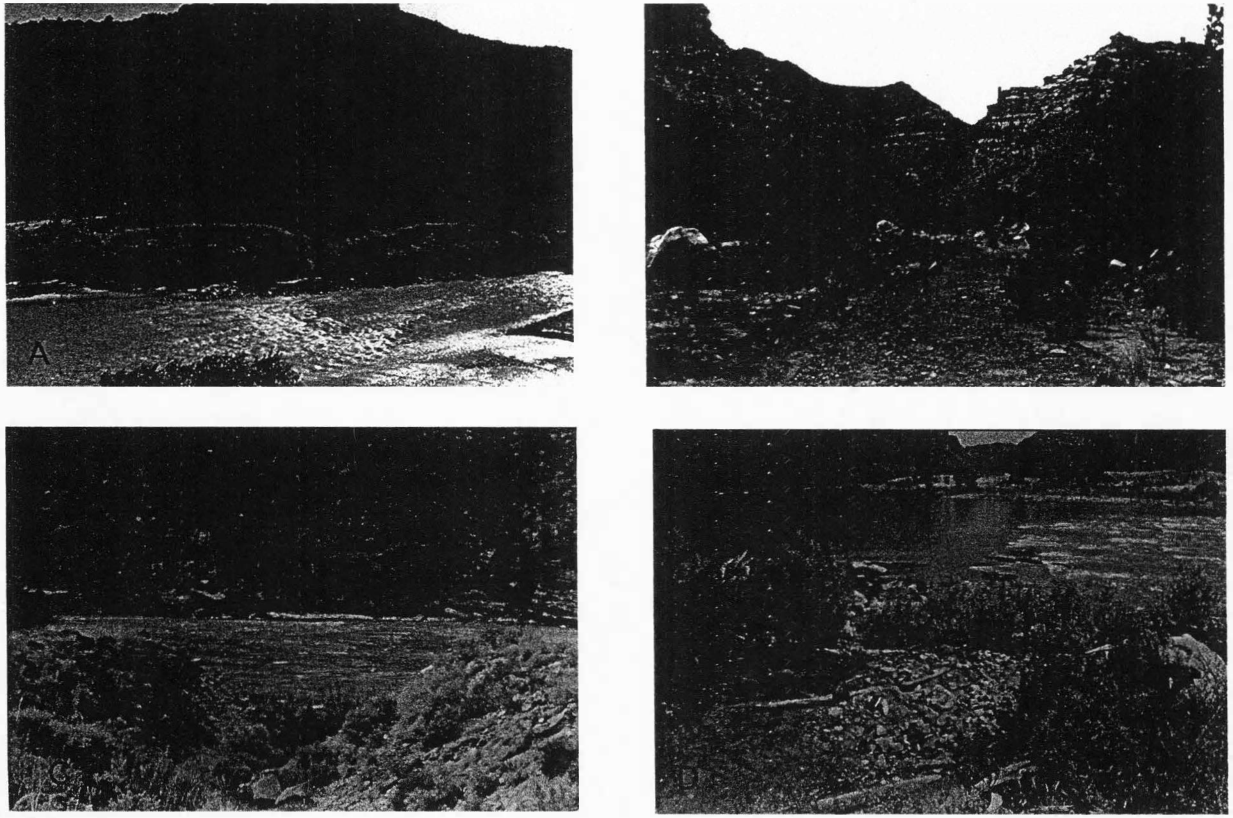

Figure 14. A. View of fan at river mile 41.6R. Debris fan is composed of a large extensive surface with pinyon-juniper forest and large extensive dunes cut by a central channel. B. Active channel at Joe Hutch Canyon (river mile 40.5R). This channel is entrenched below fan surface and experienced a large debris flow in 1994, and a flash flood event in 2000. C. View looking at deeply entrenched channel towards river from fan surface at debris fan located at Steer Ridge Rapid (river mile 56.5R). D. Small, fresh debris flow deposit in channel at Bull Canyon (river mile 44.2). This debris flow stopped just short of the Green River.

the channel, and trees growing in the channel bed (Figure 14c). Several inset terrace levels occur adjacent to the active channel.

The extent of fan entrenchment on a single fan varies because the slope of the fan surface and its channel may differ. Debris fan surface slopes vary 0.025 to 0.344 m/m (Table 3). Fan slopes are usually steeper than channel slopes, but there are a few exceptions, particularly on smaller debris fans. Fan channel entrenchment ranges between 1.08 to 7.66 m below debris fan surfaces. Channels with entrenchments over 3.5 m are considered deeply entrenched (Figure 14c).

There are a few unchannelized debris fans in the study area. They typically occur at the base of small tributary basins, less than 5 km^2, and are thus scattered throughout the course of the Green River, because small basins occur throughout the study area. These fans have aggrading surfaces, because debris flows do not reach the Green River and their surfaces are typically steeper than incised fans. Slopes of unchannelized fans are often as steep as 0.344 m/m. Their surfaces are typically strewn with boulder levees and contain multiple shallow channels with ridge and swale topography

Debris fans in Desolation and the lower 12 km of Gray Canyon are often very large and coalesce with fans from adjacent drainages, forming a bajada-like apron of alluvial sediment. These fans have multiple feeder channels, and often exhibit subtle differences in fan-slope towards their source drainages. In some cases large coalesced fans are difficult to correlate with source-basins.

V. Relations between drainage basin and debris fan characteristics

Debris fans in the 135-km study area display the wide variation of characteristics described above, including wide ranges in fan area and the degree of fan incision. Except for the occurrence of the two largest fans near river kilometer 65 and deeply entrenched fans between river kilometers 90 and 67, other characteristics are heterogeneously dispersed along the river. A wide range of fan characteristics are encountered as one travels downstream on the Green River. We sought to determine if this heterogeneous longitudinal distribution in the range of fan characteristics was due to inherent randomness in fan characteristics, or because of the heterogeneous spatial distribution of tributary catchments encountered by the river. Thus, we sought to identify whether specific attributes of tributary catchments give rise to specific attributes of debris fans.

Larger fans typically occur at the base of intermediate and large drainage basins and where the alluvial valley is wide, although there is wide scatter in the relationships among these parameters. There is not a simple power function relationship between tributary basin area and fan area (Figure 15a; n=157, $y=30243*x^{0.25}$, $R^2=0.09$) as has been found in fans that form in large structural basins (Bull, 1964, Leece, 1990, Blair and McPherson, 1994). In Desolation and Gray Canyons, large drainage basins usually produce large fans, and small fans are generally associated with smaller basins. Some of the scatter in this relationship may be a result of variations in valley width. Narrow valley settings limit debris fan size, for instance valleys under 250 m wide do not contain debris fans over 40,000 m^2. Large drainages in narrow valley settings do not form large

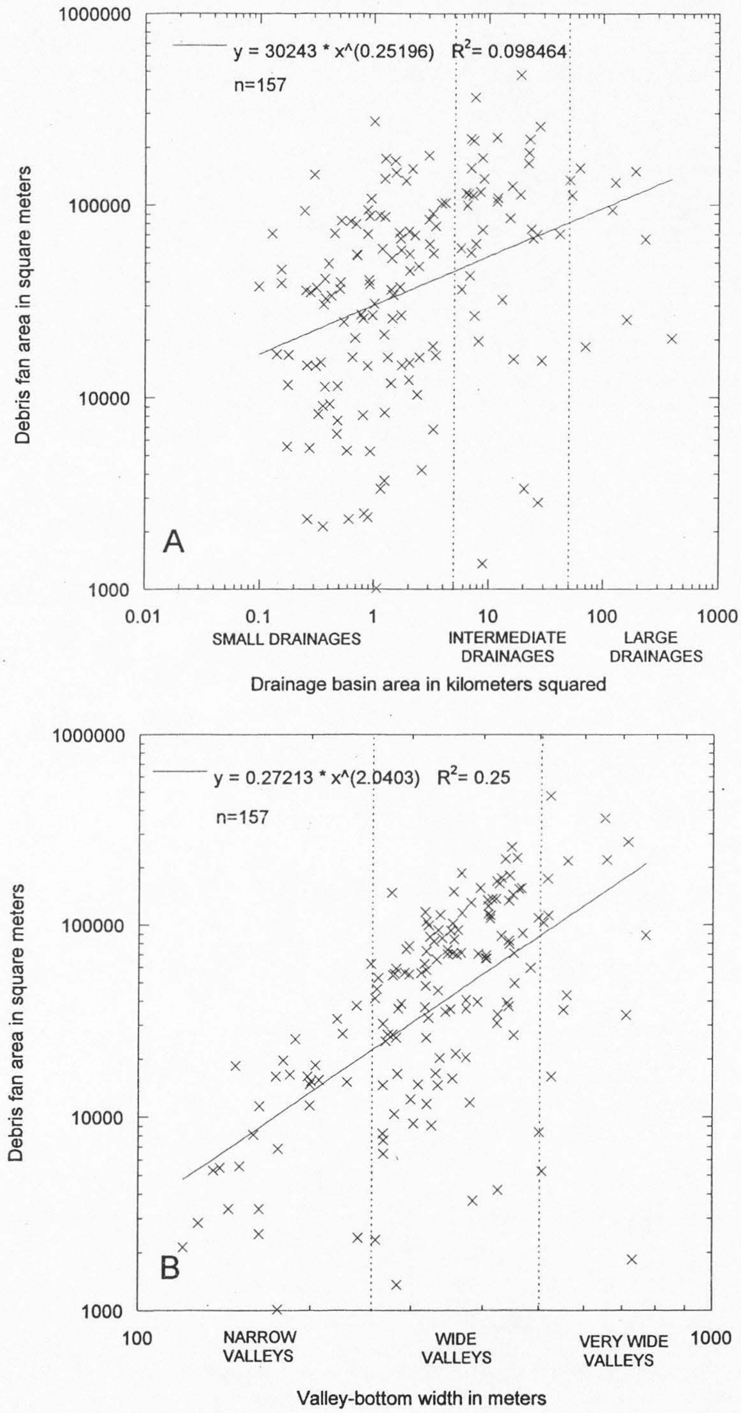

Figure 15. A.) Power function relationships between drainage basin area and debris fan area in Desolation and Gray Canyons. B) Power function between debris fan area and valley width for drainage basins over 5 km2.

debris fans. Wide valley bottom widths allow for the formation of both large and small debris fans.

Debris fans are typically larger where the width of the alluvial valley is greater (Figure 15b; n=157, $y=0.27*x^{2.04}$, $R^2=0.25$). Variability is probably due to several factors, including fan accommodation within tributary valleys and reworking of fan deposits. Weak fan area and valley width relationships have been reported for some groups of debris fans in the central Appalachians (Taylor, 1999). Taylor (1999) concluded that valley width does not necessarily dictate fan size but does affect the style and role of fan growth and preservation. Wider valleys allow inherent variation in sediment supply between drainage basins to exhibit a stronger control on fan size. Small valley widths limit fan size by restricting the amount of depositional space for fan formation.

Variation in drainage basin, fan area, and valley width relationships could be additionally due to differences in fan geometry, tributary spacing, and fan erosion by the mainstem Green River. Lateral confinement occurs when tributary spacing is close and adjacent fans either coalesce or limit space for fan formation. The river's path within the mainstem valley is determined by of the occurrence of bedrock outcrops, tributary spacing, and debris fan size and geometry. Opposing tributaries entering from either side of the river can deflect the channel, eroding one fan more than another.

Longitudinal variation in geologic and valley characteristics, fan characteristics, and the heterogeneous distribution of types of fan linkage and gravel bars led to the designation of nine distinct reaches to be discussed in detail in later in this paper. The reach-averaged relationship for debris fan size and valley-bottom width characteristics is strong (Figure 16; n=9, R^2=0.93, with a significant slope at α=0.05). Thus, the role of valley width as accommodation space available for fan formation is more clearly defined when the relationship is reach-averaged filtering out some of the inherent natural variability in fan area due to river reworking, coalesced fans, and interbasinal fans.

VI. Relationship between debris fans and the Green River

Although there is a general relationship between debris fan occurrence and average gradient of the Green River (Figure 2), the control on channel form at a smaller scale is more complex. Thus, I characterized the relationship between each debris fan and local form of the Green River based on analysis of surficial geologic mapping.

Some debris fans are tightly coupled with river process, resulting in a sequence of associated deposits; rapids and extensive gravel bars, while others exhibit very little interaction with the mainstem Green River. The degree of coupling, or linkage, was defined by the presence of incised channels, rapids, the extent of reworked gravel bar deposits, and the existence of fine-grained sediment deposited in zones recirculating flow (Figure 17).

Debris fan channels act as conduits for sediment transfer from tributary catchments to the Green River. Aggrading debris fans lack channels and do not deliver coarse sediment to the mainstem river channel. Debris fans are linked to the river by these incised channels which range in entrenchment between 1.08 and 7.66 m below the main debris fan surface (Figure 18). Fans are most deeply entrenched between river kilometers 90 and 67; the reason for this spatial pattern was not investigated.

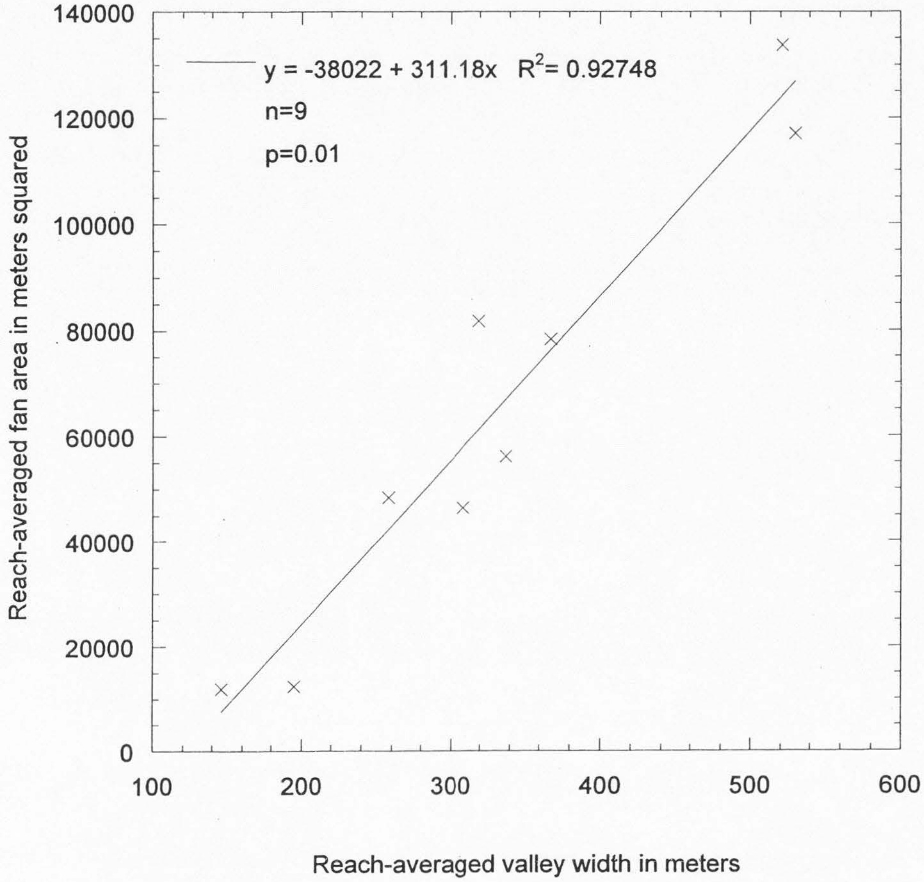

Figure 16. Reach averaged relationship between drainage basin area and debris fan area.

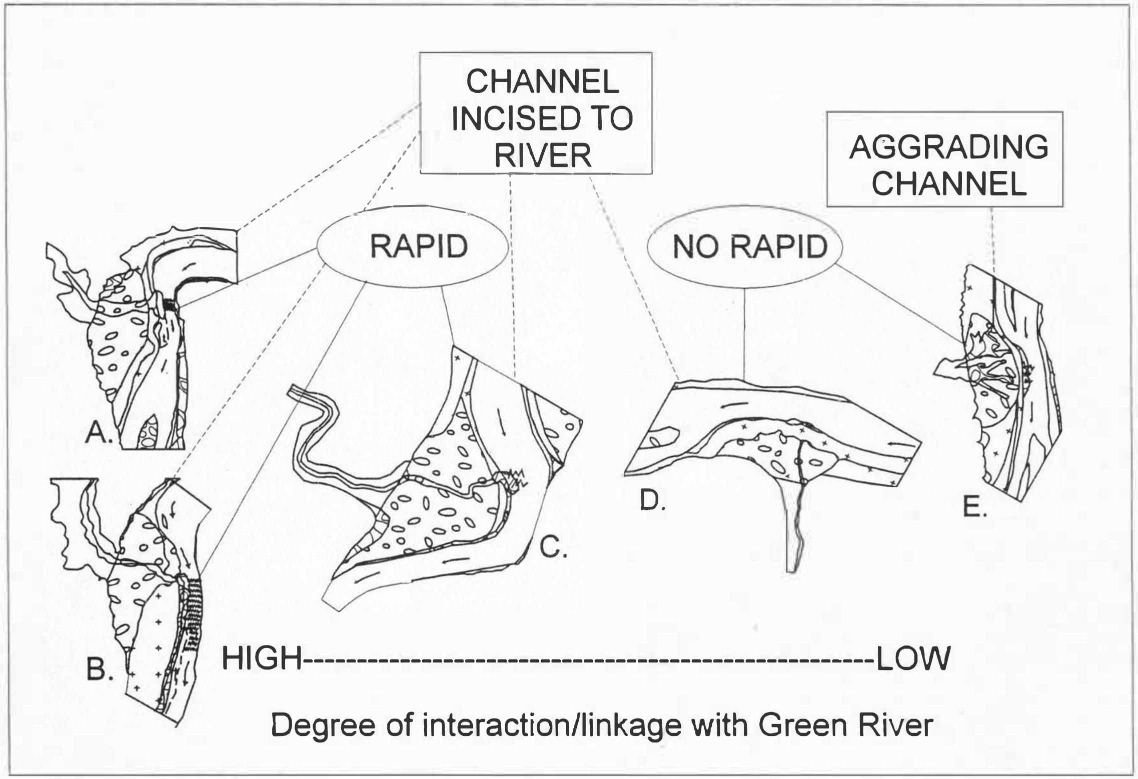

Figure 17. Types of debris fans and degree of linkage with Green River. Fans with incised channels display a high degree of linkage with the Green River. These fans include A) Debris fans with rapids, gravel bars, and sandbars deposited in zones of recirculating flow, B)Debris fans with rapids and large gravel bars (greater than 3000 meters squared); C) Fans with rapids but without significant gravel bars or zones of recirculation. Fans with low degrees of linkage with the Green River include: D: Fans

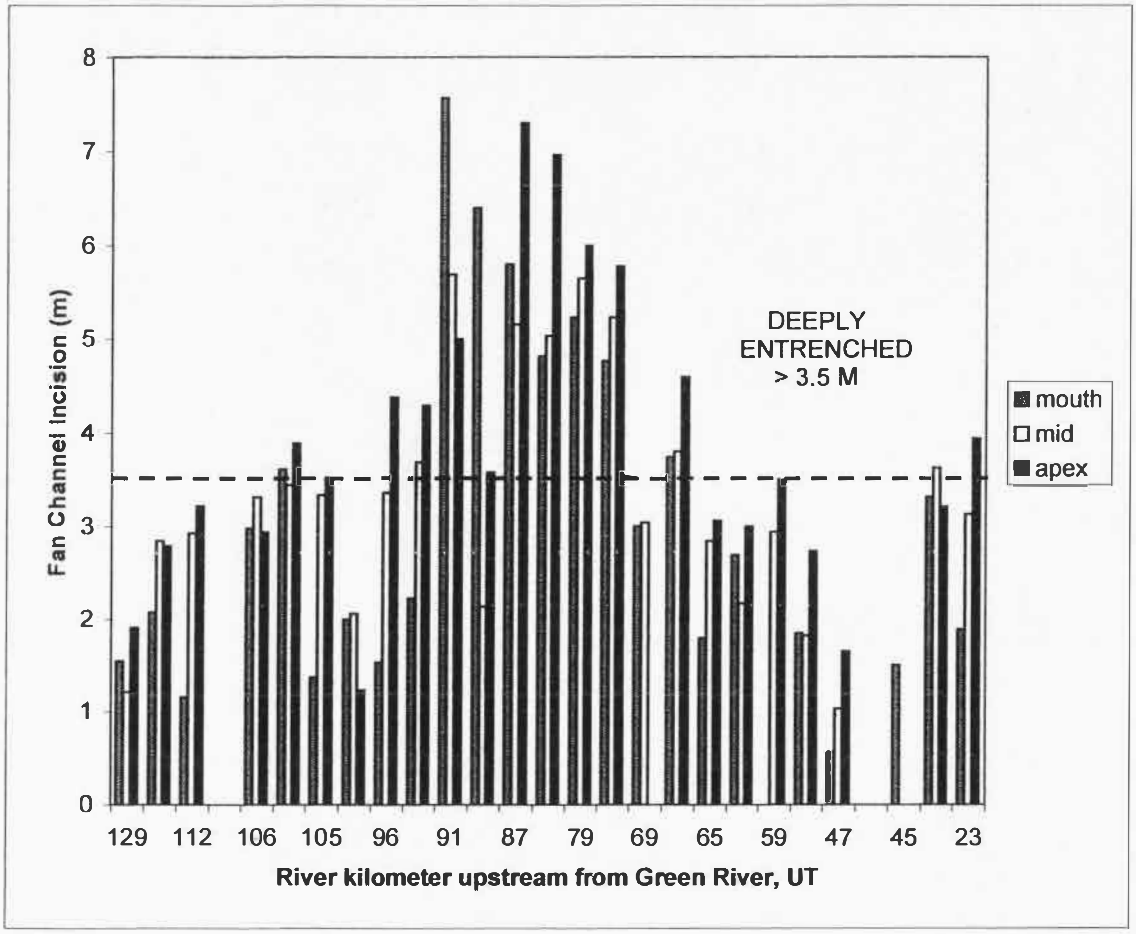

Figure 18. Longitudinal trends in channel entrenchment for detailed study sites in Desolation and Gray Canyons.

Entrenchedfans are most likely to transfer of debris flows from tributaries to the Green River rather than directly on debris fan surfaces.

Debris fans that display a high degree of linkage with mainstem river processes have incised channels with rapids at their mouths, and often have extensive gravel bars, and sandbars deposited in zones of flow recirculation below rapids. Many debris fans the study reach fit the classic model of a fan-eddy complex as defined by Schmidt and Rubin (1995). These fans constrict the river and have upstream regions of ponded flow with fine-grained sediment deposition (Figure 17a). Large gravel bars are defined as those over 3000 m^2 in plan view area. In many cases, modern eddy deposits are adjacent to higher fine-grained terraces deposited in recirculating flow at higher discharges. Rapids formed in fan-eddy complexes are usually fairly short in length and associated downstream zones of recirculation are large. Many fan channels show signs of fairly recent activity and have had historic debris flows.

A second style of debris fan with a high degree of linkage with the Green River consists of a long reworked rapid and gravel bar with little or no recirculating flow (Figure 17b). These fans have extensive downstream gravel bar deposits (with areas greater than 3000 m^2, yet lack significant eddies. Zones of lateral waves often form downstream of rapids in place of recirculating eddies. Fine-grained sediment deposition may occur in the vicinity of these lateral waves. Although flow constriction occurs extensive gravel bar deposits allow no room for significant flow recirculation. In wide valley settings these fans are large; in very narrow valleys topography constrains fan form to boulder piles in the channel that create large and long rapids. Linked debris fans in Desolation Canyon are often very large with radii up to 0.5 km and may create significant meander bends on the Green River within the incised bedrock valley walls (Figure 17c). The river flows around these fans resulting in, small rapids, extensive gravel bars, and no room for eddy recirculation. A high proportion of the fan surface is often inactive cut by small incised channels.

Many fans in the study area exhibit little to no interaction with the river. Many debris fans with little linkage are aggrading and lack incised channels that convey debris flows to the river corridor (Figure 17e). These fans tend to be quite steep and bouldery. Where small fans occur in wide canyon settings they often are too small to interact with the main-stem river unless the river's course flows near the fan. In narrow valley settings, fans with little linkage often mildly constrict the river yet often have large downstream eddies. Channelized fans with little linkage are often isolated from mainstem processes by fine-grained terraces and channel margin deposits that separate the active channels of debris fans from the main-stem river (Figure 17d). There is often no change in mainstem slope as the river flows by isolated debris fans. Small riffles and coarse material are often exposed on the river bed near these fans at very low flows suggesting that at one time these fans may have been linked to the mainstem river.

Debris fans also supply coarse sediment to the mainstem river though the process of lateral fan truncation by the Green River. This process is evident by the existence of both large cutbanks and fan-cut terraces. Highly eroded fans exhibit a reduction in fan symmetry. These fans have cutbanks up to 12 m high where the river has cut into the fan. Small riffles often extend the full length of the fan adjacent to cutbanks where coarse sediment is directly eroded into the Green River. The Trail Canyon and Bluebell Creek fans show signs of significant truncation by very large river flows in the past. This process appears to be prevalent where valleys are widest and there is more space for fan accommodation.

There is variation in where various types of fans occur longitudinally in the study area (Figure 19). Unlinked debris fans occur throughout Desolation and Gray Canyons. Linked debris fans, with the exception of three debris fans that lack extensive gravel bars do not occur above river kilometer 112 (river mile 70). Below this point, debris fans that deliver coarse material to the Green River occur in abundance. Large fans that create meander bends or are truncated by the river, (Figure 17c) occur in discrete reaches where the alluvial valley is its wide such as that occurring from river kilometers 56 to 96 (Figure 9).

Longitudinal variation in geologic and valley characteristics, fan characteristics, and the distribution of types of fan linkage and gravel bars led to the designation of nine distinct reaches to be discussed in detail in the next section. The average gradient of these reaches were used to further investigate the connection between mainstem slope and debris fan linkage.

Mainstem reworking of debris fan sediment results in the formation of gravel bars and changes rapids and the river over time. The existence and relative abundance of gravel bars is a surrogate for degree of fan-river linkage through reworking. There are longitudinal patterns of gravel bar abundance in the study area (Figure 20). This suggests that either the frequency of debris fans, or the linkage between debris fans and the Green River is variable throughout the canyons. Of the 164 tributary drainages that form fans in the Green River Valley along the 135-km study area, 89 (42%) constrict the Green River, and 80 (50%) of the total fans are associated with rapids or riffles.

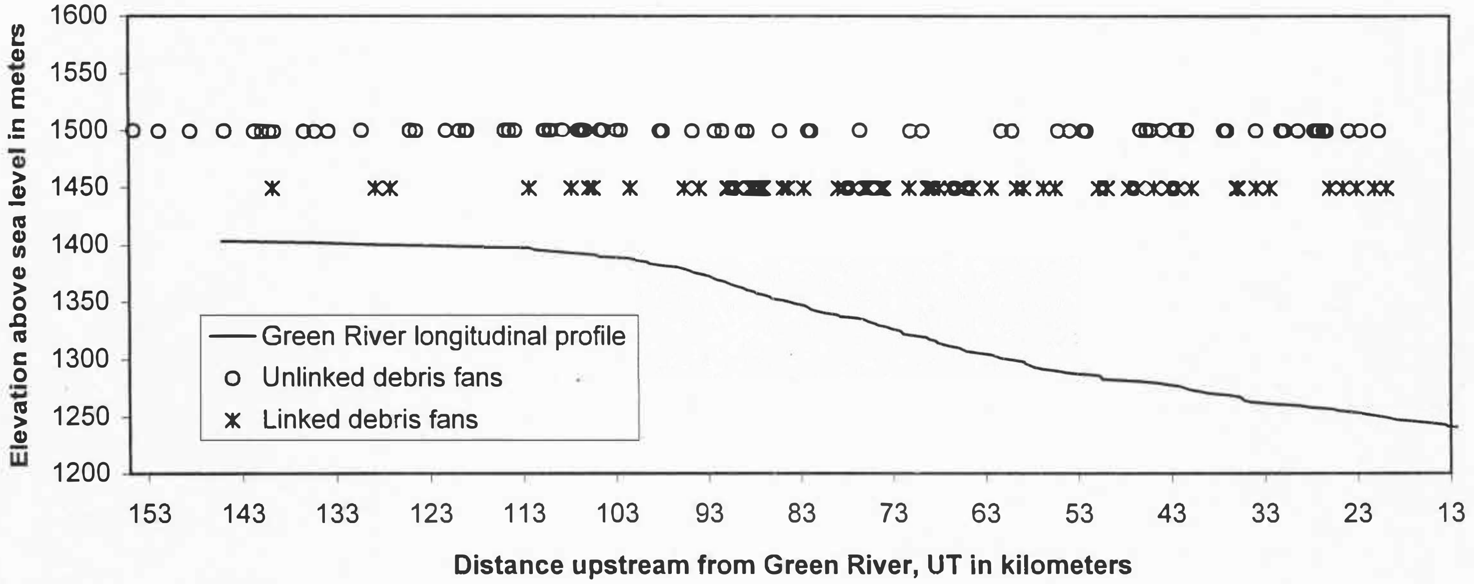

Figure 19. Longitudinal distribution of debris fan linkage. Circles represent aggrading debris fans, or debris fans with incised channels that are no longer connected to river processes (Figure 18: D and E). Linked debris fans as indicated are debris fans with incised channels,rapids, and often extensive reworked gravel bars (Figure 18: A, B, and C).

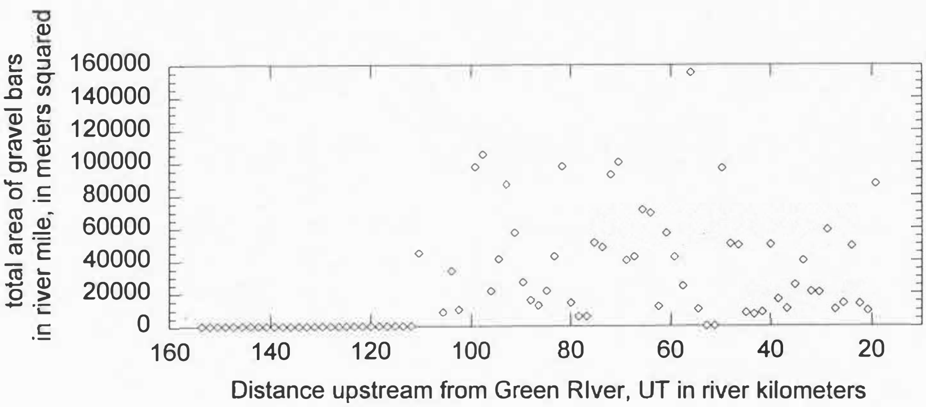

Figure 20. Longitundal pattens in gravel bar abundance in Desolation and Gray Canyons.

The gradient of the Green River is steepest in reaches where tributary debris fans deliver coarse debris (Figures 17, 19). However, the occurrence of tributary fans alone does not explain the gradient of the Green River in the study area. Debris fans that are not linked to river processes do not change the slope of the mainstem Green River. Although debris fans in narrow canyons have been shown to affect mainstem river slope, fan frequency alone does not account for the slope of the mainstem Green River (Figure 21a). Tributaries that are coupled with main-stem processes often constrict the mainstem channel and have associated coarse reworked deposits (Figure 18). Most of the longitudinal drop of the river occurs either in rapids at debris fan mouths or through gravel bars. Therefore the reach-averaged total area of gravel bars and reworked rapid deposits offers the best explanation of the slope of the Green River through the study area (Figure 21b).

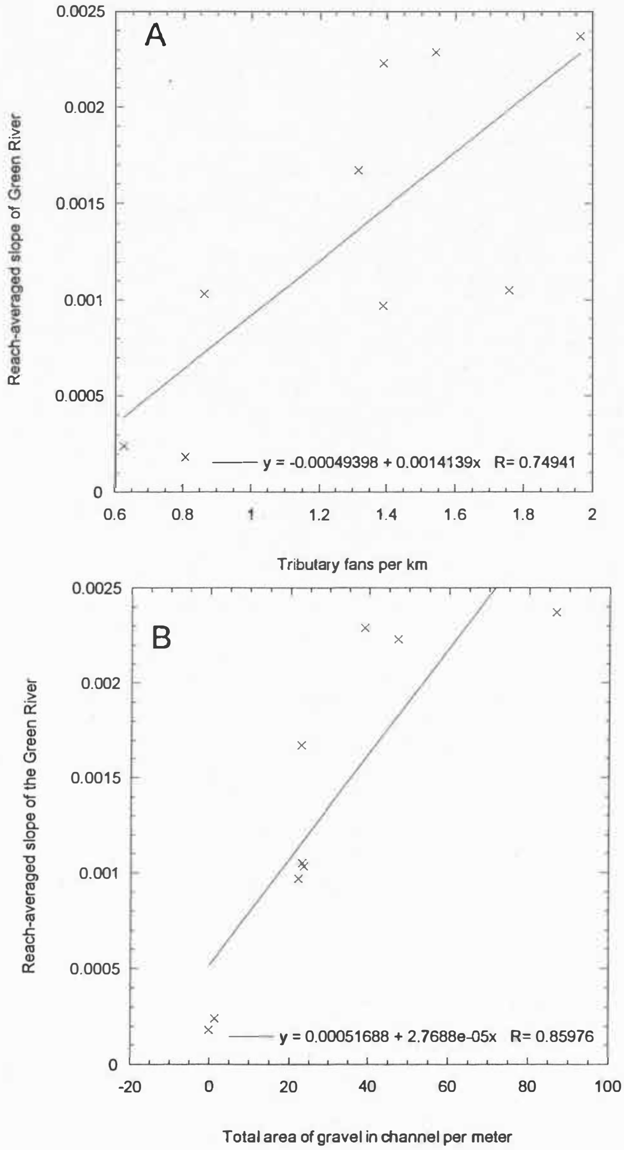

Figure 21. Relationship between reach-average Green River slope and debris fan characteristics in Desolation and Gray Canyons. Slope data comes from 1922 US Geological Survey (USGS, 1922). A) Relationship between reach-averaged river slope and debris fan frequency per km B) Relationship between constricting fan frequency and coarse deposits per meter in river for study reaches.

A classification of Desolation and Gray Canyons into geomorphically distinct reaches:

Orchard and Schmidt (1998) divided the Green River between Sand Wash and the town of Green River into three main geomorphic segments: Desolation Canyon, Gray Canyon, and a long flat gradient reach upstream from Desolation Canyon in the Uinta Basin. Each segment has similar river level geology and distinctive geomorphic attributes. We have further subdivided the designations of Orchard and Schmidt into distinct reaches based on river-level geology, valley width, debris-fan characteristics, and fan-channel linkage (Table 5).

The upper reaches of Desolation Canyon flowing through the Green River Formation has the lowest gradient of 0.00018- 0.00024 m/m, a sand bed, no significant rapids, and few constricting debris fans (Figure 19). This segment of Desolation Canyon with its flat-gradient and sand-bed has more geomorphic similarity to the Uinta Basin upstream from Sand Wash than the steeper gravel-bedded canyon reaches downstream. The first reach from river kilometers 153.6 – 128.2 (miles 96 to 80.1) has been named after the Uinta Basin, characterized by frequent tight bedrock meanders and open high terraces. Valley widths are moderate (Figure 9, Figure 22a), with fairly low debris fan areas (Figure 23b). Tributaries draining the low relief terrain adjacentt o the river form small fans on high terraces and do not interact with the Green River (Figure 2). A gradual lateral rock-type change occurs near river mile 80 and continues for many kilometers downstream, where the Green River Formation's shales begin to interfinger with sandy units of the Colton Formation. This change marks the beginning of the other low-gradient sub-reach, named for Peter's Point, a large 9.5-km incised bedrock meander

TABLE 5

Reaches in Desolation and Gray Canyons

REACH		RIVER MILE[1]	RIVER KM[1]	REACH LENGTH (KM)	AVG. SLOPE[2]	AVG. VALLEY WIDTH[3]	AVG FAN AREA[3]	% AREA DEBRIS FANS[4]	% AREA GRAVEL BARS[4]	% AREA SAND BARS[4]	% AREA TERRACES[4]
	Uinta Basin	96-80.1	153.6-128.2	25.4	0.00024	258	50,000	13.6	0.6	0.21	65.7
Desolation Canyon	Peter's Point	90.1-70.1	128-112.2	16.0	0.00018	337	56,000	12.7	0.0	0.04	30.6
	Cedar Ridge	70.1-59.5	112.2-95.2	17.0	0.00105	367	76,000	33.7	6.3	0.17	17.5
	Rock Creek	59.5-46.2	95.2-73.9	21.3	0.00229	318	80,000	36.0	12.2	0.57	45.0
	Joe Hutch	46.2-37.7	73.9-60.3	13.6	0.00223	521	134,000	40.6	9.1	0.30	15.0
	Roan Cliffs	37.7-35.8	60.3-57.3	3.0	0.00327	530	112,000	32.1	16.4	0.28	23.0
Gray Canyon	Upper Gray	35.8-28.6	57.3-45.8	11.5	0.00103	195	26,000	8.9	12.2	0.24	35.9
	Coal Creek	28.6-20.1	45.8-32.2	13.6	0.00167	146	11,000	12.0	15.7	1.17	22.5
	Lower Gray	20.1-11.6	32.2-18.6	13.6	0.00097	309	45,000	17.7	7.2	1.13	30.1
average				135.0	0.00133	330	70,000	23.0	8.8	0.46	31.7

[1]River miles and kilometers measured in distance upstream from railroad bridge in Green River, UT; [2]Slope data from USGS 1922 Survey; [3]Average valley width, fan area computed from surficial map database; [4]Percent area of debris fans, gravel bars, sand bars and terraces from surficial mapping and refers to the percent of the total area of the reach that is a particular deposit.

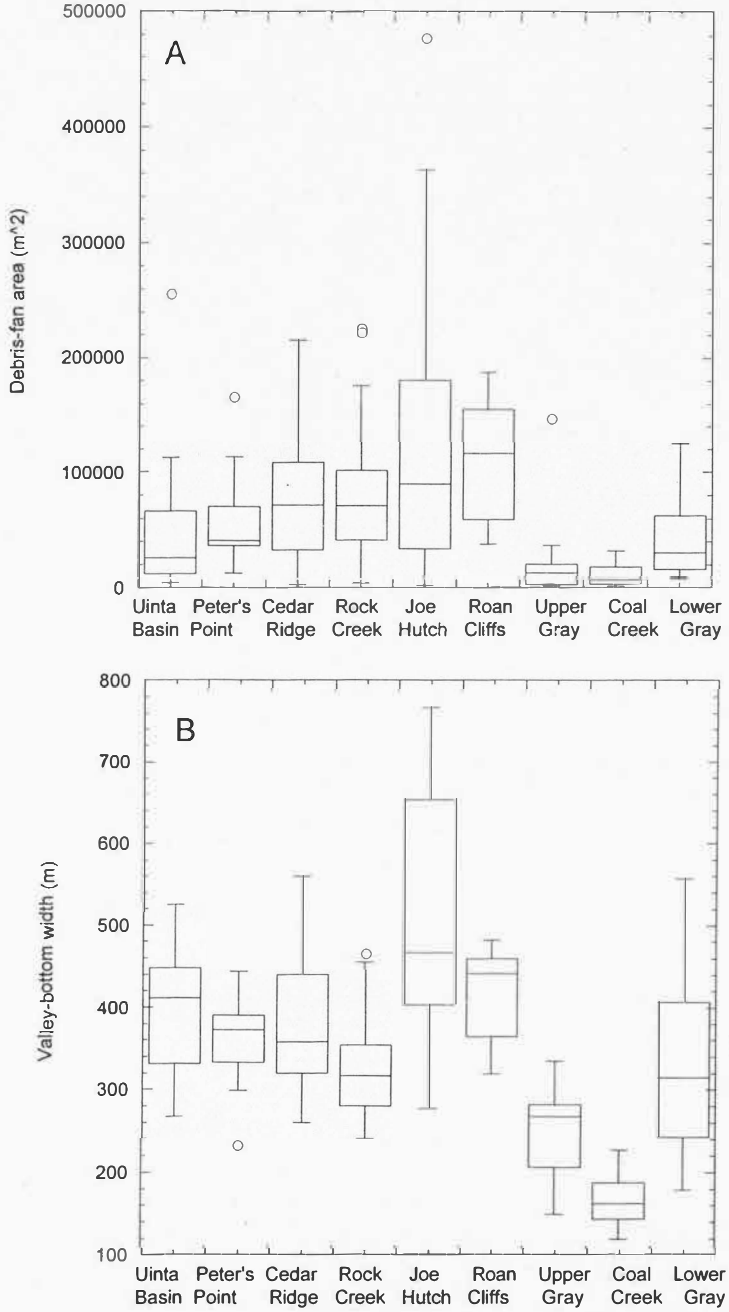

Figure 22. Box and whisker statistical plots of variation in A) Valley bottom width and B) Debris-fan area in Desolation and Gray Canyons.

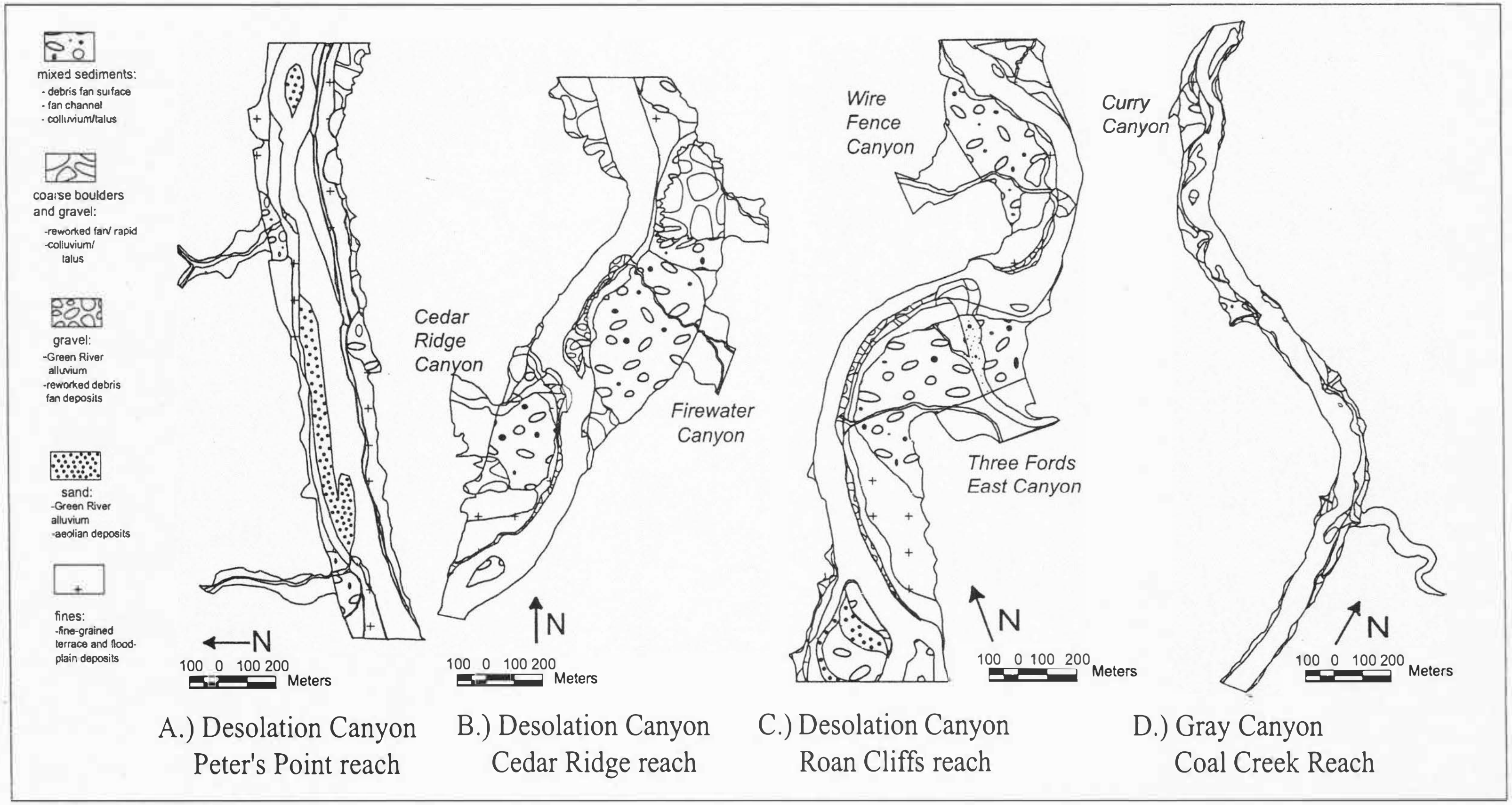

Figure 23. Representative examples of mapping in each of the four main reaches in the study region. A.) Uinta Basin (sub-reach b): small debris fans deposited on fine-grained terraces with little interaction with mainstem river, sand-bedded system with no gravel bars; B.) Desolation Canyon (sub-reach a): large debris fans in a wide-valley setting, gravel bars; C.) Roan Cliffs: large debris fans with coarse river-constricting rapids and large gravel bars; D.) Gray Canyon: (sub-reach b) small debris fans that constrict the river and create large zones of recircluation.

bend. This reach extends 16.8-km, from river kilometers 128.2 – 112.2 (miles 80.1-70.1), is low-gradient and sand-bedded, with the exception of two fan-eddy complexes where gravel locally underlies the channel at Rock House and Little Rock House canyons. With the exception of Tabyago Canyon, Rock House, and Little Rock House canyons debris fans in the sand-bedded Uinta Basin and Peter's Point reaches of Desolation Canyon do not interact with the Green River (Figure 19). These fans are deposited on high-terraces of the Green River and are not channelized to the river and often lack incised channels (Figure 23a).

Downstream from Jack Creek at river kilometer 112.2 (mile 70), the first gravel bars occur and Desolation Canyon has an order-of-magnitude considerably steeper gradient of 0.0010- 0.0023 m/m, a wider valley, frequent constricting tributary debris fans, and abundant coarse bed material (Figure 2). The Cedar Ridge sub-reach is 17.8-km long, occurring over river kilometer 112.2 – 95 .2 (miles 70.1-59.5), has a slope of 0.00105 m/m exhibits wider valley widths and larger debris fans than upstream reaches (Figure 22). The bedrock geology at river level and in the canyon walls still consist of interfingered Green River Formation and Colton Formation. Several large tributaries enter the river in the Cedar Ridge reach, including Jack Creek, Firewater Canyon and Flat Canyon. The Colton Formation is strongest and supports a narrower valley in the Rock Creek reach of Desolation Canyon through river kilometers 95.2 - 73.9 (miles 59.5 - 46.2) (Figure 23a). In this sub-reach frequent debris fans constrict the river and create rapids and downstream gravel bar constrictions (Figure 20). Downstream of Chandler Canyon the Colton Formation becomes increasingly more shale-rich, and valley widths reach the widest in the study region through river kilometers 73.9 - 60.3 (miles 46.2 -

37.7) in the Joe Hutch reach (Figure 23a). With this available accommodation space, debris fans are often very large, with sizes up to 476,000 m^2 and generally above 100,000 m^2 (Figure 23b). Truncated fans, large cutbanks, and fan-cut terraces also are abundant in the Joe Hutch reach (Figure 23). It is within the Rock Creek and Joe Hutch sub-reaches that most fan channels are deeply entrenched and fan surfaces to not grade to river level (Figure 15). In the wide valley of the Joe Hutch sub-reach it is common for the river to meander around very large debris fans, which are associated with either large reworked rapids, or little interaction (Figure 17c).

In the Roan Cliffs region from river kilometers 60.3 – 57.3 (miles 37.7 - 35.8), the river's drop is the highest in the study area at 0.0024 meters per meter, and valley widths are wide (Figure 22). Tributaries drain high terrain of the Roan Cliffs, which occur here in close proximity to the river (Figure 2). At river-level, the Flagstaff Limestone and North Horn Formation conglomerate outcrop, and form a wide valley and low-elevation terrain, yet resistant bedrock outcrops occur near the river (Figure 23c). Wire Fence Rapid, and Three Fords Rapid, catchment areas of 6.5 and 22.5 km^2 respectively are two of the largest rapids in the region (Table 4).

From the Roan Cliffs to Swazey's Rapid, the river's alluvial valley narrows in Gray Canyon. Gray Canyon was separated into three reaches also based on lithologic changes in the Cretaceous marine units. Gradients in Gray Canyon range between 0.00097 to 0.00187 m/m, lower than the upstream reaches in Desolation Canyon, yet debris fans and coarse bed material are still abundant (Figures 19 and 20). The upper Gray Canyon reach, river kilometers 57.3 – 45.8 (miles 35.8-28.6) has low topographic relief, and fairly narrow valley widths (Figure 22a). Debris fans are very small, with areas below 36,000 m^2. Fans often constrict the river, but are not associated with major riffles or rapids. The gradient of the upper Gray Canyon reach is low at 0.00103 m/m, gravel bars are less frequent, and debris fans in this reach exhibit little interaction with the river and are often isolated from the river by densely vegetated fine-grained terraces (Figure 17e). Coarse material enters the channel at Range Creek and Rabbit Valley, where there are large rapids and gravel bars that extend downstream. The valley narrows even further in the Coal Creek reach occurring between river kilometers 45.8 – 32.2 (miles 28.6-20.1) where steep cliffs of Farrer Sandstone outcrop at river level and side tributaries enter the canyon as pour-offs. Mainstem gradient is 0.00167 m/m and small debris fans with areas below 30,000 m^2 frequently constrict the river causing large zones of recirculation and fine-grained sediment deposition (Figure 23d). Gravel bars are also abundant. Two major tributaries, Coal Creek and Rattlesnake Creek create debris fans and rapids with abundant piles of coarse material obstructing the channel. Extensive fine-grained terraces occur below these tributaries at several levels. Fan-eddy complexes are common, and most debris fans interact with the Green River. Lower Gray Canyon begins as the Mancos shale appears at river level at the base of the Mesa Verde Group from river kilometers 32.2 – 18.6 (miles 20.1 - 11.6). This soft rock formation is associated with slightly lower main-stem slope of 0.00097, a wider canyon, and hillslopes are mantled with thick colluvium. Debris fans are larger than the uper reaches of Gray Canyon due to wider valley widths in lower Gray Canyon.

The reach-averaged relationship for debris fan size and valley-bottom width characteristics is strong (Figure 24). The role of valley width as accommodation space available for fan formation is more clearly defined when the relationship is reach-averaged filtering out some of the inherent natural variability in fan area due to river reworking, coalesced fans, and interbasinal fans.

Discussion and Conclusions

Over the Green River's 135-km course through Desolation and Gray Canyons there is considerable variety in debris fan size, slope, and linkage with the mainstem river. Tributary catchment size does not explain variation in debris fan size. Longitudinal heterogeneity in bedrock geology creates a canyon with varying alluvial valley widths. Where weaker rocks outcrop, wide valleys occur. In these wide valley settings both large and small debris fans build at tributary mouths. The Green River meanders around large debris fans within the main canyon in wide valleys. Where stronger rocks outcrop, narrow valleys limit the accommodation space available for fan formation and only small fans form at tributary mouths. The river'course is constrained in bedrock meanders in narrower reaches and fans are more likely to be overtopped by Green River floods.

Drainage basins that drain high relief terrain on the Tavaputs Plateau produce debris flows that reach the canyon to form debris fans. Debris-flow sediment supply, initiation, and event frequency and occurrence are important factors in maintaining linkage with the river not addressed by this study. The climatic and geologic factors influencing debris flow initiation, magnitude, and frequency in the Tavaputs Plateau region are not well understood. A more complete record of the debris flow histories of individual drainages would provide a more complete understanding of fan and river interaction.

The abundance of gravel bars is just one way to define debris fan and river linkage. Debris fan form and geometry has also been shown to constrict the river, and affect the locations and sizes of fine-grained sediment deposition (Schmidt and Graf, 1990; Melis et al., 1995). The existence of zones of recirculation and therefore fine-grained sediment deposition vary with fan and reach geometry. Orchard and Schmidt (1998) found that zones of recirculation are associated with major constrictions. Very large fans, and fans with large and long rapids tend to have limited space for flow circulation and therefore opportunity for fine-grained sediment deposition. These fans tend to occur in but are not limited to wide valley settings. In reaches with wide valley widths, or in reaches with few constricting debris fans most fine-grained sediment is stored as channel margin deposits. In narrow valley settings most debris fans constrict the river channel and have large recirculating eddies.

The debris fans in Desolation and Gray Canyons display similar control on mainstem processes as seen in other narrow canyons on the Colorado Plateau (Schmidt and Rubin, 1995). Fan-eddy complexes consisting of the same sequences of deposits occur in on the Green and Colorado Rivers, in Grand Canyon, Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon (Schmidt and Rubin, 1995; Grams and Schmidt, 1999). Many tributaries that terminate as fans in the mainstem valley in Grand Canyon and Lodore Canyon do not result in rapids, so a spectrum of fan-river linkage also exists in these canyons. Large and small debris fans as well as narrow and wide valley settings occur in all Colorado Plateau canyons.

Truncation and reduction of fan symmetry on higher fan surfaces such as described by Hereford et al. (1996) in the Furnace Flats region of Grand Canyon is seen in the widest reach of Desolation Canyon. This process appears to be prevalent in both canyons where valleys are widest and there is more space for fan accommodation. Fan deposits are likely to have a longer residence time in these wider reaches, and older deposits are preserved. Only very large river floods significantly rework debris fans (Kieffer, 1985). In narrower canyon reaches, a rise in discharge represents a much larger rise in stage than in wider reaches, and reworking of entire fans is more likely to occur on smaller fans in narrow-valley settings.

Hillslope-channel linkages occur at many different scales. In this study, hillslope-scale debris flow processes control the gradient and organization of coarse and fine-grained sediment on a large river. The Green River's rapids and eddies are a product of tributary drainage-basin scale processes, driven by slope, sediment supply, and regional climate patterns.

Debris fans control the organization of deposits on the main-stem Green River channel. Bedrock geology and drainage basin characteristics directly and indirectly influence debris fan form through sediment delivery and depositional site variation leading to geomorphically distinct reaches and sub-reaches within the canyons. Debris fan size is controlled by the amount of space available in the valley bottom where a tributary meets the Green River. Debris fans create a steeper mainstem gradient where coarse material is delivered to the river channel and debris fans are linked to river processes.

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CHAPTER III

RELATIONS BETWEEN TRIBUTARY CATCHMENTS, VALLEY-BOTTOM WIDTH, DEBRIS-FAN AREA,AND MAINSTEM GRADIENT ON THE COLORADO PLATEAU

ABSTRACT

The mainstem rivers of the Colorado Plateau cross structural barriers leading to the incision of deep canyons surrounded by steep terrain. In tributary catchments where sufficient sediment supply and a means of saturation exist, debris flows occur. These debris flows deliver slurries of sediment including coarse boulders that aggrade in the narrow canyons of the Green and Colorado Rivers to produce debris fans. Debris fan size is dependant on the accommodation space available in the mainstem valley. This is contrary to relationships developed for alluvial and debris fans deposited in unconstrained valleys where drainage basin area is directly related to fan size. Valley-bottom width varies with lithologic changes in the layer-cake stratigraphy of the Colorado Plateau giving rise to geomorphically distinct reaches with characteristic valley widths and debris fan sizes. The mainstem gradient is steepest where more debris fans occur, not where debris fans are the largest.

INTRODUCTION

On the Colorado and Green Rivers of the Colorado Plateau, longitudinal variation in river gradient, bed sediment size, and geomorphic organization are ultimately determined by: 1) lithologic characteristics of bedrock geology; and 2) lithologic, physiographic, and climate characteristics in tributary catchments that control sediment transport from tributaries to the main channel (Howard and Dolan, 1981; Webb et al., 1988). Steep, coarse-bedded reaches with frequent rapids occur in narrow canyons where debris flows deliver coarse sediment to the main valley thereby creating fan-eddy complexes (Howard and Dolan, 1981; Schmidt and Rubin, 1995; Grams and Schmidt, 1999). Variability in valley width and physical and climatic characteristics of tributaries leads to a wide variety in fan size between and within the narrow canyons of the region.

Although several studies have described debris flow processes and resultant landforms in Grand Canyon (Webb et al., 1989; Hereford et al., 1996; Melis, 1997), such studies have not been integrated with similar observations elsewhere so that a regional perspective can be provided about controls on debris fan form and river slope. The purpose of this paper is to provide and summarize available data describing tributary catchement characteristics, mainstem valley width, debris fan area, and reach-averaged gradients for most of the debris-fan affected segments of the Green and Colorado Rivers in Utah, Colorado, and Arizona.

GEOLOGIC SETTING AND BACKGROUND

Debris-fans occur in narrow canyons on the Colorado and Green Rivers of the Colorado Plateau where debris flows occur in tributary basins (Figure 24). These rivers have incised narrow canyons in the eastern Uinta Mountains, the Tavaputs Plateau, and the Grand Canyon creating regions of high relief with steep terrain adjacent to the trunk stream valleys. Hillslopes are linked to the main Colorado River system in these canyon regions through debris-flow processes which deliver coarse material to the mainstem rivers. Debris flows aggrade in the river valley and create debris fans in eastern Uinta Mountains in Red, Lodore, Whirlpool, and Split Mountain canyons over a total of 80 river kilometers (Grams and Schmidt, 1999, 2002). Downstream on the Green River, debris flows from tributaries draining the Tavaputs Plateau aggrade as debris fans over a distance of 135 kilometers through Desolation and Gray Canyons in east-Central Utah. On the Colorado River in northern Arizona, debris fans occur in 445-km long reach of Marble and Grand Canyons (Webb et al., 1988) as well as in the 25 km of Glen Canyon immediately downstream of Glen Canyon Dam (Grams et al., 2002).

These rivers flow through gently dipping Precambrian to Cenozoic rocks of the Colorado Plateau (Hunt, 1969). Where the river crosses structural uplifts, it flows in steep-sided valleys with as much as 1500 m relief between the river corridor and tributary drainage basin headwaters. Varying resistances in lithologies has led to variation in valley width in river reaches (Harden, 1990; Grams and Schmidt, 1999; Roberson and Pederson, 2001). Less erodible rocks such as well-cemented sandstones, quartzites,

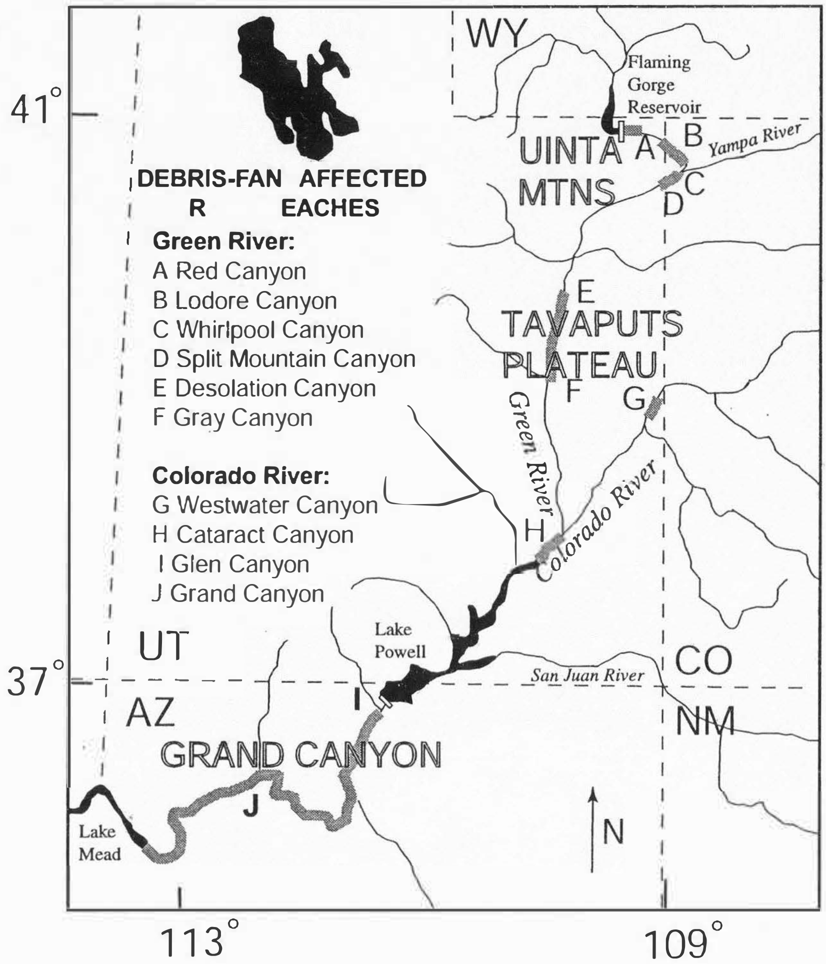


Figure 24. Map of Colorado Plateau region and the canyon reaches of the Green and Colorado Rivers analyzed in this study.

granites, and schists tend to form narrow steep-walled canyons, whereas softer rock types such as shales and conglomerates are associated with wider, open valleys, and more gently sloping valley walls (Harden, 1990).

Powell (1875) remarked on the correspondence of rapids to tributary mouths in the Grand Canyon. Subsequent researchers have described the rapids through which most of the vertical drop occurs on the Colorado River in Grand Canyon (Leopold, 1969; Webb et al., 1988) and the Green River (Graf, 1979; Schmidt and Rubin, 1995; Grams and Schmidt, 1999). Cooley et al.(1977) was the first to recognize debris flows as the sediment delivery process responsible for boulder transport, debris fan aggradation, river constriction and the formation of rapids in the Grand Canyon. Howard and Dolan (1981) documented debris-fan aggradation in the Grand Canyon. Webb et al. (1988) determined that debris flow processes are responsible for the formation of all major rapids on the Colorado River in Grand Canyon. Initiation processes have been investigated in Grand Canyon and include bedrock failures, colluvial failures, the "firehose effect" where a stream of water pours off a cliff and mobilizes debris (Johnson and Rodine, 1981), and a combination of these processes (Griffiths et al., 1996).

Webb et al. (1988), and Howard and Dolan (1981) determined that the spacing of most of the rapids on the Colorado River in Grand Canyon corresponds with tributary location, and rapids appear to be maintained by episodic debris flows. Grams and Schmidt (1999) determined this to be true in the canyons of the Eastern Uinta Mountains as well. Grams and Schmidt (1999) also argued that bedrock geology both in the lithology exposed at river level and in tributary basins strongly influences the longitudinal profile, cross-section geometry, and patterns of sediment deposition on the

Green River. Resistant boulders that remain in rapids are one way that bedrock lithology indirectly influences river form (Grams and Schmidt, 1999). In both Grand Canyon and Lodore Canyon, tributary junctions are aligned with regional geologic structures and faults (Howard and Dolan, 1981; Grams and Schmidt, 1999).

METHODS

Tributary catchment area, mainstem valley width, mainstem channel width, and debris-fan area measurements were assembled from the literature and from measurements made in the study areas (Table 1). Reach averaged values for debris fan area, valley width, and river gradient for Red Canyon, Browns Park, Whirlpool and Split Mountain Canyons and Glen Canyon are from Grams and Schmidt (1999), Grams et al. (2002a), and Grams et al. (2002b). The data for debris-fan area, drainage-basin area, and valley width for each debris fan in Lodore Canyon is from Martin (2000). For Desolation and Gray Canyons, tributary drainage area was determined by analyzing 10-m digital elevation models. A map database of the surficial deposits within the Green River's valley was created in ArcInfo using field maps and air photos. Field data, including field verification of surficial geologic maps, was collected on river expeditions. Various metrics such as plan-view fan area, valley width, and channel width were measured for every fan from this database. Drainage-basin areas and debris fan areas were complied for selected debris fans in Grand Canyon (Melis, 1997; Melis pers. comm., 2002), and GIS Databases of mapping within reaches in Grand Canyon (Schmidt et al., 1999b; and Schmidt et al., 2002). Valley width data for debris-fan sites and reaches in Grand Canyon were collected using digital orthophoto quadrangle maps, GIS maps, and

TABLE 1. REACHES OF THE GREEN AND COLORADO RIVERS WITH DEBRIS FANS

River/ Canyon/ Reach	River Mile[1]	Reach length (km)	Average gradient[2]	River level geology[3]	Valley width (m)[4]	Channel width (m)[5]	# of Debris fans[6]	Debris fans/km[7]	Average Debris Fan area (m2)[8]
Green River									
Red Canyon									
Red Canyon I	290-283.5	10.5	0.0021	pCu	49	48	31	1.7	6500
Upper Browns Park									
Debris Fan reach	278.9-273.0	9.3	0.0015	PCu; Tbp	118	65	9	0.4	7700
Swallow Canyon	265-263.5	3.8	0.0005	pCu	56	53	3	0.8	1800
Lower Browns Park									
Lower Browns Park II	258.5-243.3	25.0	0.0003	Tbp	906	141	3	0.1	2300
Eastern Uinta Mtns									
Lodore Canyon	243.3-225	28.5	0.0029	pCu	95	60	81	2.8	9000
Echo Park	225-223	3.2	0.0006	Paleo.	335	201	1	0.3	5600
Whirlpool Canyon	223-214.2	14.2	0.0023	Paleo.	79	63	53	3.7	4800
Island Park	214.2-207	11.6	0.0007	Meso.	407	138	5	0.4	2700
Split Mountain Canyon	207-199.5	12.1	0.0037	Paleo.	92	68	35	2.9	8000
Uinta Basin Canyons									
Uinta Basin A	96.0-80.1	26.7	0.0002	Tg	250	140	14	0.2	50000
Uinta Basin B	80.1-70.1	16.8	0.00019	Tg	325	130	13	0.1	55000
Desolation Canyon									
Desolation A	70.1-59.5	17.8	0.00105	Tg; Tc	350	110	30	0.8	80000
Desolation B	59.5-46.2	22.3	0.00231	Tg; Tc	305	85	31	0.9	80000
Desolation C	46.2-37.7	14.3	0.00218	Tc	500	100	19	1.0	135000
Roan Cliffs	37.7-35.8	3.2	0.00167	TKfn	510	160	6	2.0	115000
Gray Canyon									
Gray Canyon A	35.8-28.6	12.1	0.00095	Kms	185	90	10	0.4	11000
Gray Canyon B	28.6-20.1	14.3	0.00163	Kms	140	75	18	1.1	17200
Gray Canyon C	20.1-11.6	14.3	0.00109	Km	295	105	19	0.8	53000
Colorado River									
Grand Canyon									
Permian Section	0-11.3	18.08	0.00099	Pk; Ptw; Pc; Ph	200	100	15	0.88	11000
Supai Gorge	11.3-22.5	17.76	0.00140	Ps	150	80	26	1.46	6000
Redwall Gorge	22.5-35.9	21.28	0.00150	Mr	110	80	42	1.64	6000
Lower Marble Canyon	35.9-61.5	40.8	0.00100	Cm; Cb; Ct	150	130	59	1.59	19000
Furnace Flats	61.5-77.4	25.28	0.00210	Ct; pCu	230	130	49	1.938	18000
Upper Granite Gorge	77.4-117.8	64.48	0.00230	pCu; pCz	80	70	100	1.535	4000
Aisles	117.8-125.5	12.16	0.00170	Ct; pCv	110	105	24	1.97	11000
Middle Granite Gorge	125.5-139.9	22.88	0.00200	Ct; pCu; pCv	90	80	47	2.05	5000
Muav Gorge	140-159.9	31.84	0.00120	Cm	70	60	24	0.879	3000
Lower Canyon	160-213.3	86.08	0.00130	Cm; Cb	130	120	113	1.3	18000
Lower Granite Gorge	213.9-225	19.04	0.00160	PCv	90	105	30	1.62	13000

[1]River miles measured in Miles upstream from the railroad bridge in Green River, UT on the Green River, and miles downstream from Glen Canyon Dem on the Colorado River; [2] Green and Colorado River gradient data from 1922-1923 USGS survey expedition; [3]Geologic Formations: pCu-Precambrian Uinta Mtn Quartzite, Tbp- Tertiary Browns Park Formation; Paleo- Paleozoic sedimentary units; Tg- Tertiary Green River Fm Shales and sandstones; Tc- Tertiary Colton Fm sandstones; TKfn- Tertiary and Cretaceous Flagstaff Limestone and North Horn Formation Conglomerate; Kms- Creataoeous Mesa Verde Fm interbedded sandstones and shale units; Km- Cretaceous Mancos Shale; Pk- Permian Kaibab limestone; Ptw- Permian Toroweap Sandstone; Pc- Permian Coconino sandstone; Ph- Permian Hermit shale; Ps- Premian Supai Group sandstones; Mr- Mesozoic Redwall Limesone; Cm- Cambrian Muav Limestone; Cb- Cambrian Bright Angel Shale; Ct- Cambrian Tapeats Sandstone; pCu- Precambrian Unkar Group sandstones; pCv- Precambrian Vishnu Schist; pCz- Precambrian Zoraster Granite; [4] Valley width data for Red Canyon/Browns Park: Grams et al., 2002; Lodore Canyon: Grams and Schmidt, 1999; Desolation and Gray Canyons: this study; Grand Canyon: this study; [5] Channel width data: Red Canyon/Browns Park: Grams et al., 2002; Lodore Canyon: Grams and Schmidt, 1999; Desolation and Gray Canyons: this study; Grand Canyon: Schmidt and Graf, 1990; [6,7,8] Debris fan frequency and areas from: Grams et al., 20002, Martin, 2000, and Melis, unpublished data.

topographic maps. River-gradient data for the Green and Colorado Rivers is from the U. S. Geological Survey water surface elevation survey conducted on a river expedition in 1922-23 (USGS, 1923, 1924).

RESULTS

Tributary catchments that contribute sediment to debris fans in Lodore Canyon, Desolation and Gray Canyons, and Grand Canyon have areas ranging between 0.1 and 934 km^2. Tributaries to these canyons have comparably sized catchment areas. The spatial arrangement of drainages with respect to the longitudinal profile of the master stream is random in Lodore, Desolation, Gray, and Grand canyons (see Chapter II of this report for details on Desolation and Gray Canyons).

Valley-bottom widths at debris-fan locations in the canyons of the Colorado and Green Rivers range between 70 – 760 m. Average valley-width is 150 m in Lodore Canyon, 130 m in Grand Canyon, and 350 m in Desolation and Gray Canyons. Valley-bottoms are therefore, on average over twice as wide in Desolation and Gray Canyons than other Colorado Plateau Canyons (Figure 25a).

Debris fans range in size from 300 to 450,000 m^2 on the Colorado and Green Rivers. The average debris fan has an area of 17,000 m^2 in Lodore Canyon, 70,000 m^2 in Desolation and Gray Canyons, and 15,000 m^2 in Grand Canyon. Reach averaged debris fan areas for debris-fan affected reaches range between 4000 m^2 and 135,000 m^2. Debris fans on the Green River in Desolation and Gray Canyons are on average 7 times larger in plan-view area than the average fan sizes in the canyons of the eastern Uinta Mountains and in Grand Canyon (Figure 25b).

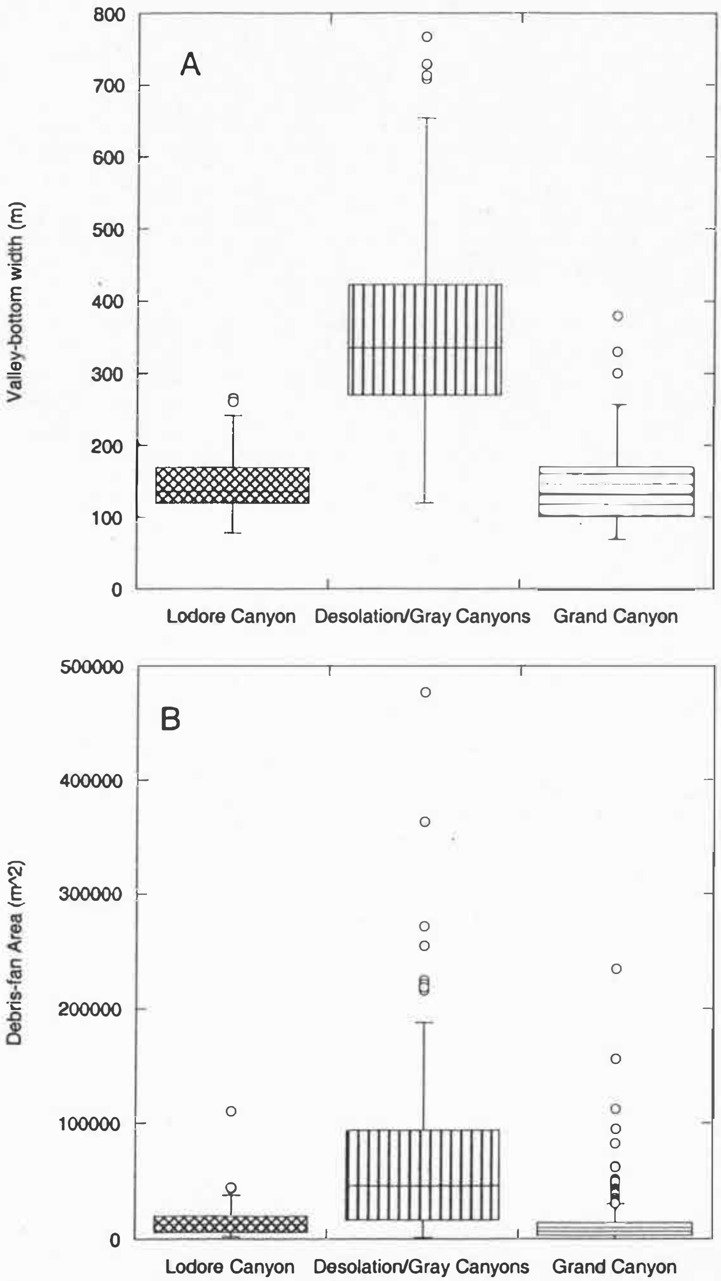
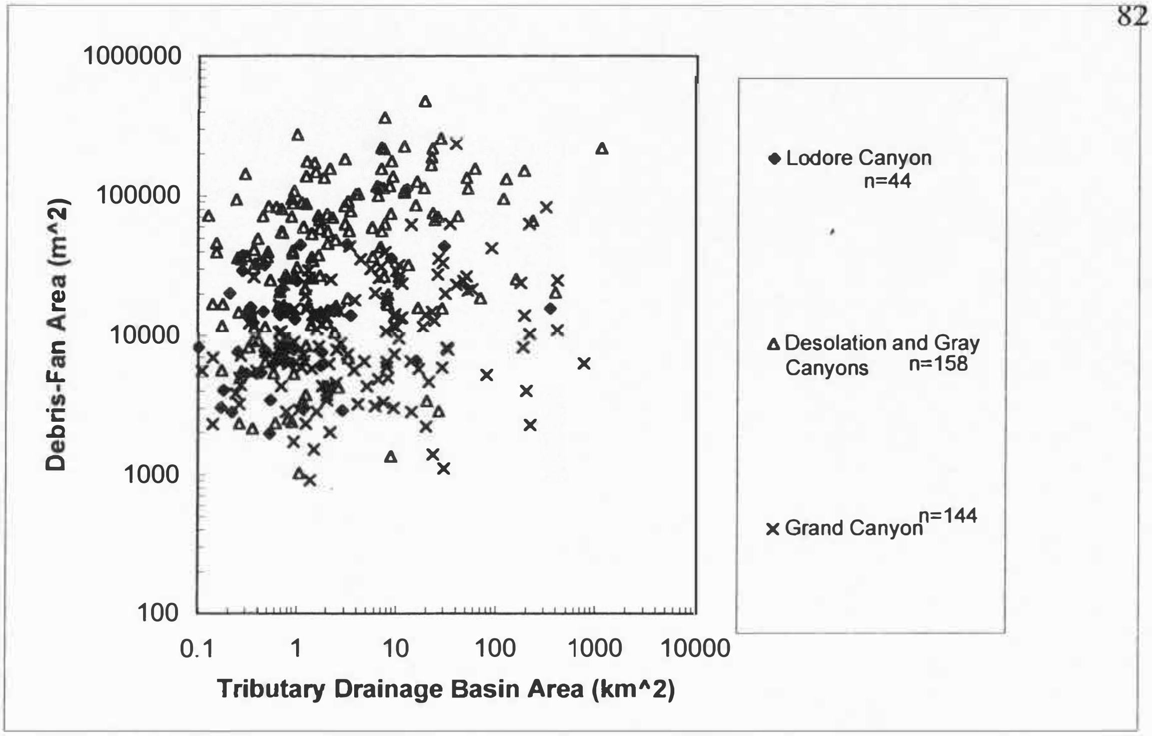


Figure 25. A) Box and whisker statistical plot of variation in the data set of valley width at debris fan locations in Lodore Canyon, Desolation and Gray Canyons, and Grand Canyon. B) Box and whisker statistical plot of variation in the data set for debris-fan area at debris fan locations in Lodore Canyon, Desolation and Gray Canyons, and Grand Canyon.

Catchment area does not predict debris fan area in Colorado Plateau canyons (Figure 26a). This is contrary to allometric relationships for alluvial fans developed in the Basin and Range and Central Valley provinces of the United States (Bull, 1968; Hooke, 1967; Leece, 1990), and later applied to alluvial and debris fan settings in a wide variety topographic and climatic settings (e.g., Kostaschuk et al., 1986; Kochel, 1990; Mills, 2000).

Instead, valley bottom width predicts debris fan area based on a power function in the canyons of the Colorado Plateau (Figure 26b). Accommodation space in the valley of the master stream provides space for debris-fan aggradation. Fundamental differences in rock strength, as well as the locations of faults and fractures allow for variation in valley width. Fans are larger in part because average valley width is wider in Desolation and Gray Canyons than the other canyon reaches. There is simply more space in the main-stem valley for debris-fan deposits.

Main-stem river slope is steeper in debris fan affected reaches than in neighboring canyon and alluvial reaches on the Colorado Plateau (Schmidt and Rubin, 1995; Grams and Schmidt, 1999). However, the steepest reaches do not occur where fans are largest (Figure 27a). The steepest reach gradients occur in Lodore Canyon and Grand Canyon, not Desolation Canyon (Figure 27b). Debris-fan frequency, as argued by previous researchers, influences main-stem slope more than debris fan size (Grams and Schmidt, 1999).



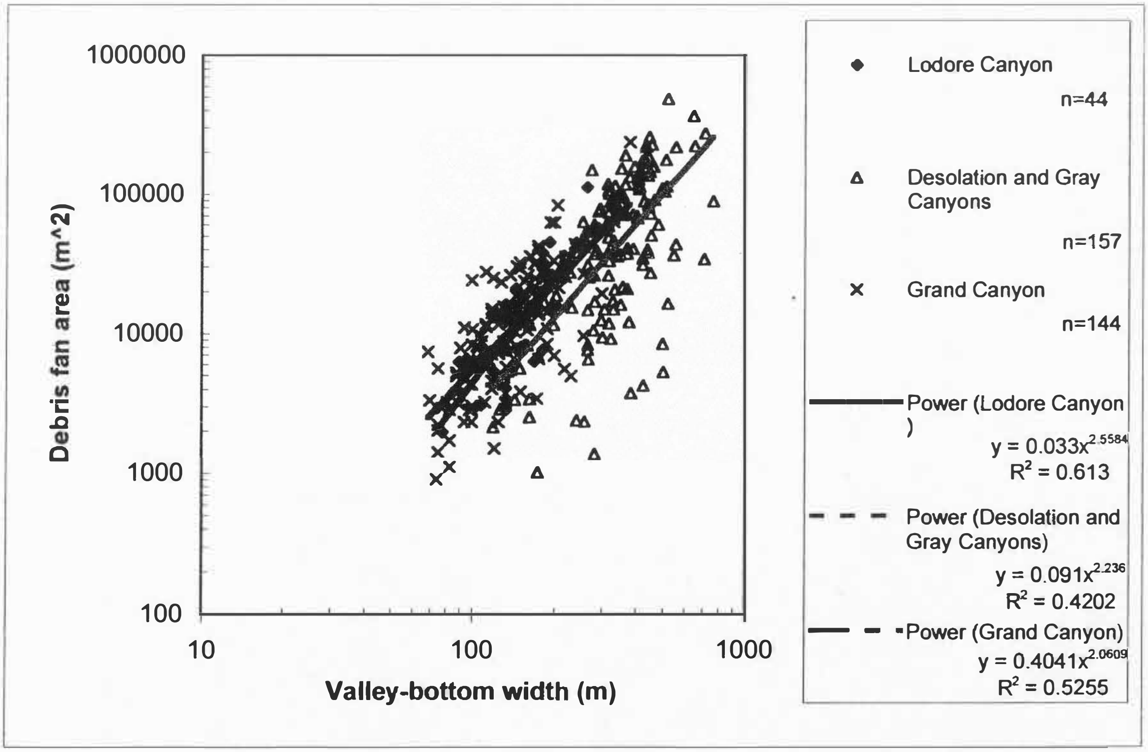
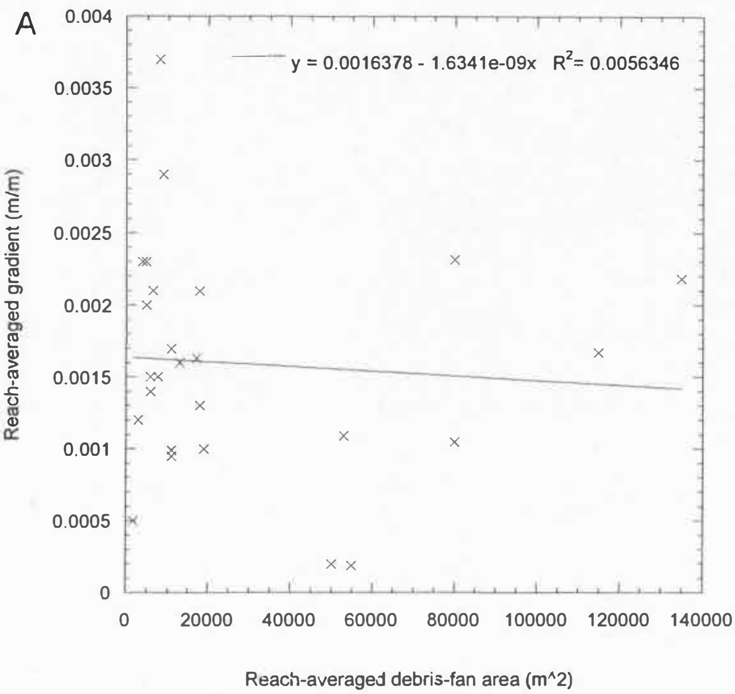


Figure 26. A) Relationship between debris-fan area and drainage-basin area for fans in Lodore Canyon, Desolation and Gray Canyons, and Grand Canyon. B) Relationship between debris-fan area and valley-bottom width in Lodore Canyon, Desolation and Gray Canyons, and Grand Canyon.



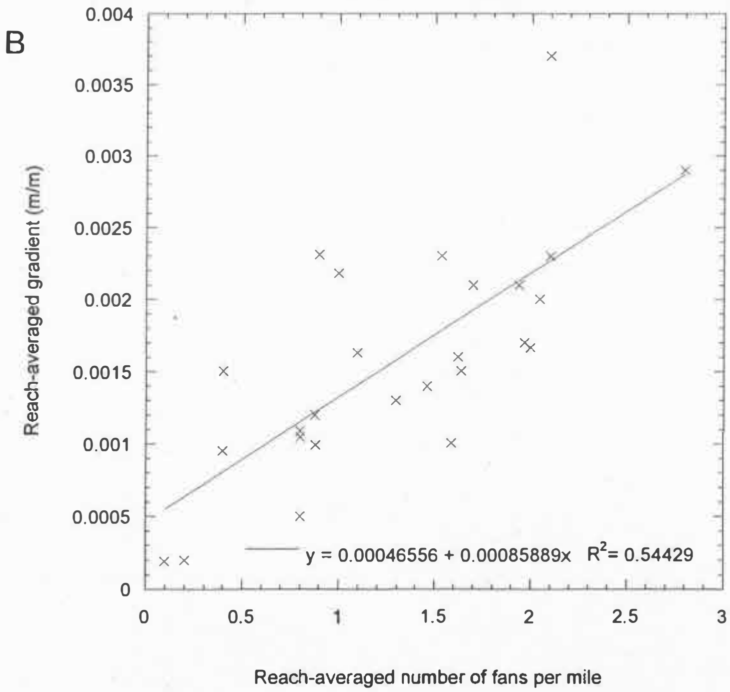


Figure 27. A) Correlation between reach-averaged debris-fan area and mainstem river slope for Colorado Plateau reaches in narrow canyons listed in Table 1. B) Relationship between reach-averaged mainstem river slope and debris-fan frequency for Colorado Plateau reaches in narrow canyons listed in Table 1.

DISCUSSION AND CONCLUSIONS

Debris-flow event frequency and magnitude, while not addressed in this study, may play important roles in determining mainstem slope. Climate variation between the northern and southern Colorado Plateau may be related to differences in debris flow activity within the region. Debris-flow generating storms in Grand Canyon have been both localized and regional including summer monsoon thunderstorms, dissipating tropical cyclones, and winter frontal storms (Melis et al., 1995). The role of the summer monsoon decreases as one moves northward on the Colorado Plateau. Martin (2000) suggested that fire cycles may play a greater role in determining debris flow frequency on the more densely forested northern edge of the region in the Uinta Mountains. It is likley also, that the varying lithologies in catchments affects debris flow magnitude and frequecy, and therefore debris fan size.

Desolation and Gray Canyons have the largest debris fan areas and widest valley widths on the Colorado Plateau. Allometric fan-basin relationships deveoloped for alluvial and debris fans in unconstrained valleys do not apply to narrow canyons. Instead, debris fan size is controlled by valley the accomodation space avalible for fan formation in valley bottoms. Bedrock valley width is determined by the lithology and structure of geologic units. Ultimately, tributary spacing is also dependant on canyon lithology and structure, therefore mainstem slope is most directly related to the geologic setting of the canyon, both in determining fan spacing, valley width, whether debris flows occur, and the sizes and lithologies of boulders that end up in the river channel.

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CHAPTER IV

CONCLUSION

Debris flow processes and debris fans are not unique attributes of streams of the Colorado Plateau. They occur in a wide variety of climatic settings and regions throughout the world. However, debris fans that form in narrow gorges with considerable trunk streams are unique attributes of the Colorado and Green Rivers. These debris fans are limited in size by the alluvial valley width of their depositional site. Characteristic alluvial valley widths of the Colorado and Green Rivers are created by differential erosion of the geologic units that outcrop on the Colorado Plateau.

The secondary process of debris fan re-working by the Colorado and Green Rivers is important as it shapes both debris fan and river form. In most settings the Colorado and Green Rivers do not flow on bedrock, but through alluvium and tributary debris fan deposits that have filled these canyons. In narrow canyon settings where resistant lithologies outcrop the alluvial valley is hardly wider than a channel width, debris fans often occur as boulder piles in the channel significantly constricting the channel creating large rapids that are substantial obstacles to navigation. In wide valley settings where less resistant rock units outcrop debris fans can reach considerable sizes, yet may mildly constrict the river which meanders around debris fans much like an alluvial stream meanders through a wide floodplain. Large debris fans in wide valley settings typically support smaller rapids yet frequent gravel bars.

In contrast to debris fans formed in unconstrained structural valleys, or debris fans formed in narrow valleys with minor trunk streams, the sizes of debris fans in narrow canyons are controlled by both the size of the alluvial valley at a depositional site, and the degree to which the mainstem river reworks the debris fan. Therefore, drainage basin size does not play a major role in determining debris fan size for debris-fan affected canyons on the Colorado Plateau. Bedrock valley width is determined by the lithology and structure of geologic units and ultimately, tributary spacing is also dependant on canyon lithology and structure, therefore mainstem river slope is most directly related to the geologic setting of the canyon, both in determining fan spacing, valley width, whether debris flows occur, and the sizes and lithologies of boulders that end up in the river channel. Thus, the unique geologic history and varied lithologies of the Colorado Plateau, as well as the hydrology of the Colorado and Green Rivers and their tributaries shape the landscape to create the unique landforms of the region.

APPENDICES

APPENDIX A. List of Geomorphically Significant Tributaries

River mile	River km	side	Tributary Name	Rapid Name And Rating (Belknap, 1992)	USGS Topographic Quadrangle
96	154.5	R	Sand Wash	-	Duches Hole
94.3	151.8	R	-	-	Duches Hole
93.7	150.8	R	9-Mile Canyon	-	Duches Hole
92.2	148.4	L	-	-	Duches Hole
90	144.8	L	-	-	Duches Hole
88	141.6	R	-	-	Duches Hole
87.5	140.8	L	-	-	Duches Hole
87	140.0	L	-	-	Duches Hole
86.8	139.7	L	Tabyago Canyon	Tabaygo Riffle	Duches Hole
86.7	139.5	L	-	-	Duches Hole
84.7	136.3	R	-	-	Duches Hole
84	135.2	R	Maverick Bottom	-	Duches Hole
83.1	133.7	R	-	-	Duches Hole
82.8	133.3	R	-	-	Duches Hole
81.5	131.2	L	Gold Hole- Rincon	-	Duches Hole
81.4	131.0	L	Gold Hole- Rincon	-	Duches Hole/Firewater Cyn N
80.9	130.2	R	-	-	Duches Hole/Firewater Cyn N
80	128.7	R	Rock House Canyon	Rock House Rapids (1)	Firewater Canyon North
79	127.1	L	Little Rock House Canyon	Little Rock House Rapids (1)	Firewater Canyon North
77.7	125.0	L	-	-	Firewater Canyon North
77.3	124.4	L	-	-	Firewater Canyon North
75.3	121.2	R	-	-	Firewater Canyon North
74.4	119.7	R	-	-	Firewater Canyon North
74	119.1	R	-	-	Firewater Canyon North
73.9	118.9	R-A	-	-	Firewater Canyon North
73.9	118.9	R-B	-	-	Firewater Canyon North
71.4	114.9	L	-	-	Firewater Canyon North
71.1	114.4	L	-	-	Firewater Canyon North
70.7	113.8	L	-	-	Firewater Canyon North
69.8	112.3	R	Jack Creek	Jack Creek Rapids (3)	Firewater Canyon North
68.8	110.7	R	Lunt's Horse Pasture	-	Cedar Ridge Canyon
68.7	110.6	R	Lunt's Horse Pasture	-	Cedar Ridge Canyon
68.4	110.1	R	Lunt's Horse Pasture	-	Cedar Ridge/Firewater Cyn N
68.3	109.9	R	Lunt's Horse Pasture	-	Firewater Canyon North
67.5	108.6	R		-	Firewater Canyon North
67.5	108.6	L	-	-	Firewater Canyon North
67	107.8	L	Big Canyon	Big Canyon Rapids (2)	Firewater Canyon North
66.5	107.0	L	-	-	Firewater Canyon North
66.3	106.7	R	-	-	Firewater Canyon North
66.1	106.4	L		-	Firewater Canyon North
66	106.2	L	Upper Firewater Canyon	-	Firewater Canyon North
65.8	105.9	L	Firewater Canyon	Firewater Rapids (2)	Firewater Canyon North
65.5	105.4	R	Cedar Ridge Canyon	Cedar Ridge Rapids (2)	Firewater Canyon North
65	104.6	L	-	riffle (1)	Firewater Canyon North

River mile	River km	side	Tributary Name	Rapid Name And Rating (Belknap, 1992)	USGS Topographic Quadrangle
64.8	104.3	L	-	-	Firewater Canyon North
63.9	102.8	R	-	-	Cedar Ridge Canyon
63.6	102.4	R	-	-	Cedar Ridge Canyon
63	101.4	R	Flat Canyon	Flat Canyon Rapids (2)	Cedar Ridge Canyon
62.2	100.1	L	-	-	Cedar Ridge Canyon
62.1	99.9	L	-	-	Cedar Ridge Canyon
62	99.8	L	Dripping Springs	riffle (2)	Firewater Canyon North
61.9	99.6	L	-	-	Firewater Canyon North
61	98.2	R	-	-	Steer Ridge
60.8	97.8	L	-	-	Steer Ridge
60.4	97.2	L	-	-	Steer Ridge
60.2	96.9	L	-	-	Steer Ridge
60.2	96.9	R	-	riffle (2)	Steer Ridge
60	96.6	L	-	-	Steer Ridge
60	96.6	R	-	riffle (2)	Steer Ridge
59.4	95.6	R	Fretwater	Fretwater Falls (3)	Steer Ridge
58.8	94.6	R	-	-	Steer Ridge
58.4	94.0	L	Wild Horse Canyon	Wild Horse Rapids (1)	Steer Ridge
57.9	93.2	L	-	riffle	Steer Ridge
57.6	92.7	L	-	-	Steer Ridge
57.5	92.5	L	-	riffle (3)	Steer Ridge
57.3	92.2	R	-	riffle (3)	Steer Ridge
56.8	91.4	L	-	-	Steer Ridge
56.5	90.9	R	-	Steer Ridge Rapids (5)	Steer Ridge
56.4	90.8	R	Steer Ridge Canyon	-	Steer Ridge
55.9	90.0	R	-	riffle (2)	Steer Ridge
55.8	89.8	R	Surprise Canyon	Surprise Rapid (4)	Steer Ridge
55.4	89.2	L	-	-	Steer Ridge
55.1	88.7	L	-	-	Steer Ridge
54.9	88.4	L	-	-	Steer Ridge
54.7	88.0	L	Log Cabin	Log Cabin Rapids (3)	Steer Ridge
54.3	87.4	L	-	small rapid (3)	Steer Ridge
54.2	87.2	L	-	-	Steer Ridge
54	86.9	R	Rock Creek	Rock Creek Rapids (2)	Steer Ridge
52.9	85.1	R	-	-	Steer Ridge
52.7	84.8	R	-	riffle (1)	Steer Ridge
52.4	84.3	R	Calf Canyon	Calf Canyon Rapids (2)	Steer Ridge
51.3	82.6	R	Snap Canyon	riffle (3)	Steer Ridge
51	82.1	L	-	Snap Canyon Rapids (4)	Steer Ridge
50.8	81.8	L	-	riffle (2)	Steer Ridge
49.8	80.1	R	Three Canyon Rincon	riffle (1)	Steer Ridge/Chandler Falls
49.7	80.0	R	Three Canyon Rincon	-	Chandler Falls
49	78.9	L	-	small rapid (2)	Chandler Falls
48.6	78.2	L	Belknap	Belknap Falls (5)	Chandler Falls
48	77.2	R	Lion Hollow	riffle (1)	Chandler Falls
47.5	76.4	L	-	-	Chandler Falls
47.2	76.0	R	-	riffle (1)	Chandler Falls

River mile	River km	side	Tributary Name	Rapid Name And Rating (Belknap, 1992)	USGS Topographic Quadrangle
47	75.6	L	Chandler Canyon	Chandler Falls (3)	Chandler Falls
46.1	74.2	R	-	riffle	Chandler Falls
45.9	73.9	R	Trail Canyon	Trail Canyon Rapids (3)	Chandler Falls
45.8	73.7	L	-	riffle	Chandler Falls
45.7	73.5	L	-	riffle	Chandler Falls
45.5	73.2	L	Bluebell Creek	riffle	Chandler Falls
44.2	71.1	R	Bull Canyon	Bull Canyon Rapids (2)	Chandler Falls
44.1	71.0	L	-	riffle	Chandler Falls
43.3	69.7	R	-	very small riffle	Chandler Falls
43	69.2	L	-	riffle	Chandler Falls
42.9	69.0	R	Moonwater Canyon	Moonwater Rapids (3)	Chandler Falls
42.6	68.6	R	Big Canyon	Red Point Rapids (3)	Chandler Falls
42.2	67.9	L	-	riffle	Chandler Falls
41.5	66.8	L	Joe Hutch Creek	Joe Hutch Creek Rapid (4)	Chandler Falls
40.9	65.8	R	-	riffle	Chandler Falls
40.5	65.2	R	Joe Hutch Canyon	Joe Hutch Canyon Rapid (4)	Chandler Falls
39.9	64.2	L	-	riffle (2)	Chandler Falls
39.6	63.7	L	-	riffle (2)	Chandler Falls
38.9	62.6	R	Rain Canyon	riffle	Chandler Falls
38.7	62.3	L	Florence Creek	riffle (2)	Three Fords Canyon
38	61.2	L	-	-	Three Fords Canyon
37.3	60.0	L	-	-	Three Fords Canyon
37	59.5	R	Wire Fence Canyon	Wire Fence Rapid (4)	Three Fords Canyon
36.5	58.7	L	Three Fords Canyon	Three Fords Rapid (6)	Three Fords Canyon
35.2	56.6	R	Three Fords Canyon-R	riffle	Three Fords Canyon
35.2	56.6	L	-	riffle	Three Fords Canyon
34.4	55.4	L	-	-	Three Fords Canyon
34.2	55.0	L	-	-	Three Fords Canyon
33.4	53.8	R	-	-	Three Fords Canyon
32.5	52.3	R	Last Chance Canyon	-	Three Fords Canyon
32.3	52.0	L	Spring Wash Canyon	Last Chance Rapid (1)	Three Fords Canyon
31.5	50.7	R	Range Creek	Range Creek Rapids (3)	Three Fords Canyon
30.9	49.7	L	-	-	Three Fords Canyon
29.5	47.5	L	Beaver Slide Bottom	-	Three Fords Canyon
28.9	46.5	R	Rabbit Valley	Rabbit Valley Rapids (3)	Three Fords Canyon
28.7	46.2	L	-	-	Three Fords Canyon
28.3	45.5	R	Curry Canyon	riffle (1)	Three Fords Canyon
28	45.1	R		Curry Rapids (1)	Three Fords Canyon
27.8	44.7	R	-	-	Three Fords Canyon
27.2	43.8	L	-	-	Three Fords Canyon
26.8	43.1	L	Saleratus Canyon	Saleratus Rapids (1)	Three Fords Canyon
26.8	43.1	R	-	Saleratus Rapids	Three Fords Canyon
26.3	42.3	R	-	-	Three Fords Canyon
26.2	42.2	R	-	Coal Creek Rapid	Three Fords Canyon
26.2	42.2	L	Coal Creek	Coal Creek Rapid (6)	Three Fords Canyon
25.6	41.2	R	-	-	Butler Canyon
25.3	40.7	L	Poverty Canyon	Poverty Rapid (1)	Butler Canyon

River mile	River km	side	Tributary Name	Rapid Name And Rating (Belknap, 1992)	USGS Topographic Quadrangle
23.1	37.2	R	-	riffle	Butler Canyon
23	37.0	R	-	-	Butler Canyon
22.9	36.9	R	-	-	Butler Canyon
22.3	35.9	R	School Section Canyon	-	Butler Canyon
22.2	35.7	L	Rattlesnake Canyon	Rattlesnake Rapids (4)	Butler Canyon
21	33.8	R	-	-	Butler Canyon
21	33.8	L	-	riffle (1)	Butler Canyon
20.1	32.3	L	Nefertiti Canyon	Nefertiti Rapids (2)	Butler Canyon
19.3	31.1	R	-	-	Butler Canyon
19.1	30.7	R	-	-	Butler Canyon
18.2	29.3	R	Price River	-	Butler Canyon
17.1	27.5	L	-	Riffle (1)	Butler Canyon
17	27.4	L	-	-	Butler Canyon
16.8	27.0	R	-	-	Butler Canyon
16.5	26.6	R	-	-	Butler Canyon
16.3	26.2	R	-	-	Butler Canyon
16.1	25.9	R	-	Butler Rapids	Butler Canyon
16.1	25.9	L	Butler Canyon	Butler Rapids (2)	Butler Canyon
15.2	24.5	R	Sand Knolls Canyon	Sand Knolls Rapids (3)	Tusher Canyon
14.8	23.8	L	-	-	Tusher Canyon
14.3	23.0	L	Stone House	Stone Cabin Rapids (4)	Tusher Canyon
14	22.5	L	-	-	Tusher Canyon
13.1	21.1	R	Short Canyon	Short Canyon Rapids (3)	Tusher Canyon
12.8	20.5	R	-	-	Tusher Canyon
12.3	19.7	R	Long Canyon	Swasey's Rapid (2)	Tusher Canyon
12.3	19.7	L	Swasey's	Swasey's Rapid (2)	Tusher Canyon

APPENDIX B. Drainage-basin Characteristics

River Mile	River km	side	Tributary name	Drainage Basin Area (km^2)	Basin Max. elev. (m)	Basin Min. elev. (m)	Basin total relief (m)	Trib. Chan. Total slope (m/m)	Slope of last 1000m Trib Ch.	Basin Max length (m)	Basin Max. Width (m)	Basin l/w	Basin Rugg.
96	154.5	R	Sand Wash	27.66	2073	1418	655	0.0405	0.0269	12450	3264	3.81	0.12
94.3	151.8	R	-	2.62									
93.7	150.8	R	9-Mile Canyon	1156.0	2819	1406	1413	0.0076	0.0006	56718	17851	3.18	0.04
92.2	148.4	L	-	7.51									
90	144.8	L	-	1.69									
88	141.6	R	-	0.93	1727	1411	316	0.1385	0.1160	1231	1048	1.17	0.33
87.5	140.8	L	-	0.64									
87	140.0	L	-	0.80									
86.8	139.7	L	Tabyago Canyon	231.30									
86.7	139.5	L	-	1.41									
84.7	136.3	R	-	1.46									
84	135.2	R	Maverick Bottom	7.32	1868	1407	461	0.0682	0.0390	4387	2901	1.51	0.17
83.1	133.7	R	-	0.41									
82.8	133.3	R	-	0.88									
81.5	131.2	L	Gold Hole- Rincon	0.09									
81.4	131.0	L	Gold Hole- Rincon	3.26									
80.9	130.2	R	-	2.05	1874	1404	470	0.1104	0.1130	2633	1170	2.25	0.33
80	128.7	R	Rock House Canyon	22.19	2055	1402	653	0.0371	0.0294	8595	4310	1.99	0.14
79	127.1	L	Little Rock House Canyon	18.92	2058	1400	658	0.0584	0.0450	15340	4920	3.12	0.15
77.7	125.0	L	-	0.51									
77.3	124.4	L	-	0.69									
75.3	121.2	R	-	2.01									
74.4	119.7	R	-	2.04									
74	119.1	R	-	3.31	2021	1401	620	0.1200	0.0771	2984	1812	1.65	0.34
73.9	118.9	R-A	-	1.40									
73.9	118.9	R-B	-	0.91									
71.4	114.9	L	-	0.88									
71.1	114.4	L	-	0.50									
70.7	113.8	L	-	0.68									
69.8	112.3	R	Jack Creek	126.06	2750	1396	1354	0.0352	0.0277	24002	7170	3.35	0.12
68.8	110.7	R	Lunt's Horse Pasture	0.13	2065	1397	668	0.1923	0.0840	2400	852	2.82	1.87
68.7	110.6	R	Lunt's Horse Pasture	9.08	2130	1394	736	0.0936	0.0609	5270	3172	1.66	0.24
68.4	110.1	R	Lunt's Horse Pasture	0.15	1845	1399	446	0.3203	0.3203	656	400	1.64	1.14
68.3	109.9	R	Lunt's Horse Pasture	0.45	2009	1398	611	0.3761	0.3760	1250	840	1.49	0.91
67.5	108.6	R		0.48									
67.5	108.6	L	-	0.48									
67	107.8	L	Big Canyon	61.48	2423	1392	1031	0.0362	0.0360	15340	4290	3.58	0.13
66.5	107.0	L	-	0.26									
66.3	106.7	R	-	0.31									
66.1	106.4	L		0.14	1850	1397	453	0.3766	0.3768	790	340	2.32	1.21
66	106.2	L	Upper Firewater Canyon	3.02	2066	1393	673	0.1541	0.1205	3200	1270	2.52	0.39
65.8	105.9	L	Firewater Canyon	50.61	2519	1391	1128	0.0531	0.0460	14640	5555	2.64	0.16

River Mile	River km	side	Tributary name	Drainage Basin Area (km^2)	Basin Max. elev. (m)	Basin Min. elev. (m)	Basin total relief (m)	Trib. Chan. Total slope (m/m)	Slope of last 1000m Trib Ch.	Basin Max length (m)	Basin Max. Width (m)	Basin l/w	Basin Rugg.
65.5	105.4	R	Cedar Ridge Canyon	26.28	2632	1391	1241	0.0548	0.0572	12275	3700	3.32	0.24
65	104.6	L	-	0.71	2107	1390	717	0.3098	0.2230	1540	590	2.61	0.85
64.8	104.3	L	-	0.31	2025	1390	635	0.3754	0.3757	860	710	1.21	1.14
63.9	102.8	R	-	0.88	2036	1390	646	0.2878	0.1855	1520	1060	1.43	0.69
63.6	102.4	R	-	1.51	2169	1391	778	0.3191	0.1715	2130	980	2.17	0.63
63	101.4	R	Flat Canyon	118.47	2362	1391	971	0.0495	0.0310	12330	3760	3.28	0.09
62.2	100.1	L	-	1.71									
62.1	99.9	L	-	1.23									
62	99.8	L	Dripping Springs	0.30									
61.9	99.6	L	-	4.12									
61	98.2	R	-	0.38	2077	1384	693	0.4677	0.4670	1000	540	1.85	1.13
60.8	97.8	L	-	0.17									
60.4	97.2	L	-	0.51	1929	1382	547	0.1604	0.0920	1330	760	1.75	0.77
60.2	96.9	L	-	7.45	2269	1382	887	0.1383	0.0560	4780	2710	1.76	0.33
60.2	96.9	R	-	0.25									
60	96.6	L	-	1.24	2031	1381	650	0.1761	0.0930	1960	1410	1.39	0.58
60	96.6	R	-	11.93	2489	1380	1109	0.0946	0.0590	8425	1875	4.49	0.32
59.4	95.6	R	Fretwater	8.43	2449	1383	1066	0.1421	0.0623	6050	2700	2.24	0.37
58.8	94.6	R	-	0.36	2052	1379	673	0.4489	0.4490	1050	580	1.81	1.13
58.4	94	L	Wild Horse Canyon	23.26	2469	1377	1092	0.0838	0.0516	9200	4100	2.24	0.23
57.9	93.2	L	-	0.62									
57.6	92.7	L	-	0.51	2124	1375	749	0.3420	0.2580	1540	640	2.41	1.04
57.5	92.5	L	-	11.87	2378	1375	1003	0.1229	0.0550	6290	2982	2.11	0.29
57.3	92.2	R	-	1.24									
56.8	91.4	L	-	0.96	2152	1369	783	0.2740	0.2880	1780	1020	1.75	0.80
56.5	90.9	R	-	2.46	2302	1371	931	0.2010	0.0980	2940	1270	2.31	0.59
56.4	90.8	R	Steer Ridge Canyon	15.47	2513	1369	1144	0.1176	0.0503	8181	3451	2.37	0.29
55.9	90	R	-	0.36	1921	1372	549	0.2559	0.2560	1040	540	1.93	0.91
55.8	89.8	R	Surprise Canyon	1.42	2155	1370	785	0.2492	0.1576	1770	1400	1.26	0.66
55.4	89.2	L	-	0.15	2033	1365	668	0.4238	0.4237	890	280	3.18	1.71
55.1	88.7	L	-	0.37	2152	1365	787	0.4902	0.4900	1125	580	1.94	1.30
54.9	88.4	L	-	0.10	2151	1366	785	0.4888	0.4888	1140	480	2.38	2.52
54.7	88	L	Log Cabin	3.42	2375	1363	1012	0.2871	0.0926	3230	1420	2.27	0.55
54.3	87.4	L	-	1.17	2318	1339	979	0.3200	0.0175	2000	1100	1.82	0.90
54.2	87.2	L	-	0.70									
54	86.9	R	Rock Creek	146.59	3000	1358	1642	0.0506	0.0215	21255	13810	1.54	0.14
52.9	85.1	R	-	0.54									
52.7	84.8	R	-	0.91	2168	1353	815	0.3195	0.2290	1560	1050	1.49	0.85
52.4	84.3	R	Calf Canyon	7.03	2597	1358	1239	0.1555	0.0617	5025	2070	2.43	0.47
51.3	82.6	R	Snap Canyon	11.82	2721	1349	1372	0.0965	0.0510	9600	1690	5.68	0.40
51	82.1	L	-	7.00	2383	1347	1036	0.1681	0.0550	4820	2160	2.23	0.39
50.8	81.8	L	-	8.82	2421	1345	1076	0.1148	0.0659	6560	2140	3.07	0.36
49.8	80.1	R	Three Canyon Rincon	2.04									
49.7	80	R	Three Canyon Rincon	41.16									
49	78.9	L	-	3.88	2900	2000	1345	0.2432	0.0662	2900	2000	1.45	0.68

River Mile	River km	side	Tributary name	Drainage Basin Area (km^2)	Basin Max. elev. (m)	Basin Min. elev. (m)	Basin total relief (m)	Trib. Chan. Total slope (m/m)	Slope of last 1000m Trib Ch.	Basin Max length (m)	Basin Max. Width (m)	Basin l/w	Basin Rugg.
48.6	78.2	L	Belknap	0.91	2146	1338	808	0.3037	0.2183	1490	1311	1.14	0.85
48	77.2	R	Lion Hollow	3.05	2378	1341	1037	0.2007	0.0790	3530	1070	3.30	0.59
47.5	76.4	L	-	0.24									
47.2	76	R	-	1.65	2320	1339	981	0.2537	0.0950	2358	1225	1.92	0.76
47	75.6	L	Chandler Canyon	189.50	2709	1332	1377	0.0518	0.0307	18080	19719	0.92	0.10
46.1	74.2	R	-	1.70	2377	1329	1048	0.2475	0.1410	2860	840	3.40	0.80
45.9	73.9	R	Trail Canyon	22.68	2820	1330	1490	0.1064	0.0418	9230	3290	2.81	0.31
45.8	73.7	L	-	0.42	1806	1330	476	0.2510	0.2510	940	660	1.42	0.73
45.7	73.5	L	-	1.11	2184	1327	857	0.1921	0.0668	1943	775	2.51	0.81
45.5	73.2	L	Bluebell Creek	1.01	2594	1327	1267	0.1603	0.0500	5130	2820	1.82	1.26
44.2	71.1	R	Bull Canyon	6.31	2465	1324	1141	0.1351	0.0600	4950	1800	2.75	0.45
44.1	71	L	-	1.25									
43.3	69.7	R	-	2.27									
43	69.2	L	-	3.23	2404	1320	1084	0.2464	0.0600	3210	1560	2.06	0.60
42.9	69	R	Moonwater Canyon	1.26	1981	1318	663	0.1726	0.0560	2035	700	2.91	0.59
42.6	68.6	R	Big Canyon	24.36	2709	1318	1391	0.0868	0.0380	8600	5185	1.66	0.28
42.2	67.9	L	-	1.24	2065	1315	750	0.2145	0.1121	1650	1010	1.63	0.67
41.5	66.8	L	Joe Hutch Creek	19.22	2637	1317	1320	0.1335	0.0560	7135	4360	1.64	0.30
40.9	65.8	R	-	1.01									
40.5	65.2	R	Joe Hutch Canyon	6.68	2502	1311	1191	0.1387	0.0433	5615	2260	2.48	0.46
39.9	64.2	L	-	2.01	2309	1307	1002	0.2128	0.0509	2780	1150	2.42	0.71
39.6	63.7	L	-	2.99	2466	1307	1159	0.1880	0.0601	4150	1150	3.61	0.67
38.9	62.6	R	Rain Canyon	7.58	2448	1308	1140	0.1226		5147	2630	1.96	0.41
38.7	62.3	L	Florence Creek	143.12	2846	1313	1533	0.0493	0.0232	19430	12060	1.61	0.13
38	61.2	L	-	2.14									
37.3	60	L	-	1.88									
37	59.5	R	Wire Fence Canyon	6.47	2325	1300	1025	0.1087	0.0308	5630	2165	2.60	0.40
36.5	58.7	L	Three Fords Canyon	22.46	2723	1300	1423	0.0923	0.0402	6875	5320	1.29	0.30
35.2	56.6	R	Three Fords Canyon-R	5.70	2846	1313	1533	0.0934	0.0370	1298	2194	0.59	0.64
35.2	56.6	L	-	1.67	2012	1298	714	0.1292	0.0663	2270	970	2.34	0.55
34.4	55.4	L	-	1.54									
34.2	55	L	-	0.89	1565	1295	270	0.1431	0.1170	1530	770	1.99	0.29
33.4	53.8	R	-	0.61									
32.5	52.3	R	Last Chance Canyon	8.92	2137	1293	844	0.0583	0.0600	5015	2019	2.48	0.28
32.3	52	L	Spring Wash Canyon	5.79	2139	1291	848	0.0983	0.0416	4620	2310	2.00	0.35
31.5	50.7	R	Range Creek	369.55	3135	1290	1845	0.0211	0.0120	40000	15000	2.61	.096
30.9	49.7	L	-	2.39									
29.5	47.5	L	Beaver Slide Bottom	2.49	1812	1289	523	0.1171	0.1590	2545	1240	2.05	0.33
28.9	46.5	R	Rabbit Valley	28.73	1941	1285	656	0.0519	0.0190	8635	6165	1.40	0.12
28.7	46.2	L	-	0.17	1648	1285	363	0.2207	0.2207	835	310	2.69	0.87
28.3	45.5	R	Curry Canyon	8.18	1925	1283	642	0.0952	0.0660	4570	1950	2.34	0.25
28	45.1	R		0.80	1834	1283	551	0.2973	0.2550	2090	770	2.71	0.62
27.8	44.7	R	-	0.37	1764	1282	482	0.2543	0.2543	1185	550	2.15	0.79
27.2	43.8	L	-	0.58									
26.8	43.1	L	Saleratus Canyon	20.37	2673	1279	1394	0.0821	0.0248	9570	3165	3.02	0.31

River Mile	River km	side	Tributary name	Drainage Basin Area (km^2)	Basin Max. elev. (m)	Basin Min. elev. (m)	Basin total relief (m)	Trib. Chan. Total slope (m/m)	Slope of last 1000m Trib Ch.	Basin Max length (m)	Basin Max. Width (m)	Basin l/w	Basin Rugg.
26.8	43.1	R	-	0.82									
26.3	42.3	R	-	0.36									
26.2	42.2	R	-	1.16									
26.2	42.2	L	Coal Creek	69.84	2846	1278	1568	0.0523	0.0272	18665	8185	2.28	0.19
25.6	41.2	R	-	0.27									
25.3	40.7	L	Poverty Canyon	26.83	2190	1273	917	0.1726	0.0517	10940	3770	2.90	0.18
23.1	37.2	R	-	3.23									
23	37	R	-	0.34									
22.9	36.9	R	-	0.77									
22.3	35.9	R	School Section Canyon	13.16	1947	1270	677	0.0832	0.0533	5470	3330	1.64	0.19
22.2	35.7	L	Rattlesnake Canyon	158.91	2881	1268	1613	0.0393	0.0168	25670	9980	2.57	0.13
21	33.8	R	-	1.07									
21	33.8	L	-	3.27									
20.1	32.3	L	Nefertiti Canyon	8.18	1948	1265	683	0.0992	0.0348	4730	1900	2.49	0.24
19.3	31.1	R	-	1.31									
19.1	30.7	R	-	1.74									
18.2	29.3	R	Price River	3026.94	2998	1260	1738	0.0040	0.0033				0.31
17.1	27.5	L	-	8.77									
17	27.4	L	-	0.40									
16.8	27	R	-	0.26									
16.5	26.6	R	-	0.48									
16.3	26.2	R	-	0.32									
16.1	25.9	R	-	1.43	1789	1257	532	0.1920	0.5889	2200	990	2.22	0.44
16.1	25.9	L	Butler Canyon	16.58	1948	1257	691	0.0465	0.0395	9000	4300	2.09	0.17
15.2	24.5	R	Sand Knolls Canyon	7.66	1842	1256	586	0.0880	0.0379	5260	2200	2.39	0.21
14.8	23.8	L	-	0.18									
14.3	23	L	Stone House	7.06	1746	1250	496	0.0989	0.0294	3180	2800	1.14	0.19
14	22.5	L	-	0.28									
13.1	21.1	R	Short Canyon	16.01	1884	1256	628	0.0620	0.0259	5400	2670	2.02	0.16
12.8	20.48	R	-	0.94									
12.3	19.68	R	Long Canyon	52.19	1890	1251	639	0.1041	0.0287	4500	2600	1.73	0.09
12.3	19.68	L	Swasey's	6.86	2073	1418	655	0.0405	0.0269	12450	3264	3.81	0.12

APPENDIX C. Valley-bottom Characteristics

River mile	River km	side	Tributary name	Bedrock unit exposed at river level	Average valley-bottom width (m)	Tributary valley bottom width (m)	Ratio of valley width to average channel width
96	154.5	R	Sand Wash	Green River Fm	448	145	1.95
94.3	151.8	R	-	Green River Fm	425	70	2.74
93.7	150.8	R	9-Mile Canyon	Green River Fm	439	175	2.86
92.2	148.4	L	-	Green River Fm	451	120	2.73
90	144.8	L	-	Green River Fm	405	80	2.66
88	141.6	R	-	Green River Fm	505	85	
87.5	140.8	L	-	Green River Fm	525	90	3.18
87	140.0	L	-	Green River Fm	281	85	1.88
86.8	139.7	L	Tabyago Canyon	Green River Fm	331	180	5.10
86.7	139.5	L	-	Green River Fm	379	95	3.79
84.7	136.3	R	-	Green River Fm	424	110	3.10
84	135.2	R	Maverick Bottom	Green River Fm	411	155	2.22
83.1	133.7	R	-	Green River Fm	303	75	1.89
82.8	133.3	R	-	Green River Fm	268	100	1.95
81.5	131.2	L	Gold Hole- Rincon	Green River Fm	455	235	2.28
81.4	131.0	L	Gold Hole- Rincon	Green River Fm	500	340	3.03
80.9	130.2	R	-	Green River Fm	333	65	2.29
80	128.7	R	Rock House Canyon	Green River/Colton	426	145	2.22
79	127.1	L	Little Rock House Canyon	Green River/Colton	335	180	2.18
77.7	125.0	L	-	Green River/Colton	390	95	3.18
77.3	124.4	L	-	Green River/Colton	444	60	3.11
75.3	121.2	R	-	Green River/Colton	299	140	2.30
74.4	119.7	R	-	Green River/Colton	231	90	1.71
74	119.1	R	-	Green River/Colton	311	90	2.49
73.9	118.9	R-A	-	Green River/Colton	350	114	2.92
73.9	118.9	R-B	-	Green River/Colton	373	110	2.57
71.4	114.9	L	-	Green River/Colton	391	85	2.90
71.1	114.4	L	-	Green River/Colton	373	105	3.10
70.7	113.8	L	-	Green River/Colton	373	95	3.47
69.8	112.3	R	Jack Creek	Green River/Colton	380	155	2.48
68.8	110.7	R	Lunt's Horse Pasture	Green River/Colton	353	60	4.15
68.7	110.6	R	Lunt's Horse Pasture	Green River/Colton	414	285	4.07
68.4	110.1	R	Lunt's Horse Pasture	Green River/Colton	440	85	3.66
68.3	109.9	R	Lunt's Horse Pasture	Green River/Colton	452	120	3.47
67.5	108.6	R		Green River/Colton	268	35	1.76
67.5	108.6	L	-	Green River/Colton	268	65	1.75
67	107.8	L	Big Canyon	Green River/Colton	394	205	2.79
66.5	107.0	L	-	Green River/Colton	260	15	2.00
66.3	106.7	R	-	Green River/Colton	333	70	2.15
66.1	106.4	L		Green River/Colton	330	90	2.20
66	106.2	L	Upper Firewater Canyon	Green River/Colton	354	150	2.92
65.8	105.9	L	Firewater Canyon	Green River/Colton	406	200	4.67
65.5	105.4	R	Cedar Ridge Canyon	Green River/Colton	358	175	2.49

River mile	River km	side	Tributary name	Bedrock unit exposed at river level	Average valley-bottom width (m)	Tributary valley bottom width (m)	Ratio of valley width to average channel width
65	104.6	L	-	Colton Formation	278	150	2.78
64.8	104.3	L	-	Colton Formation	316	90	2.81
63.9	102.8	R	-	Colton Formation	333	110	4.16
63.6	102.4	R	-	Colton Formation	421	145	3.16
63	101.4	R	Flat Canyon	Colton Formation	360	160	2.10
62.2	100.1	L	-	Colton Formation	318	150	3.43
62.1	99.9	L	-	Colton Formation	358	150	4.77
62	99.8	L	Dripping Springs	Colton Formation	450	125	6.00
61.9	99.6	L	-	Colton Formation	509	235	3.13
61	98.2	R	-	Colton Formation	320	80	2.06
60.8	97.8	L	-	Colton Formation	319	75	2.97
60.4	97.2	L	-	Colton Formation	528	230	5.86
60.2	96.9	L	-	Colton Formation	560	120	6.59
60.2	96.9	R	-	Colton Formation	550	15	6.23
60	96.6	L	-	Colton Formation	323	110	2.42
60	96.6	R	-	Colton Formation	498	250	4.66
59.4	95.6	R	Fretwater	Colton Formation	316	190	1.69
58.8	94.6	R	-	Colton Formation	325	140	2.17
58.4	94	L	Wild Horse Canyon	Colton Formation	293	180	2.19
57.9	93.2	L	-	Colton Formation	328	150	2.18
57.6	92.7	L	-	Colton Formation	443	50	4.54
57.5	92.5	L	-	Colton Formation	456	140	2.85
57.3	92.2	R	-	Colton Formation	384	30	3.34
56.8	91.4	L	-	Colton Formation	273	100	2.87
56.5	90.9	R	-	Colton Formation	317	120	3.39
56.4	90.8	R	Steer Ridge Canyon	Colton Formation	338	175	3.56
55.9	90	R	-	Colton Formation	267	93	1.98
55.8	89.8	R	Surprise Canyon	Colton Formation	263	123	2.82
55.4	89.2	L	-	Colton Formation	261	30	2.09
55.1	88.7	L	-	Colton Formation	259	30	2.77
54.9	88.4	L	-	Colton Formation	240	90	2.29
54.7	88	L	Log Cabin	Colton Formation	296	105	3.12
54.3	87.4	L	-	Colton Formation	281	70	3.38
54.2	87.2	L	-	Colton Formation	296	80	3.17
54	86.9	R	Rock Creek	Colton Formation	298	175	2.59
52.9	85.1	R	-	Colton Formation	270	80	1.77
52.7	84.8	R	-	Colton Formation	429	90	3.68
52.4	84.3	R	Calf Canyon	Colton Formation	436	170	3.85
51.3	82.6	R	Snap Canyon	Colton Formation	318	150	2.93
51	82.1	L	-	Colton Formation	465	150	4.89
50.8	81.8	L	-	Colton Formation	430	105	5.55
49.8	80.1	R	Three Canyon Rincon	Colton Formation	280	330	2.43
49.7	80	R	Three Canyon Rincon	Colton Formation	345	215	5.31
49	78.9	L	-	Colton Formation	353	145	3.85
48.6	78.2	L	Belknap	Colton Formation	288	95	2.92

River mile	River km	side	Tributary name	Bedrock unit exposed at river level	Average valley-bottom width (m)	Tributary valley bottom width (m)	Ratio of valley width to average channel width
48	77.2	R	Lion Hollow	Colton Formation	255	95	2.22
47.5	76.4	L	-	Colton Fm- shale unit	350	20	2.92
47.2	76	R	-	Colton Fm- shale unit	365	110	3.84
47	75.6	L	Chandler Canyon	Colton Fm- shale unit	354	280	2.87
46.1	74.2	R	-	Colton Fm- shale unit	278	110	2.16
45.9	73.9	R	Trail Canyon	Colton Fm- shale unit	654	190	5.23
45.8	73.7	L	-	Colton Fm- shale unit	708	30	5.15
45.7	73.5	L	-	Colton Fm- shale unit	767	135	6.26
45.5	73.2	L	Bluebell Creek	Colton Fm- shale unit	713	210	6.20
44.2	71.1	R	Bull Canyon	Colton Fm- shale unit	366	320	3.05
44.1	71	L	-	Colton Fm- shale unit	500	75	4.35
43.3	69.7	R	-	Colton Fm- shale unit	404	115	3.85
43	69.2	L	-	Colton Fm- shale unit	468	165	3.90
42.9	69	R	Moonwater Canyon	Colton Fm- shale unit	516	250	4.13
42.6	68.6	R	Big Canyon	Colton Fm- shale unit	403	185	3.22
42.2	67.9	L	-	Colton Fm- shale unit	421	190	2.57
41.5	66.8	L	Joe Hutch Creek	Colton Fm- shale unit	523	385	2.80
40.9	65.8	R	-	Colton Fm- shale unit	423	95	3.52
40.5	65.2	R	Joe Hutch Canyon	Colton Fm- shale unit	408	220	4.53
39.9	64.2	L	-	Colton Fm- shale unit	318	150	3.81
39.6	63.7	L	-	Colton Fm- shale unit	444	140	4.23
38.9	62.6	R	Rain Canyon	Colton Fm- shale unit	649	230	5.72
38.7	62.3	L	Florence Creek	Colton Fm- shale unit	729	100	4.86
38	61.2	L	-	North Horn Fm	460	170	2.85
37.3	60	L	-	North Horn Fm	443	190	3.05
37	59.5	R	Wire Fence Canyon	North Horn Fm	320	240	2.78
36.5	58.7	L	Three Fords Canyon	Flagstaff Limestone	365	335	2.03
35.2	56.6	R	Three Fords Canyon-R	Flagstaff Limestone	483	230	2.00
35.2	56.6	L	-	Mesa Verde Fm	443	110	2.39
34.4	55.4	L	-	Mesa Verde Fm	276	115	2.81
34.2	55	L	-	Mesa Verde Fm	243	5	2.49
33.4	53.8	R	-	Mesa Verde Fm	260	10	2.89
32.5	52.3	R	Last Chance Canyon	Mesa Verde Fm	283	40	5.30
32.3	52	L	Spring Wash Canyon	Mesa Verde Fm	284	80	2.79
31.5	50.7	R	Range Creek	Mesa Verde Fm	335	95	2.45
30.9	49.7	L	-	Mesa Verde Fm	280	105	2.55
29.5	47.5	L	Beaver Slide Bottom	Mesa Verde Fm	174	75.0	1.53
28.9	46.5	R	Rabbit Valley	Mesa Verde Fm	206	150	2.03
28.7	46.2	L	-	Mesa Verde Fm	150	35	2.07
28.3	45.5	R	Curry Canyon	Mesa Verde Fm	184	20	2.04
28	45.1	R		Mesa Verde Fm	159	25	1.51
27.8	44.7	R	-	Mesa Verde Fm	163	25	1.57
27.2	43.8	L	-	Mesa Verde Fm	135	30	1.69
26.8	43.1	L	Saleratus Canyon	Mesa Verde Fm	163	60	1.68
26.8	43.1	R	-	Mesa Verde Fm	163	30	1.84

River mile	River km	side	Tributary name	Bedrock unit exposed at river level	Average valley-bottom width (m)	Tributary valley bottom width (m)	Ratio of valley width to average channel width
26.3	42.3	R	-	Mesa Verde Fm	120	10	1.71
26.2	42.2	R	-	Mesa Verde Fm	144	10	1.18
26.2	42.2	L	Coal Creek	Mesa Verde Fm	148	55	1.34
25.6	41.2	R	-	Mesa Verde Fm	139	10	1.34
25.3	40.7	L	Poverty Canyon	Mesa Verde Fm	128	30	1.20
23.1	37.2	R	-	Mesa Verde Fm	204	120	2.31
23	37	R	-	Mesa Verde Fm	200	60	2.11
22.9	36.9	R	-	Mesa Verde Fm	228	55	2.28
22.3	35.9	R	School Section Canyon	Mesa Verde Fm	223	65	2.02
22.2	35.7	L	Rattlesnake Canyon	Mesa Verde Fm	188	100	1.63
21	33.8	R	-	Mesa Verde Fm	175	45	1.98
21	33.8	L	-	Mesa Verde Fm	175	75	1.75
20.1	32.3	L	Nefertiti Canyon	Mesa Verde Fm	179	100	1.79
19.3	31.1	R	-	Mancos Shale	198	130	1.98
19.1	30.7	R	-	Mancos Shale	199	130	1.73
18.2	29.3	R	Price River	Mancos Shale	243	370	1.64
17.1	27.5	L	-	Mancos Shale	345	130	2.62
17	27.4	L	-	Mancos Shale	454	160	3.18
16.8	27	R	-	Mancos Shale	308	100	3.15
16.5	26.6	R	-	Mancos Shale	199	85	2.09
16.3	26.2	R	-	Mancos Shale	268	75	2.10
16.1	25.9	R	-	Mancos Shale	318	115	3.34
16.1	25.9	L	Butler Canyon	Mancos Shale	353	145	3.20
15.2	24.5	R	Sand Knolls Canyon	Mancos Shale	315	85	2.05
14.8	23.8	L	-	Mancos Shale	283	30	3.32
14.3	23	L	Stone House	Mancos Shale	291	80	2.65
14	22.5	L	-	Mancos Shale	343	75	3.26
13.1	21.1	R	Short Canyon	Mancos Shale	408	140	3.40
12.8	20.48	R	-	Mancos Shale	410	75	2.89
12.3	19.68	R	Long Canyon	Mancos Shale	518	80	4.14
12.3	19.68	L	Swasey's	Mancos Shale	558	100	3.31

APPENDIX D. Debris-Fan Characteristics

River Mile	River km	side	Tributary name	Debris fan area (m^2)	Fan length (parallel to ch.) (m)	Fan Width (m)	Debris fan l/w	Debris fan channel Aggrading or Incising	Debris flow history/channel activity index 1-5 1=most active 5=most inactive
96	154.5	R	Sand Wash	254763	1095	405	2.7	I	flash flood events common ; 1
94.3	151.76	R	-	4194	125	40	3.13	A	
93.7	150.8	R	9-Mile Canyon	218451	850	360	2.36	I	perinnial tributary ; 0
92.2	148.38	L	-	26622	310	160	1.94	A	
90	144.84	L	-	66448	565	160	3.5[illegible]	I	
88	141.62	R	-	5255	170	50	3.4	A	
87.5	140.82	L	-	16150	235	90	2.61	A	
87	140.01	L	-	25675	300	125	2.4	A	
86.8	139.69	L	Tabyago Canyon	65988	400	230	1.74	I	perinnial streamflow ; 0
86.7	139.53	L	-	11880	195	80	2.44	A	
84.7	136.31	R	-	34142	275	190	1.45	A/I	
84	135.18	R	Maverick Bottom	112436	585	250	2.34	A	
83.1	133.74	R	-	9220	160	75	2.13	A	
82.8	133.25	R	-	14574	210	85	2.47	A	
81.5	131.16	L	Gold Hole- Rincon	abandoned Green River meander- two main drainages; coalesced fans					
81.4	131	L							
80.9	130.2	R	-	45603	330	195	1.69	A	
80	128.75	R	Rock House Canyon	165174	710	340	2.09	A/I	2
79	127.14	L	Little Rock House Canyon	113201	295	115	2.57	I	small debris flow 2001 deposited in fan channel ; 1
77.7	125.05	L	-	39743	235	180	1.31	I	
77.3	124.4	L	-	79331	415	215	1.93	A	
75.3	121.18	R	-	12330	250	60	4.17	I	
74.4	119.73	R	-	15162	230	90	2.56	I	
74	119.09	R	-	55926	295	200	1.48	A	
73.9	118.93	R-A	-	36344	190	210	0.9	A	
73.9	118.93	R-B	-	40539	260	185	1.41	A	
71.4	114.91	L	-	70255	400	250	1.6	A	
71.1	114.42	L	-	36559	310	155	2	I	
70.7	113.78	L	-	20497	215	125	1.72	I	
69.8	112.33	R	Jack Creek	130504	800	300	2.67	I	streamflow 2001 spring/summer ; 2
68.8	110.72	R	Lunt's Horse Pasture	71326	300	245	1.22	A/I	3
68.7	110.56	R	Lunt's Horse Pasture	136731	326.1	338	0.96	A/I	3
68.4	110.08	R	Lunt's Horse Pasture	39425	177	263	0.67	A	3
68.3	109.92	R	Lunt's Horse Pasture	71254	360	217	1.66	A	3
67.5	108.63	R		6438	125	65	1.92	A	
67.5	108.63	L	-	7595	175	70	2.5	A	
67	107.83	L	Big Canyon	155990	785	280	2.8	I	2
66.5	107.02	L	-	2325	100	50	2	A	
66.3	106.7	R	-	14644	165	114	1.45	A	
66.1	106.38	L		16869	300	120	2.5	A	
66	106.22	L	Upper Firewater Canyon	84333	228	437	0.52	A	4
65.8	105.89	L	Firewater Canyon	134378	5[illegible]5	330	1.62	I	2

River Mile	River km	side	Tributary name	Debris fan area (m^2)	Fan length (parallel to ch.) (m)	Fan Width (m)	Debris fan l/w	Debris fan channel Aggrading or Incising	Debris flow history/channel activity index 1-5 1=most active 5=most inactive
65.5	105.41	R	Cedar Ridge Canyon	69950	415	215	1.93	I	Large channelized debris flow changed rapid in the late 1980's ; 1
65	104.61	L	-	54440	370	205	1.8	I	4
64.8	104.29	L	-	37231	210	200	1.05	I	
63.9	102.84	R	-	93947	560	230	2.43	I	
63.6	102.35	R	-	170021	785	280	2.8	I	
63	101.39	R	Flat Canyon	94181	590	325	1.82	I	perinnial streamflow ; 3
62.2	100.1	L	-	58021	325	260	1.25	I	
62.1	99.94	L	-	21327	150	175	0.86	A	
62	99.779	L	Dripping Springs	143151	220	410	0.54	I	
61.9	99.618	L	-	102831	215	385	0.56	A	
61	98.17	R	-	32706	180	110	1.64	A	
60.8	97.848	L	-	11662	175	85	2.06	A	
60.4	97.204	L	-		670	375	1.79	A	
60.2	96.882	L	-	215523	275	235	1.17	A	
60.2	96.882	R	-	35921	245	170	1.44	I	
60	96.56	L	-	87081	310	150	2.07	I	
60	96.56	R	-	108662	485	290	1.67	I	
59.4	95.595	R	Fretwater	116702	670	245	2.73	A	4
58.8	94.629	R	-	9061	120	100	1.2		
58.4	93.985	L	Wild Horse Canyon	74629	450	250	1.8	I	2
57.9	93.181	L	-	81989	460	230	2	A	
57.6	92.698	L	-	82972	330	340	0.97	A	
57.5	92.537	L	-	224722	505	445	1.13	I	3
57.3	92.215	R	-	3698	90	50	1.8	I	
56.8	91.411	L	-	26880	330	165	2	I	
56.5	90.928	R	-	48187	410	190	2.16	I	3
56.4	90.767	R	Steer Ridge Canyon	85231	490	260	1.88	I	3
55.9	89.962	R	-	30548	255	170	1.5	I	4
55.8	89.801	R	Surprise Canyon	53081	450	170	2.65	I	3
55.4	89.157	L	-	46096	325	160	2.03	I	
55.1	88.675	L	-	41216	365	230	1.59	I	4
54.9	88.353	L	-	37868	300	175	1.71	I	
54.7	88.031	L	Log Cabin	77452	530	210	2.52	A in Ch.	3
54.3	87.387	L	-	59280	320	225	1.42	I	3
54.2	87.226	L	-	54974	315	220	1.43	I	
54	86.904	R	Rock Creek	Cultivated fan/terrace				I	perinnial streamflow ; 3
52.9	85.134	R	-	24840	270	140	1.93	A	
52.7	84.812	R	-	87676	310	370	0.84	I	5
52.4	84.329	R	Calf Canyon	220981	830	365	2.27	I	5
51.3	82.559	R	Snap Canyon	104813	555	320	1.73	I	streamflow 2001 spring/summer ; 0
51	82.076	L	-	154983	490	460	1.07	I	4
50.8	81.754	L	-	175662	700	380	1.84	I	5
49.8	80.145	R	Three Canyon Rincon	abandoned Green River meander (2 drainages)					streamflow 2001 spring/summer ; 0
49.7	79.984	R							

River Mile	River km	side	Tributary name	Debris fan area (m^2)	Fan length (parallel to ch.) (m)	Fan Width (m)	Debris fan l/w	Debris fan channel Aggrading or Incising	Debris flow history/channel activity index 1-5 1=most active 5=most inactive
49	78.858	L	-	101440	575	285	2.02	I	3
48.6	78.214	L	Belknap	38715	260	210	1.24	I	Large debris flow event late summer 1987 ; 1
48	77.248	R	Lion Hollow	62736	650	150	4.33	I	4
47.5	76.444	L	-	93163	640	230	2.78		
47.2	75.961	R	-	71468	260	460	0.57		4
47	75.639	L	Chandler Canyon	149631	860	290	2.97	I	periennial streamflow; debris flow event in mid 1980's washed out road ; 0
46.1	74.191	R	-	26713	147	250	0.59	I	4
45.9	73.869	R	Trail Canyon	218535	480	623	0.77	I	4
45.8	73.708	L	-	33734	180	160	1.13	I	
45.7	73.547	L	-	88312	275	310	0.89	I	3
45.5	73.225	L	Bluebell Creek	271774	790	550	1.44	I	flash flood event summer 2000 ; 1
44.2	71.133	R	Bull Canyon	116062	625	300	2.08	I	recent (2001?) small debris flow stopped short of Green River in debris fan channel ; 1
44.1	70.972	L	-	8322	130	115	1.13	I	
43.3	69.684	R	-	69338	490	240	2.04	I	
43	69.202	L	-	90105	520	330	1.58	I	
42.9	69.041	R	Moonwater Canyon	173430	370	280	1.32	I	8/94 debris flow event deposited large boulders in channel ; 1
42.6	68.558	R	Big Canyon	66806	310	155	2	I	1
42.2	67.914	L	-	137233	670	280	2.39	I	2
41.5	66.788	L	Joe Hutch Creek	476450	1415	495	2.86	I	2
40.9	65.822	R	-	30695	150	250	0.6	I	
40.5	65.178	R	Joe Hutch Canyon	113897	355	160	2.22	I	1994 major debris flow event; channel flash flood 2000 season; some gravel deposited on fan at mouth and sandbar ; 1
39.9	64.213	L	-	73048	270	250	1.08	I	
39.6	63.73	L	-	181023	650	350	1.86	I	
38.9	62.603	R	Rain Canyon	363089	800	560	1.43	I	
38.7	62.281	L	Florence Creek	1833	30	15	2		perinnial streamflow ; 0
38	61.155	L	-	154925	705	300	2.35		
37.3	60.028	L	-	133739	555	315	1.76	I	
37	59.546	R	Wire Fence Canyon	99547	535	270	1.98	I	1974 debris flow altered rapid; 8/87 large debris flow overtopped channel and deposited on fan, backed up Green River, and altered rapid; channel flash flood event 2000 some gravel deposited at channel mouth; 2001 summer flood event ; 1
36.5	58.741	L	Three Fords Canyon	187405	350	200	1.75	I	1987 debris flow reached Green River ; 1
35.2	56.649	R	Three Fords Canyon-R	59363	410	235	1.74	I	
35.2	56.649	L	-	37612	330	190	1.74	I	
34.4	55.361	L	-	146621	390	260	1.5	I	
34.2	55.039	L	-	2376	55	55	1		
33.4	53.752	R	-	2325	60	45	1.33		
32.5	52.304	R	Last Chance Canyon	1356	60	40	1.5	I	2
32.3	51.982	L	Spring Wash Canyon	36696	185	45	4.11	I	2
31.5	50.694	R	Range Creek	20271	210	140	1.5	I	2
30.9	49.729	L	-	10391	180	105	1.71	I	

River Mile	River km	side	Tributary name	Debris fan area (m^2)	Fan length (parallel to ch.) (m)	Fan Width (m)	Debris fan l/w	Debris fan channel Aggrading or Incising	Debris flow history/channel activity index 1-5 1=most active 5=most inactive
29.5	47.477	L	Beaver Slide Bottom	16268	250	100	2.5	I	3
28.9	46.512	R	Rabbit Valley	15528	230	150	1.53	I	1
28.7	46.19	L	-	5564	100	70	1.43	I	3
28.3	45.546	R	Curry Canyon	16611	160	100	1.6	A	2
28	45.063	R	-	8110	115	105	1.1	A	2
27.8	44.741	R	-	11405	210	115	1.83	I	small debris flow deposit in channel mid-fan ; 1
27.2	43.776	L	-	5300	120	90	1.33	I	
26.8	43.132	L	Saleratus Canyon	3349	115	65	1.77		
26.8	43.132	R	-	2500	95	55	1.73	I	
26.3	42.327	R	-	2122	80	45	1.78	I	
26.2	42.166	R	-	3341	110	50	2.2	I	
26.2	42.166	L	Coal Creek	18423	submerged debris fan			I	3
25.6	41.201	R	-	5461	105	75	1.4		
25.3	40.718	L	Poverty Canyon	2838	65	55	1.18	I	perinnial stream flow ; 3
23.1	37.177	R	-	18492	205	105	1.95	I	
23	37.016	R	-	15382	225	105	2.14	I	
22.9	36.855	R	-	27063	270	130	2.08	I	
22.3	35.89	R	School Section Canyon	32195	360	175	2.06	I	
22.2	35.729	L	Rattlesnake Canyon	25324	160	40	4		perinnial streamflow activity; large flash flood event fall 1999 ; 0
21	33.797	R	-	1012	45	22	2.05		
21	33.797	L	-	6803	190	105	1.81		
20.1	32.349	L	Nefertiti Canyon	19706	110	60	1.83	I	
19.3	31.061	R	-	16235	245	110	2.23	I	
19.1	30.74	R	-	14683	210	120	1.75	I	
18.2	29.291	R	Price River	no debris fan at mouth of Price River					perinnial streamflow USGS gage 09314500 mean annual discharge = 8 cms Woodside ; 0
17.1	27.521	L	-	73877	375	310	1.21	I	3
17	27.36	L	-	49575	245	180	1.36	I	3
16.8	27.038	R	-	14658	175	100	1.75	I	
16.5	26.555	R	-	11438	160	80	2	I	
16.3	26.233	R	-	8203	130	75	1.73	I	
16.1	25.911	R	-	25674	210	215	0.98	I	
16.1	25.911	L	Butler Canyon	15798	225	145	1.55	I	3
15.2	24.463	R	Sand Knolls Canyon	62666	370	320	1.16	I	
14.8	23.819	L	-	16737	200	130	1.54	I	
14.3	23.014	L	Stone House	56297	385	250	1.54	I	3
14	22.532	L	-	35065	250	215	1.16	I	
13.1	21.083	R	Short Canyon	125292	550	375	1.47	I	
12.8	20.6	R	-	107281	460	310	1.48	I	
12.3	19.796	R	Long Canyon	111971	435	320	1.36	I	
12.3	19.796	L	Swasey's	43124	280	250	1.12	I	

APPENDIX E. Green River Channel Characteristics at Debris Fans

River Mile	River km	side	Tributary name	Channel width upstream of fan (m)	Channel width downstream of fan (m)	Channel width at rapid (m)	Average Channel Width at fan (m)	Rapid Length (m)	Constriction width in % (after Webb. et al., 1996)
96	154.5	R	Sand Wash	240	215	205	230		9.9
94.3	151.76	R	-	150	160		155		
93.7	150.8	R	9-Mile Canyon	275	100	85	153.3		54.7
92.2	148.38	L	-	115	215		165		
90	144.84	L	-	130	175		152.5		
88	141.62	R	-	30	40		35		
87.5	140.82	L	-	180	150		165		
87	140.01	L	-	175	125		150		
86.8	139.69	L	Tabyago Canyon	100	95		65	160	
86.7	139.53	L	-	100	100		100		
84.7	136.31	R	-	160	165	85	136.7		47.7
84	135.18	R	Maverick Bottom	225	220	110	185		50.6
83.1	133.74	R	-	150	170		160		
82.8	133.25	R	-	145	130		137.5		
81.5	131.16	L	Gold Hole- Rincon	200	200		200		
81.4	131	L	Gold Hole- Rincon	200	130		165		
80.9	130.2	R	-	100	190		145		
80	128.75	R	Rock House Canyon	200	270	105	191.7	160	55.3
79	127.14	L	Little Rock House Canyon	220	165	75	153.3	115	61
77.7	125.05	L	-	125	120		122.5		
77.3	124.4	L	-	135	150		142.5		
75.3	121.18	R	-	125	135		130		
74.4	119.73	R	-	150	120		135		
74	119.09	R	-	140	110		125		
73.9	118.93	R-A	-	105	135		120		
73.9	118.93	R-B	-	130	160		145		
71.4	114.91	L	-	155	115		135		
71.1	114.42	L	-	130	110		120		
70.7	113.78	L	-	115	100		107.5		
69.8	112.33	R	Jack Creek	235	135	90	153.3	297	51.4
68.8	110.72	R	Lunt's Horse Pasture	85	85		85		
68.7	110.56	R	Lunt's Horse Pasture	90	130	85	101.7		22.7
68.4	110.08	R	Lunt's Horse Pasture	120	120		120		
68.3	109.92	R	Lunt's Horse Pasture	130	130		130		
67.5	108.63	R		170	135		152.5		
67.5	108.63	L	-	170	135		152.5		
67	107.83	L	Big Canyon	200	138	85	141	180	49.7
66.5	107.02	L	-	130	130		130		
66.3	106.7	R	-	160	150		155		
66.1	106.38	L		170	130		150		
66	106.22	L	Upper Firewater Canyon	148	94	85	121		29.8
65.8	105.89	L	Firewater Canyon	94	87	80	87	140	11.6
65.5	105.41	R	Cedar Ridge Canyon	205	130	95	143.3	120	43.3
65	104.61	L	-	135	75	90	100		14.3
64.8	104.29	L	-	95	130		112.5		

River Mile	River km	River side	Tributary name	Channel width upstream of fan (m)	Channel width downstream of fan (m)	Channel width at rapid (m)	Average Channel Width at fan (m)	Rapid Length (m)	Constriction width (after Webb. et al., 1996)
63.9	102.84	R	-	115	115	90	80		21.7
63.6	102.35	R	-	170	160	70	133.3		57.6
63	101.39	R	Flat Canyon	165	260	90	171.7		57.6
62.2	100.1	L	-	110	75		92.5		
62.1	99.94	L	-	75	75		75		
62	99.779	L	Dripping Springs	75	75		75		
61.9	99.618	L	-	105	220		162.5		
61	98.17	R	-	250	135	80	155		58.4
60.8	97.848	L	-	145	70		107.5		
60.4	97.204	L	-	110	70		90		
60.2	96.882	L	-	90	80		85		
60.2	96.882	R	-	100	75	90	88.33		
60	96.56	L	-	150	135	115	133.3		19.3
60	96.56	R	-	90	150	80	106.7	60	33.3
59.4	95.595	R	Fretwater	280	200	80	186.7	170	66.7
58.8	94.629	R	-	150	150		150		
58.4	93.985	L	Wild Horse Canyon	100	240	60	133.3	128	64.7
57.9	93.181	L	-	210	90		150	80	
57.6	92.698	L	-	90	105		97.5		
57.5	92.537	L	-	110	210		160	170	
57.3	92.215	R	-	80	150		115		
56.8	91.411	L	-	90	100		95		
56.5	90.928	R	-	110	90	80	93.33	170	20
56.4	90.767	R	Steer Ridge Canyon	90	100		95	160	
55.9	89.962	R	-	90	90	90	135		
55.8	89.801	R	Surprise Canyon	94	110	75	93	165	26.5
55.4	89.157	L	-	110	170	95	125		32.1
55.1	88.675	L	-	135	90	55	93.33		51.1
54.9	88.353	L	-	100	110		105		100
54.7	88.031	L	Log Cabin	110	105	70	95	300	34.9
54.3	87.387	L	-	100	75	75	83.33	135	14.3
54.2	87.226	L	-	75	125	80	93.33		20
54	86.904	R	Rock Creek	135	130	80	115		39.6
52.9	85.134	R	-	185	120		152.5		
52.7	84.812	R	-	160	110	80	116.7	185	40.7
52.4	84.329	R	Calf Canyon	135	140	65	113.3	215	52.7
51.3	82.559	R	Snap Canyon	140	120	65	108.3	140	50
51	82.076	L	-	150	70	65	95	185	40.9
50.8	81.754	L	-	75	80		77.5	280	
49.8	80.145	R	Three Canyon Rincon	160	70		115		
49.7	79.984	R	Three Canyon Rincon	55	75		65		
49	78.858	L	-	120	75	80	91.67	215	17.9
48.6	78.214	L	Belknap	120	110	65	98.33	80	43.5
48	77.248	R	Lion Hollow	110	140	95	115	75	24
47.5	76.444	L	-	120	120		120		
47.2	75.961	R	-	130	80	75	95	176	28.6

River Mile	River km	side	Tributary name	Channel width upstream of fan (m)	Channel width downstream of fan (m)	Channel width at rapid (m)	Average Channel Width at fan (m)	Rapid Length (m)	Constriction width (after Webb. et al., 1996)
47	75.639	L	Chandler Canyon	75	220	75	123.3	200	49.2
46.1	74.191	R	-	205	85	95	128.3	170	34.5
45.9	73.869	R	Trail Canyon	140	150	85	125	190	41.4
45.8	73.708	L	-	130	145		137.5	95	
45.7	73.547	L	-	140	105		122.5	100	
45.5	73.225	L	Bluebell Creek	105	145	95	115	200	24
44.2	71.133	R	Bull Canyon	125	150	85	120	211	38.2
44.1	70.972	L	-	115	115		115		
43.3	69.684	R	-	160	90	65	105		48
43	69.202	L	-	115	160	85	120	140	38.2
42.9	69.041	R	Moonwater Canyon	165	130	80	125	280	45.8
42.6	68.558	R	Big Canyon	120	140	115	125	155	11.5
42.2	67.914	L	-	140	260	90	163.3	280	55
41.5	66.788	L	Joe Hutch Creek	270	205	85	186.7	210	64.2
40.9	65.822	R	-	200	90	70	120	70	51.7
40.5	65.178	R	Joe Hutch Canyon	100	110	60	90	160	42.9
39.9	64.213	L	-	80	90	80	83.33	90	5.9
39.6	63.73	L	-	95	120	100	105	90	7.0
38.9	62.603	R	Rain Canyon	100	100	140	113.3	60	
38.7	62.281	L	Florence Creek	130	160	160	150	160	
38	61.155	L	-	125	290	70	161.7		66.3
37.3	60.028	L	-	290	85	60	145		68
37	59.546	R	Wire Fence Canyon	120	150	75	115	120	44.4
36.5	58.741	L	Three Fords Canyon	160	320	60	180	200	75
35.2	56.649	R	Three Fords Canyon-R	450	205	70	241.7	135	78.6
35.2	56.649	L	-	280	205	70	185	75	71.1
34.4	55.361	L	-	110	130	55	98.33		54.2
34.2	55.039	L	-	110	85		97.5		
33.4	53.752	R	-	90	90		90		
32.5	52.304	R	Last Chance Canyon	100	60		53.33		
32.3	51.982	L	Spring Wash Canyon	100	110	95	101.7	40	9.52
31.5	50.694	R	Range Creek	195	120	95	136.7	450	39.7
30.9	49.729	L	-	120	100		110		
29.5	47.477	L	Beaver Slide Bottom	115	160	65	113.3		52.7
28.9	46.512	R	Rabbit Valley	100	125	80	101.7	250	28.9
28.7	46.19	L	-	60	85		72.5		
28.3	45.546	R	Curry Canyon	100	120	50	90	85	54.5
28	45.063	R		125	130	60	105		52.9
27.8	44.741	R	-	130	120	60	103.3		52
27.2	43.776	L	-	80	110	50	80		47.4
26.8	43.132	L	Saleratus Canyon	95	105	90	96.67		10
26.8	43.132	R	-	95	105	65	88.33	125	35
26.3	42.327	R	-	60	80		70		
26.2	42.166	R	-	145	125	95	121.7		29.6
26.2	42.166	L	Coal Creek	135	115	80	110	260	36
25.6	41.201	R	-	130	110	70	103.3		41.7

River Mile	River km	side	Tributary name	Channel width upstream of fan (m)	Channel width downstream of fan (m)	Channel width at rapid (m)	Average Channel Width at fan (m)	Rapid Length (m)	Constriction width (after Webb. et al., 1996)
25.3	40.718	L	Poverty Canyon	130	130	60	106.7	120	53.8
23.1	37.177	R	-	105	95	65	88.33		35
23	37.016	R	-	95	95		95		
22.9	36.855	R	-	100	100		100		
22.3	35.89	R	School Section Canyon	100	175	55	110		60
22.2	35.729	L	Rattlesnake Canyon	150	120	75	115	245	44.4
21	33.797	R	-	110	80	75	88.33		21.1
21	33.797	L	-	110	130	60	100		50
20.1	32.349	L	Nefertiti Canyon	110	130	60	100	60	50
19.3	31.061	R	-	105	95		100		
19.1	30.74	R	-	90	195	60	115	160	57.9
18.2	29.291	R	Price River	125	170		147.5		
17.1	27.521	L	-	140	190	65	131.7	70	60.6
17	27.36	L	-	175	110		142.5		
16.8	27.038	R	-	105	90		97.5		
16.5	26.555	R	-	80	110		95		
16.3	26.233	R	-	115	140		127.5		
16.1	25.911	R	-	90	130	65	95	75	40.9
16.1	25.911	L	Butler Canyon	135	130	65	110	75	50.9
15.2	24.463	R	Sand Knolls Canyon	160	250	50	153.3	180	75.6
14.8	23.819	L	-	80	90		85		
14.3	23.014	L	Stone House	150	100	80	110	100	36
14	22.532	L	-	100	110		105		
13.1	21.083	R	Short Canyon	175	100	85	120	160	38.2
12.8	20.6	R	-	100	250	75	141.7		57.1
12.3	19.796	R	Long Canyon	180	110	85	125	220	41.4
12.3	19.796	L	Swasey's	320	100	85	168.3	220	59.5

APPENDIX F.

Unit Descriptions for mapping of mainstem Green River Deposits and tributary debris fans in Desolation and Gray Canyons, East-Central, Utah

Tributary alluvial and colluvial deposits

Debris fan surface: Extensive fan-shaped surfaces occurring at the mouths of most tributary canyons. Debris fan surfaces range between approximately 1000 km^2 to 500,000 km^2 in plan-view area. Stratigraphy consists of both tributary debris flow and stream flow deposits. Debris flow deposits are poorly sorted and lobate in cross-section containing clasts of varying sizes (from several mm to several meters in diameter) suspended in a fine-grained matrix of sand, silt, and clay. Some debris flow deposits exhibit inverse grading. Stream-flow deposits exhibit sorting, stratification, and downstream imbrication and occur alternately with poorly sorted debris-flow deposits. Debris fan surfaces often exhibit ridge and swale topography with abandoned channels flanked by boulder levees. A prominent active channel exists on most debris fans that cuts through the main fan surface and connects with the Green River Channel. Large and often weathered and varnished boulders in excess of 2 m in diameter usually occur scattered on debris fan surfaces. Clasts consist of locally-derived sandstones and shales and vary according to the geology of the tributary source area. Cryptogamic crusts are prevalent on most debris-fan surfaces, and some debris fans surfaces have an incipient calcic soil horizon, although soil development in general is weak. Greasewood () and sagebrush () communities are often well established on debris fan surfaces. In some regions of the canyons pinion () and juniper () forests colonize fan surfaces. Debris fan surfaces are between 1.5 and 9 meters in elevation above the modern Green River in the study region. Debris fan surfaces slope downstream from tributary source areas towards the Green River, and slopes in the field area range between 0.01 to 0.34 m/m.

Main tributary channel: Channel cut into debris fan surface, which acts as a conduit for sediment deposition from tributary drainage basins to the Green River. Channel widths vary from 1.5-20 meters wide throughout field area. Channel entrenchment relative to debris fan surface elevation also varies, ranging from 1.2 to 10.7 meters. Channels display a wide range of activity varying from very active to inactive (See Appendix 7 for more details). Active channels display a 1-2 meter wide region of bare sands, silts, and gravels inset into the main channel flanked by inset terraces, gravel bars, and a mixture of streamflow and debris-flow deposits. Active channels have less vegetation than inactive channels. Very wide channels display ridge-and-swale topography and contain lobes and levees of debris flow deposits. Sediment in channel is deposited by either streamflow or debris-flow processes, yet is likely to be re-worked by flash floods between debris-flow events or by recessional streamflow activity following debris flows. Active tributary channel deposits are generally well sorted and often show downstream imbrication. Channels often exhibit a step-pool morphology, steepening at their upstream ends as the channel enters a more confined, tributary channel and often flows on bedrock. Channel walls of more active channels are vertical in cross-section and contain exposures of debris fan sediment. Woody debris and high water marks are seen in and above the channel in active channels. Less active channels are generally narrower, v-shaped in cross-section, with eroding and gently sloping banks with few exposures of debris fan material. Less active channels contain denser vegetation including trees and show no signs of recent inundation. Boulders are often well weathered and covered in lichens and varnish in inactive channels.

Active channel debris fans: Bouldery tributary debris fan material regularly inundated by the active Green River channel. Deposits occur on the distal end of tributary fans where the fan splays into the mainstem Green River channel. Fines and small clasts are typically winnowed away during inundation, leaving large angular to sub-angular boulders up to 6 meters in diameter behind. The average clast size for debris fan deposits in the active channel ranges from 123 - 427 mm. These deposits often constrict the main channel to form riffles and rapids where coarse gravel and boulders are exposed.

Alluvial deposits of the Mainstem Green River

Channel margin fines: Fine-grained deposit near channel margin composed mostly of silts, sands, and muds. Highly cohesive, and slippery/sticky when wet. Can have high organic content. Horizontal bedded deposits are common where flow velocities are low such as in backwater reaches above channel constrictions and flatwater reaches. Sand deposited along main channel in regions of downstream flow. Generally exhibits horizontal bedding or bedforms such as small wave ripples. Occurs at low elevations adjacent to the channel.

Gravel bars: Accumulation of coarse sub to well-rounded gravels that have been transported by the Green River. Clasts include local sandstones, limestones, and some shales with fine-grained sands and silts filling interstitial spaces. Average clast sizes for gravel bars range from 33- 89 mm. Material is moderately to well sorted and often imbricated. Gravel bars often occur at the downstream end of tributary junctions and rapids. From river kilometers 112 to 20 gravel bars are very frequent in the channel and often occur as mid-channel bars.

Eddy bars: Undifferentiated sand bar deposited in recirculating flow. Includes both separation bars formed as recirculating flow separates from the main downstream current, and reattachment bars where flow once again joins the main current. Stratigraphy exhibits cross-stratification and signs of upstream flow such as migrating ripples.

Colluvium deposited in the Active Channel

Active channel talus: Angular to sub-angular unconsolidated debris deposited by rockfall or other slope processes at the bottoms of hillslopes and cliffs into the active channel. Clast size is highly variable from several mm to tens of meters in diameter. Talus deposited in the active channel usually has large interstitial spaces where fine-grained material deposition occurs. Talus in the channel often obstructs the downstream current near the banks and causes small zones of flow recirculation where sand deposition occurs.

Green River Terraces and Terrace-like Deposits

Floodplain: The modern floodplain of the Green River. This surface consists of fine-grained sands and silts, and occurs adjacent to the active channel. It is often vegetated with thick stands of tamarisk (*tamarix sp.*), as well as willows and other riparian species. It is typically higher in elevation than sands deposited in the active channel, and is inundated less frequently than deposits in the active channel, overtopped by flooding approximately 2 out of every 3 years (Orchard and Schmidt, 1998).

Undifferentiated intermediate terrace: Fine-grained alluvial intermediate terrace level often referred to as the "cottonwood terrace", or the "box-elder terrace". This level is the prominent surface of large Fremont Cottonwood (*populus fremonti*) germination in the fan-eddy complex dominated canyons below river kilometer 112, and in the restricted meandering reaches occurring between river kilometers 156 and 112 is the prominent surface of box-elder germination. The surface is also vegetated with mature tamarisk (*tamarix sp.*), and willow (*salix*) as well as non-riparian vegetation including grasses, greasewood, sagebrush, and cacti. This terrace level is higher in elevation than modern floodplain, usually 3+ meters above the modern Green River and is no longer inundated by Green River floods. However, driftwood found on this elevation is very weathered but contains evidence of historic inundation such as sawn logs in drift piles. It is likely that this surface was the Green River's floodplain during the early third of this century. Abandonment of this floodplain by the Green River has been linked to climate changes since the 1930's (Allred and Schmidt, 1999), possibly the invasion of non-native species such as tamarisk (*tamarix sp.*), and the closure of Flaming Gorge Dam, which is approximately 300 km upstream from Sand Wash and was closed in 1963 (Allred and Schmidt, 1999).

Undifferentiated high terrace: High terrace deposit of sandy fine-grained alluvium above intermediate terrace level. Stratigraphic exposures sometimes exhibit horizontal laminations, and some exposures exhibit intertounging with debris fan material. Terrace is often vegetated with thick grasses, greasewood (), sagebrush () and box-elder (), as well as pinion () and juniper () in some locales. Soils show an incipient calcic horizon, and few other signs of development although this terrace often has well-developed cryptogamic crusts on its surface. This terrace level is generally 5+ meters above the modern channel of the Green River and does not contain evidence of historic inundation.

High gravel terrace (Pleistocene?): High abandoned channel surfaces of the Green River. Cobble sized gravel lag contains abundant local clasts and trace amounts of exotic clasts including quartzites with sources in the Uinta Mountains, and igneous and metamorphic rocks from the Wind River Range and Yampa River Drainage. Gravels are sometimes capped with fine-grained silts. These terraces are often eroding, and exist as remnants. Calcic soil horizon development varies from stage I-IV. High gravel terraces tend to be preserved in regions where the alluvial valley is very wide, or where the channel has shifted or abandoned a meander bend and left a rincon.

Colluvium

talus: Piles of pebble to boulder size angular clasts mantling hillslopes and spilling onto debris fans and Green River terraces. Largest clasts can be in excess of 10 m in diameter. Talus generally made up of large angular sandstone clasts including rockfall and landslide deposits. Interstitial spaces generally are open, although when moderately to well consolidated interstitial spaces can be filled in with fine-grained material. Source areas of talus deposits are local; talus often falls from a nearby cliff and accumulates in plies at the base of the slope. Various stages of weathering exist on talus deposits from little to no varnish or lichens on clasts to very weathered friable clasts with dark varnished surfaces with abundant lichens.

Colluvial fan: Undifferentiated piles of talus, slopewash, and other locally derived material mantling hillslopes. Collects as fan-shaped piles in colluvial hollows often with bedrock pour-offs. Generally contain a higher percentage of fine-grained deposits and fewer large boulders than talus deposits. Deposited on debris fans and Green River terrace deposits that fill the bottom of the alluvial valley in the canyons.

Aeolian deposits

aeolian sands and silts: Wind blown sand dunes, often colonized with sagebrush, grasses, prickly pear cactus, and greasewood . Some areas have cryptogamic crust soil growth and lichens. Few clasts are evident, except for a surface mantle of small gravels occasionally found in swales. Fine-grained sands and silts, cross bedded dune forms, usually light brown in color. Hummocky topography. Found at the toes of large fans above the modern river channel or on high or intermediate level Green River Terraces.

Appendix G. Channel Activity Index

Activity Level Index	**I**	**II**	III	**IV**	**V**
Primary Debris-Fan Channel	Recently Active	Active	Moderately Active	Inactive	Very Inactive
Debris flow activity	Recent debris flow deposit in channel activity; a record of a large debris flow event in past 25 years	No debris flow history available; signs of activity in channel such as broken or stained vegetation or woody debris debris under boulders	No debris flow history	No debris flow history	No debris flow history
Channel bottom condition	Bare active-looking gravels or recent debris flow-deposit in channel bottom	Bare gravels in channel bottom, signs of recent streamflow activity		Some cryptogamic crust on channel bottom	Cryptogamic crusts on channel bottom High percentage of gravels and boulders in channel bottom covered in CaCO3, lichen, and varnish
vegetation	Little to no woody vegetation; some perennial vegetation (rabbitbrush)	Woody vegetation on intermediate terraces, but not prevalent in active channel	Woody vegetation such as sagebrush exists in channel bottom and on inset terraces	Sagebrush, and rabbitbrush in channel bottom, small Juniper, cottonwood and tamrisk grow in channel bottom	Large diameter woody vegetation (sagebrush) dominant in channel bottom and on intermediate terraces Large Juniper, cottonwood and tamrisk grow in channel bottom
Low intermediate Terrace Condition	Low or intermediate terrace generally sparsely or not vegetated, bare gravels				Terraces have developed cryptogams, lichen, varnish and CaCO3 on rocks and large woody vegetation
Channel Cutbanks	Vertical or nearly vertical channel banks				V-shaped cross section; eroding banks, many boulders from channel walls have fallen into the main channel
Cross-section					
Example Fans	Joe Hutch Canyon Wire Fence Canyon	Big Canyon	Steer Ridge	Trail Canyon	Lion Hollow Calf Canyon

APPENDIX H. Climate Stations and Data around Desolation Canyon

Station	Location	Elev. (m)	Record length	Mean annual precipitation (mm)	Summer Precipation %	Winter Precipitation %	July-Sept Precipitation %
Sunnyside, UT	39 34'N 110 22' W	2068	4/58-7/88	1335.0	56	44	33
Nutters Ranch, UT	39 48'N 110 15'W	1764	7/63-10/01	1162.0	57	43	31
Price BLM, UT	39 36'N 110 49'W	1690	7/68-10/01	1523.0	52	48	32
Myton, UT	40 12'N 110 04'W	1548	7/48-10/01	669.3	59	41	30
Wellington, UT	39 33'N 110 41'W	1645	6/80-10/01	931.4	58	42	36
Bonanza	40 01' N 101 11'W	1661	7/48- 6/93	886.3	57	43	29
Ouray	40 08 N 109 39 W	1423	8/55-10/01	696.0	58	42	30
Woodside, UT	39 16'N 110 21'W	1414	5/40-12/58	693.1	52	48	28
Green River, UT Aviation	38 59'N 110 09' W	1240	1/47-10/01	665.8	54	46	31

Station	Station number	Elev. (m)	Record length	Mean annual precipitation (mm)	Avg annual high temp (F)	Avg. annual low temp (F)	Avg. annual snowfall (in)
Sunnyside, UT	428474	2068	4/58-7/88	1335.0	58	33.4	36.5
Nutters Ranch, UT	426340	1764	7/63-10/01	1162.0	62.1	30.2	45.6
Price BLM, UT		1690	7/68-10/01	1523.0			
Myton, UT	425969	1548	7/48-10/01	669.3	61.9	30.2	14.49
Wellington, UT		1645	6/80-10/01	931.4			
Bonanza	420802	1661	7/48- 6/93	886.3	62.6	33.5	24.5
Ouray 4NE	42658	1423	8/55-10/01	696.0	63.7	31.7	15.5
Woodside, UT		1414	5/40-12/58	693.1			
Green River, UT Aviation	423418	1240	1/47-10/01	665.8	69.6	35.4	6.29

APPENDIX I. Air Photo Information

Date	Discharge m3/s	ft3/s	Scale	Source
Aerial Photographs				
9/16/36	64	2260	1: 12,000	National Archives
Fall or Spring 1963	57	2000	1: 4,000	Unknown
10/5/93	55	1950	1: 5000	Bureau of Reclamation, Salt Lake City, UT
Digital Orthophotos				
7/87	255	9000	1: 25,000	USGS

APPENDIX J. Grain-size data for detailed study sites

River Mile[1]		Fan Name	Average size of reworked particles[2] (cm)	Largest boulder Diameter[3] (m)	Average diameter of 10 largest boudlers [3](m)
80	R	Rock House Canyon	13.21	1.90	1.32
79	L	Little Rock House Canyon	25.74	1.85	1.48
69.8	R	Jack Creek	20.67	1.50	1.19
66	L	-	-	-	-
65.8	L	Firewater Canyon	31.64	2.10	1.59
65.5	R	Cedar Ridge Canyon	17.6	1.25	0.95
65	L	-	-	-	-
63	R	Flat Canyon	13.79	1.25	0.89
59.4	R	Fretwater	42.76	4.30	3.19
58.4	L	Wild Horse Canyon	24.71	1.20	0.89
56.5	R	-	25.38	6.71	2.85
54.7	L	Log Cabin	23.11	2.28	1.24
54.3	L	-	38.89	4.30	3.4
51.3	R	Snap Canyon	24.49	3.10	1.36
49	L	-	26.14	3.30	2.79
48.6	L	Belknap	21.95	4.70	2.46
45.9	R	Trail Canyon	28.86	2.76	2.30
42.9	R	Moonwater Canyon	23.26	1.89	1.44
41.5	L	Joe Hutch Creek	35.57	4.33	3.20
40.5	R	Joe Hutch Canyon	34.17		2.03
37	R	Wire Fence Canyon	26.53	2.65	1.71
36.5	L	Three Fords Canyon	26.53	4.70	3.55
32.3	L	Spring Wash Canyon	15.22	1.90	1.45
28.9	R	Rabbit Valley	27.76	2.45	1.60
28.3	R	Curry Canyon	26.07	1.85	1.38
28	R	-	-	-	-
16.1	L	Butler Canyon	-	-	-
14.3	L	Stone House	33.21	1.77	1.65
Cyn Avg.					

[1] River mile upstream from the railroad bridge at Green River, UT; [2] Gravel counts were conducted in reworked segment of debris fan at low Green River flow (42.5 m^3/s); [3] Largest boulders also located in reworked segment of debris fan

Appendix K. Rock Hardness Data

Parameter	Green River Fm-sh1	Mesa Verde Group-Sst1	Mesa Verde Group-sst2	Mesa Verde Group sst3
rock type	Shale/sst	Sandstone	grey sandstone	sandstone
age	Tertiary	Createaceous	Cretaceous	Cretaceous
location	Uinta Basin	RL@ Nefertiti RM 20	RL above Nefertiti RM 21	RL below Rattlesnake M22
Intact rock strength (Schmidt Hammer 'R')	24-42	44-60	44-56	46-52
average	35.3	55.9	52.65	55.2
r:	5	18	18	18
Weathering	moderately wx	slightly weathered	slightly wx	slightly wx
r:	7	9	9	9
Joint Spacing (m)	1-0.3	1-0.3	1--.3	1-0.3
r:	21	21	21	21
Joint orientations	fair; nearly horizontal dips	fair; nearly horizontal dips	fair; nearly horizontal dips	fair; nearly horizontal dips
r:	14	14	14	14
Width of Joints (mm)	5--20	1-5 mm	1--5	5-20 mm
r:	4	5	5	4
continuity of joints	few; continuous	continuous; thin infill	continous; thin infill	continuous; no infill
r:	5	4	4	5
outflow of groundwater	none	none	trace	none
r:	6	6	5	6
	Moderate (3)	Strong (2)	Strong (2)	Strong (2)
Total Rating	62	77	76	77
Harden (1980) rating	2	7	7	7

	28	38	33	52	60	58	52	48	50	52	50	62
Schmidt Hammer Data:	34	28	40	46	60	58	48	48	52	60	48	54
	36	42	40	56	56	60	44	54	52	52	54	48
	42	44	40	52	52	54	50	52	54	46	56	48
	44	38	42	52	58	44	52	54	48	58	52	52
	24	38	28	46	60	58	48	56	48	56	52	46
	30	24	30	52	60	54	56	52	52	60	46	50
	34	38	28	48	58	54	56	52	52	52	48	48
	34	40	38	50	56	56	56	56	58	62	52	1600
	28	32	26	58	52	60	58	56	56	58	58	29
	38	44	*1164.0*	48	56	58	56	48	48	62	58	**55.1724**
	32	22	**35.3**	50	60	54	48	52	54			*379*
	20			52	56	52	48	50	50			
Total:				46	60	56	54	58	56			
Average:				50	60	56	46	56	2580			
				50	60	*2796*	48	48				
				60	54	**55.92**	50	42	**52.653**			
				58	60		42	56	*0612*			

Parameter	Mesa Verde Group sst4	Mesa Verde Group sst5	Mancos Shale1	Mancos Shale2
rock type	sandstone	sandstone	shale/siltstone	shale/siltstone
age	Cretaceous	Cretaceous	Cretaceous	Cretaceous
location	RL below Rattlesnake M22	RL@mouth of Rattlesnake	RM11 DS from swasey's	Jensen Bridge- RM182
Intact rock strength (Schmidt Hammer 'R')	54-64	30-52	18-28	20-40
average	59.8	46.3	22.3	29.18
r:	18	14	5	5
Weathering	slightly wx	slightly wx	moderately wx	moderately wx
r:	9	9	7	7
Joint Spacing (m)	1--.3	1-.3	300-50 mm	300-50
r:	21	21	15	15
Joint orientations	fair;nearly horizontal dips	fair; nearly horizontal dips	fair; nearly horizontal dips	fair; nearly horizontal dips
r:	14	14	14	14
Width of Joints (mm)	5-20mm	5--20mm	5-20mm	>20 mm
r:	4	4	4	2
continuity of joints	continuous; no infill	continuous; no infill	continuous; thin infill	continuous; thin infill
r:	5	5	4	4
outflow of groundwater	none	none	none	none
r:	6	6	6	6
	Strong (2)	Strong (2)	weak (4)	weak (4)
Total Rating	**77**	**73**	**55**	**53**
Harden (1980) rating	7	7		

	sst4			sst5			Shale1			Shale2		
Schmidt Hammer Data:	56	58	56	30	46	42	28	24	24	22	26	20
	60	58	62	42	44	42	28	22	26	22	22	28
	54	62	58	50	40	52	12	16	20	22	26	38
	54	60	64	50	38	50	40	16	22	24	22	40
	62	52	60	48	42	42	22	20	18	26	18	18
	68	62	62	48	46	48	18	18	12	30	26	40
	50	54	58	50	46	42	18	18	20	28	28	42
	56	54	54	52	38	50	28	20	22	26	24	42
	58	58	*1736*	52	48	*1344*	30	22	*646*	30	32	44
	58	62		34	44		14	20		18	36	*934*
Total:	54	52	**59.86**	42	46	**46.34**	26	22	**22.27**	20	22	
Average:										26	26	**29.18**
										20		

PLATE 1:
Surficial Geology of Desolation Canyon on the Green River, east-central Utah

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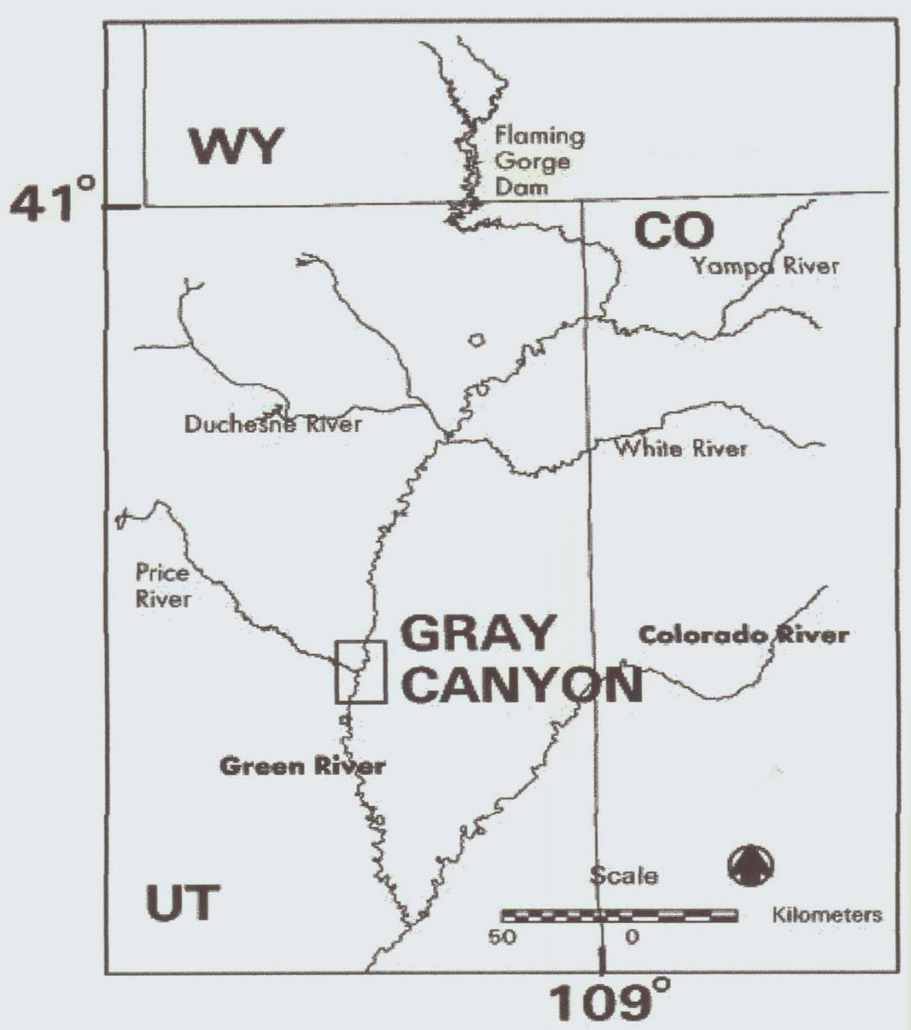
PLATE 2:
Surficial Geology of Gray Canyon on the Green River east-central Utah



Legend

Green River deposits in the active channel
- Green River

Alluvium
- sand
- gravel
- Submerged sand
- Submerged gravel

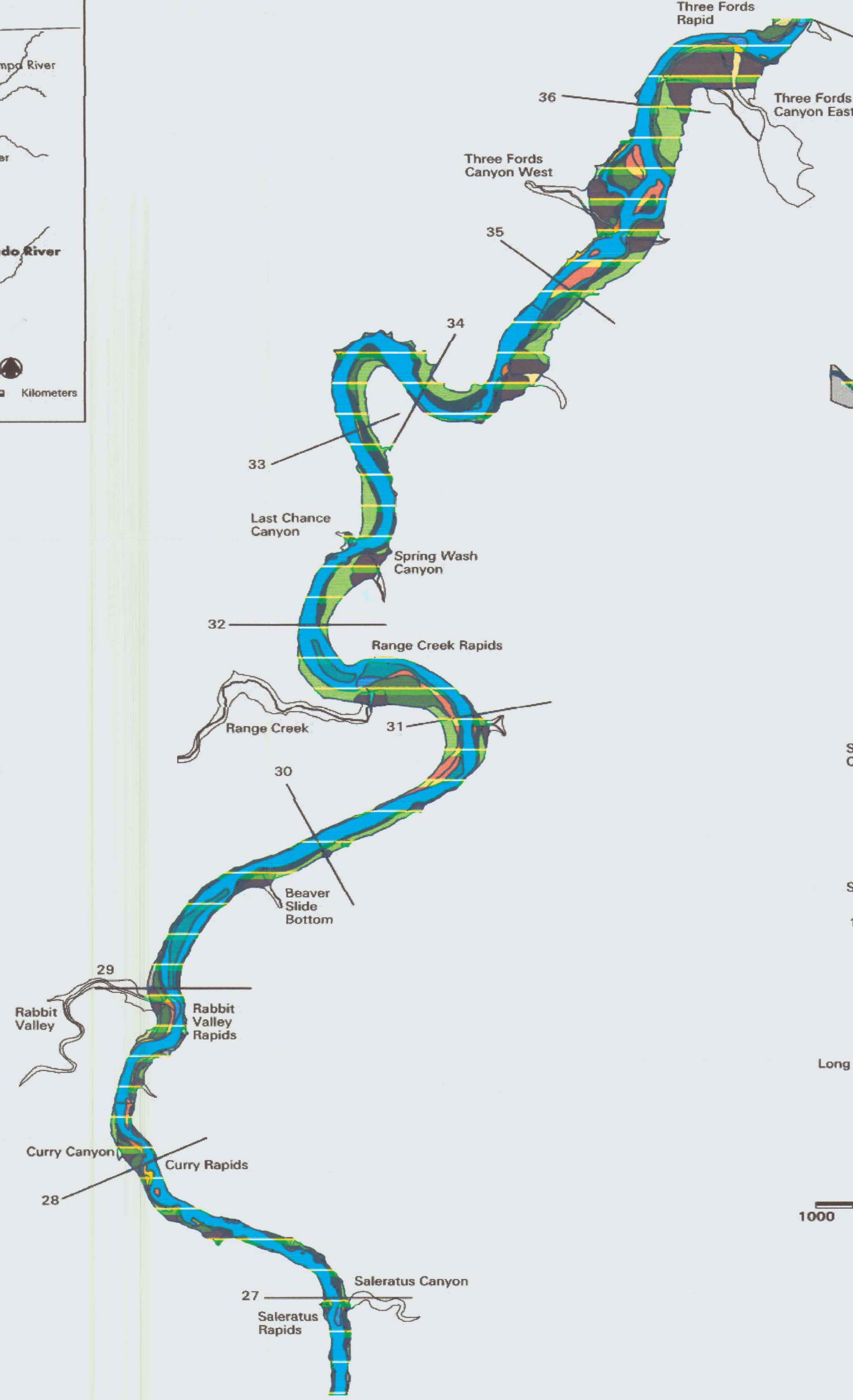
Colluvium
- Colluvium/talus
- Submerged colluvium/talus
- Active channel debris fan
- Submerged debris fan deposit

Terraces and terrace-like deposits
- Floodplain
- Intermediate Terrace
- High terrace
- High gravel terrace

Tributary alluvium and colluvium
- Debris fan surface
- Tributary channel
- Tributary terrace

Colluvium
- Talus/colluvium
- Colluvial fans
- Large block talus

Other
- Aeolian deposits
- Bedrock
- Rincon



Scale: 1:20,000

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