Debris-Flow Activity in Canyon of Lodore, Colorado: Implications for Debris-Fan Formation and Evolution

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DEBRIS-FLOW ACTIVITY IN CANYON OF LODORE, COLORADO:
IMPLICATIONS FOR DEBRIS-FAN FORMATION AND EVOLUTION

by

Jennifer A. Martin

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Geology

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Logan, Utah

2000
Large-scale characteristics of Lodore Canyon debris fans are dependent upon the bedrock and lithology of the mainstem and tributary canyons. The largest fans occur in the widest section of the mainstem canyon, which typically correlates with the location of large faults. The steepest fans are found at the mouths of tributaries where cliffs are formed by resistant lithologies. Smaller-scale fan characteristics are dependent upon the magnitude and frequency of events from the respective drainage basin, which is controlled primarily by climate. Three distinct deposit ages (oldest, intermediate, youngest) were distinguished on individual fans and were tentatively correlated throughout the canyon based on observations of boulder weathering, boulder concentration, soil development, vegetation, and topography.

During fall 1997 and late spring 1998, four debris flows aggraded fans in Lodore Canyon. The largest of the four events, Wild Mountain, deposited a 3,800-m² fan in the
mainstem canyon, significantly constricting the Green River. Three of the four debris flows occurred in drainages that had been burned by forest fires during summer 1996. The debris flows were initiated during rainfall events with precipitation totaling more than 3 cm. Events of this magnitude have rarely been recorded in the region during the period of record.

Measurements from the Wild Mountain debris fan indicate that under current operating conditions of Flaming Gorge Dam, the Green River has a limited capacity to mobilize newly deposited debris-flow material; therefore, particles eroded from the fan face cannot replenish downstream gravel bars. High release discharges equivalent to the 1997 high releases from Flaming Gorge Dam have a greater potential to rework newly deposited debris fans.
ACKNOWLEDGMENTS

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Jennifer Martin
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CHAPTER 1

INTRODUCTION

Introduction

Debris flows are an important control on the geomorphic organization of large rivers that flow in narrow canyons (Schmidt and Rubin, 1995) because the fans that these debris flows create determine river hydraulics (Wiele et al., 1996) and influence patterns of alluvial deposition. Debris fans constrict channels, cause upstream ponding, and cause eddies to form immediately downstream from fans. Schmidt and Rubin (1995) defined fan-eddy complexes as the reach of a stream where hydraulics are determined by a debris fan. These complexes extend from the upstream end of ponded flow to the downstream edge of each mid-channel bar (Figure 1). Large fans also have the potential to exert long-term control on the planform of rivers by creating meanders at sites where fans force the flow toward the opposite bank where erosion occurs (Hamblin and Rigby, 1968).

Although some research has argued that rapids located in narrow canyons are randomly (Graf, 1979) or systematically (Leopold, 1969) distributed, recent studies have clearly demonstrated that rapids occur where there are debris fans or constricting gravel bars (Dolan et al., 1978; Webb et al., 1989; Grams and Schmidt, 1999).

Although tributary canyons have long been recognized as the source of coarse sediment to mainstem rivers, the delivery of this sediment has often been mistakenly attributed to stream flow floods (Cooley et al., 1977; Graf, 1980). Webb et al. (1988)
Figure 1. Fan-eddy complex at RM 233 in the Lodore Canyon showing distribution of alluvial and colluvial deposits. Stripes indicate debris-flow deposits, circles are gravel, and dotted areas are sand. Figure is adapted from Grams (1997).
recognized that debris flows are the primary process of coarse sediment delivery to the Colorado River in Grand Canyon and are thereby the the process that creates rapids.

The stability of rapids formed by debris flows depends on the magnitude and frequency of debris-flow events from tributaries and the capacity of the river to transport the coarse sediment downstream from the fans. In a natural system, the frequency and timing of mainstem river discharges sufficient to rework debris fans depends on the hydrology of the mainstem river’s watershed. In the majority of the canyon river systems of the western United States, however, dams control river hydrology, and the stability of rapids is determined by water resource operations.

During the past decade, research has addressed the issue of debris fan-river interactions, particularly on the Colorado River in Grand Canyon where debris-flow activity has been frequent enough to affect river navigation in rapids. Yet the general applicability of the results of this work to other canyon rivers in the Colorado River basin and elsewhere has not been well established. In order to verify the generality of models derived from Grand Canyon research, some important questions must be answered. These questions include: Are the factors that influence the initiation, magnitude, and frequency of debris flows different in the northern and southern parts of the Colorado River basin? What initiating factors or debris-flow processes are dependent upon the geologic characteristics of the specific canyon where debris flows occur? Is fan morphology in other canyons similar to the morphology of Grand Canyon fans? How often do mainstem floods rework tributary debris fans?
With the exception of the 1965 Warm Springs debris flow on the Yampa River in Dinosaur National Monument, recent debris-flow activity in the upper Colorado River basin has not been well documented, although debris-fan-affected canyons occur throughout the basin (Schmidt and Rubin, 1995). During fall 1997 and late spring 1998, tributary debris flows aggraded four debris fans in the Canyon of Lodore in Dinosaur National Monument. The largest of the four events occurred on or around September 22, 1997 in the Wild Mountain drainage and deposited a 3,800-m$^2$ fan in the mainstem canyon, significantly increasing the constriction of the Green River. This event focused the attention of this study to the characteristics of debris flows and fans in the Canyon of Lodore, hereafter referred to as Lodore Canyon.

These four debris flows provide the opportunity to test the models that have arisen from research in Grand Canyon and to test other conceptual models of debris flows and debris-fan formation. The purpose of this study is to document and describe the debris flows that occurred in the Lodore Canyon in 1997 and 1998 in an attempt to gain a greater understanding of 1) the initiating conditions for debris flows, 2) the magnitude and frequency of debris flows, 3) the formation and evolution of debris fans, and 4) the capacity of debris-fan reworking by the mainstem river.

**Geologic Setting and Description of Study Sites**

The regional geology and topography of southwestern Wyoming, northeastern Utah, and northwestern Colorado is controlled by the Uinta Mountain range. The Uinta Mountains are an arcuate, east-west trending compound anticline consisting of an eastern
and western dome separated by a structural and topographic low (Hansen, 1986). The domes were uplifted beginning in latest Cretaceous time during the Laramide orogeny and thereafter subjected to post-Laramide extension during the middle to late Tertiary. Weakly metamorphosed sedimentary rocks of the Precambrian Uinta Mountain Group core both domes.

The course of the Green River in northwestern Colorado runs approximately perpendicular to the axis of the eastern dome of the Uinta Mountain anticline. Hansen (1986) attributed the development of the Green River canyons in the Uinta Mountains (Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon) to the establishment of the course of the Green River in the Tertiary Bishop Conglomerate, thereby allowing the Green River drainage to be superimposed upon the underlying resistant rocks of the Uinta Mountains. The majority of the drainages tributary to the Green River where it crosses the eastern Uinta Mountains are coincident with faults and joints formed during the pre-Cambrian (Hansen et al., 1983). Consecutively younger units in the region are exposed as the river flows southeast cutting through the south-southwest dipping rocks.

The headwaters of the Green River are in the high mountains of the Wind River Range in Wyoming. The Green River is joined by the Blacks Fork River in southwestern Wyoming and flows southward into Utah. Flaming Gorge Dam, located 50 km south of the Wyoming border in northeastern Utah, regulates the flow of the Green River and creates a 24,000-km² reservoir. The course of the river turns east-southeast just upstream from Flaming Gorge Dam then continues in that direction for about 100 km through a canyon reach (Red Canyon) and an alluvial reach (Brown’s Park) into northwestern
Colorado where the river turns to the southwest. At this point, the river’s path is perpendicular to the trend of the eastern Uinta Mountains and the river flows through Lodore Canyon, the most upstream of three deep, narrow canyons of Dinosaur National Monument. The confluence with the unregulated Yampa River at Echo Park marks the end of Lodore Canyon. The course of the Green River continues south through alternating narrow canyons and wider, meandering alluvial reaches until it joins the Colorado River in southern Utah (Figure 2).

The focus of this study is Lodore Canyon, the 30-km, narrow, debris fan-affected canyon reach located between Brown’s Park and the confluence of the Green and Yampa Rivers. For two-thirds of its length, the upper portion of the Precambrian Uinta Mountain Group is exposed in this canyon. A thick Paleozoic sequence of sandstones and cliff-forming carbonate rocks (Lodore Formation, Madison Limestone, Donut and Humbug Formation, Round Valley Limestone, Morgan Formation and Weber Sandstone) are exposed and dip southward in the downstream third of the canyon (Hansen et al., 1983).

Hansen et al. (1983) mapped and described the bedrock stratigraphy exposed in Lodore Canyon (Figure 3). The Precambrian Uinta Mountain Group consists of a 10 to 2,700 m thick cliff-forming quartz and hematite-cemented sandstone unit and a thinner, intermittent, evenly bedded shale unit. The overlying Late Cambrian Lodore Formation is 70 to 180 m thick and composed of an upper sandstone unit, a slope-forming shale interbedded with marine sandstone and a lower marine sandstone unit. In Lodore Canyon, the 180 to 200 m thick marine, cliff-forming early Mississippian Madison Limestone
Figure 2. Location map of Lodore Canyon in relation to Flaming Gorge Dam. The locations of climate stations used in the study are indicated by Xs.
Figure 3. Generalized stratigraphic column for Lodore Canyon. Not to scale.
overlies the Lodore Formation. The 75 to 90 m thick, late Mississippian Donut Shale and Humbug Formation consists of a ledge-forming lower unit (Humbug Formation) of sandstone interbedded with marine limestone and shale and an upper landslide-prone, largely marine shale unit (Donut Shale) that overlies the Madison Limestone. The Round Valley Limestone, a second 50 to 75 m thick, cliff-forming, marine limestone, overlies the Donut and Humbug Formation. Overlying the Round Valley Limestone are the lower and upper units of the 60 to 120 m thick, Middle Pennsylvanian Morgan Formation. The lower member consists of a slope-forming, landslide-prone unit of shale and siltstone interbedded with sandstone and marine limestone and the upper member is composed entirely of sandstone and marine limestone. The cliff-forming, cross-bedded, 100 m thick, Weber Sandstone, positioned above the Morgan Formation, is the youngest unit exposed in Lodore Canyon.

Infrequent debris flows are initiated at high elevations in the tributary drainages of Lodore Canyon and transport unsorted sediment to the river corridor. Grams (1997) identified 66 debris fans in Lodore Canyon that form 39 rapids. In some cases, two fans located opposite of each other form a single rapid. Fourteen rapids are formed by gravel bars located downstream from fans.

The four drainages that produced debris flows in 1997 and 1998 are 1) Middle Disaster Canyon (river km 378.9L); 2) Mile 233 Canyon (river km 372.8L); 3) Rippling Brook (river km 368.8R); and 4) Wild Mountain Creek (river km 367.2R). The first two of these canyon names are informal names not shown on topographic maps. By
convention, locations on the river are expressed as river miles measured upstream from Green River, Utah. These distances have been converted to river kilometers.

Middle Disaster is the only one of these tributaries that entirely drains the Uinta Mountain Group (Figure 4). The Mile 233 drainage is unique in Lodore Canyon because one of the thickest exposures (150 m) of the Uinta Mountain Group shale unit outcrops in this basin. In most other areas, exposures of the Uinta Mountain shale are approximately 50 m thick (Hansen et al., 1983). The Rippling Brook and Wild Mountain tributaries drain the Uinta Mountain Group as well as the entire Paleozoic sequence exposed in Lodore Canyon.

Regional Climate

The climate in the Lodore Canyon region is fundamentally different than the lower Colorado River basin. The yearly precipitation totals for the Grand Canyon region and the Lodore Canyon region are similar, 15-30 cm and 20-26 cm, respectively (Figure 5). However, the average temperatures are not. (All of the climate data used in this study have been published by the U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, North Carolina and can be found on the internet). Therefore, Grand Canyon is classified as arid and Lodore Canyon is classified as semi-arid. The classification of aridity is dependent upon both precipitation and evapotranspiration, which is a function of temperature (Hanson, 1991). In the arid Grand Canyon region, the average summer temperature of 29.3°C results in
Figure 4. Geology of the (a) Middle Disaster, (b) Mile 233, (c) Rippling Brook, and (d) Wild Mountain drainages, as mapped by Hansen et al. (1983). Probable initiation sites and debris-flow paths for Middle Disaster and Mile 233 are indicated with a box and dashed lines.
Figure 5. (A) Average daily rainfall for four stations on the Southern Colorado Plateau (Hereford and Webb, 1992, Figure 3). Gray area denotes the warm season precipitation peak. (B) Average daily rainfall for at three precipitation stations in the Lodore Canyon region. Gray areas denote two periods of peak precipitation.
high rates of evapotranspiration and consequently, low soil moisture. While the semiarid Lodore Canyon region does not receive higher amounts of annual precipitation, the average summer temperature of 22.1°C results in greater retention of moisture in the soil. Soil moisture content is an important factor controlling vegetation.

The timing of precipitation in the two regions is also different. Using climate data from multiple stations in the Grand Canyon region, Hereford and Webb (1992) determined that the regional climate is characterized by a “warm season” between June 15 and October 15 when precipitation reaches its yearly peak (Figure 5). The Lodore Canyon region does not experience a comparable warm season precipitation peak. Instead, the yearly rainfall pattern is distinguished by two periods of increased precipitation, one in the spring between mid-April and mid-June and the other during the months of September and October.

**Previous Work**

*Debris flows in canyons*

Debris flows are an important landscape-forming process in many regions of high relief. In the United States, debris flows have been mapped and described on Cascade Range volcanoes (Pierson, 1982), in the Pacific Northwest (Benda, 1990), in Owens Valley, CA (Whipple and Dunne, 1992), in Yellowstone National Park (Meyer et al., 1995), in Puerto Rico (Larsen and Torres-Sanchez, 1996), in the Blue Ridge of Virginia (Liebens, 1996) and North Carolina (Gori and Burton, 1996), and on the Colorado Plateau (Hereford et al., 1996; Webb et al., 1996).
Blackwelder (1928) first recognized the importance of debris-flow processes as geomorphic agents. Since that time, researchers have been studying the initiating factors and mechanics of debris flows (see Coussot and Meunier, 1996, for a comprehensive summary). However, the study of debris flows and debris flow-river interactions in canyon river systems only began during the last decade with studies of the Colorado River in Grand Canyon. The focus of the Grand Canyon studies has been the identification of factors that initiate debris flows in a region, the determination of magnitude and frequencies of debris flows in that region, and the discharges of the mainstem river that rework debris fans.

The study of precipitation patterns is important to the identification of factors controlling debris-flow frequency because intense rainfall is needed for debris-flow initiation (Caine, 1980). The numerous documented debris-flow events during the period of historical record have enabled Grand Canyon researchers to correlate three storm types to the initiation of debris flow events in Grand Canyon (Melis et al., 1994): 1) convective thunderstorms during the summer monsoon, 2) dissipating tropical cyclones, and 3) warm winter storms.

Extensive field work has shown that four principal slope failure processes initiate debris flows in Grand Canyon tributaries: 1) failure of colluvial wedges, 2) failure of weathered bedrock, 3) mobilization of unconsolidated colluvium by a waterfall ("firehose effect"), and 4) combinations of the other three processes (Melis et al., 1994). The "firehose effect" (Johnson and Rodine, 1984) is not endemic to Grand Canyon, but the
majority of the debris flows there are mobilized by this process. This process involves water pouring off steep cliffs and initiating failures of colluvial wedges.

Griffiths et al. (1996) contended that the presence of shales, in particular, in tributary drainages determines the likelihood of debris-flow activity. Weathered shales can play an important role in the failures of colluvial slopes or overlying bedrock that are the initiating forces for some debris flows in Grand Canyon tributaries. Research in Grand Canyon has shown that the potential for debris flows increases where the elevation of the Hermit Shale is greater than 100 m above the river (Griffiths et al., 1996). Yet, the most crucial role of shales is to provide the silt and clay that give debris flows mechanical stability. The strong electrochemical attraction between clay particles is believed to provide matrix strength because their water absorption potential promotes the high pore pressures necessary to support large particles in the flow (Hampton, 1975; Pierson and Costa, 1987; Griffiths et al., 1997).

Historical photograph matches have allowed Grand Canyon researchers to determine the frequency of debris flows since the turn of the century and, in combination with climatic and lithologic evidence, identify those tributary canyons most susceptible to future flows (Griffiths et al., 1996). Other dating methods, such as, cosmogenic $^3\text{He}$ dating of basalt boulders, radiocarbon ($^{14}\text{C}$) dating of organic matter, and $^{137}\text{Ce}$ dating of surface sediment, have extended the timeframe of study beyond the historical photographic record (Webb et al., 1998; Hereford et al., 1996).

Dissolution pitting rates of carbonate boulders on debris-fan surfaces in eastern Grand Canyon have also been calibrated by Hereford et al. (1997, 1998) using radiometrically-
dated surfaces and archaeological sites to calculate ages of debris-fan surfaces. This process enabled correlation of similar-age surfaces between fans and the recognition of discrete periods of increased debris-flow activity in Grand Canyon (Hereford et al., 1997).

Hammock and Wohl (1996) also determined the prehistoric frequency of debris-flow events that aggraded the Warm Springs debris fan on the Yampa River in Dinosaur National Monument using $^{14}$C dating of debris-flow deposits. The watershed of Warm Springs Creek is adjacent to some of the Lodore Canyon watersheds in this study (Figure 6). Hammock and Wohl argued that there have been distinct periods of increased debris-flow activity, but the dates of these periods are different than those of Grand Canyon fans (Figure 7).

Magnitudes of individual debris flows have been measured using two principal methods. Peak discharges of debris flows have been estimated by surveying super-elevated debris flow deposits in bends of debris-flow channels (Apmann, 1973; Hungr et al., 1984; Pierson, 1985; Webb et al., 1989; Wohl and Pearthree, 1991). Debris-flow volumes have been determined by surveying the aerial extent of fan deposition and then multiplying that number by the deposit thickness determined from trenching (Webb et al., 1998).

Using evidence of the large-scale depositional morphology and stratigraphic exposures of debris-flow deposits, Melis et al. (1997) proposed three different types of debris-fan morphology for Grand Canyon fans. Various combinations of debris-flow and stream-flow processes form the three fan types. Their type I and III fans both form as a result of a single debris-flow phase followed by low recessional stream-flow discharges
Figure 6. Topographic map of Lodore Canyon with drainage basin boundaries of major tributaries delineated. The Pot Creek drainage extends more than 4 km beyond the map boundary to the northeast. Drainages where debris flows occurred in 1997-98 are outlined in bold.
<table>
<thead>
<tr>
<th>Grand Canyon</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
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<tr>
<td>Warm Springs</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

YEARS, BP

Figure 7. Comparative timelines of fan-forming debris flows from Grand Canyon fans using carbonate pitting relationships (Hereford et al., 1996) (top) and the Warm Springs fan on the Yampa River using 14C dating of organic material (Hammock and Wohl, 1996) (bottom). Stippled box indicates the only time period (aside from the present) when activity in the two areas overlaps.
(Type I) or high recessional stream-flow discharges, respectively. Type II fans occur as the result of debris-flow processes alternating with hyperconcentrated flow (higher water content flows) and stream-flow processes. Using depositional evidence, Melis et al. (1997) also proposed hydrographs for each type of debris-flow event.

Research in Grand Canyon has provided a model that has been useful in predicting basins where the highest frequency of debris flows occur. In order to determine the applicability of this work to other canyon river systems, however, the generality of the Grand Canyon model still needs to be tested.

**Relationship between fire and debris flows**

Initiating conditions for debris flows are not the same in all landscapes. Differences in lithology, vegetation, and precipitation affect the occurrence of debris flows. Forest fires, for instance, are not important initiation factors in arid environments with sparse vegetation, such as Grand Canyon. Yet, an important relationship between forest fires, precipitation, and debris-flow activity has been established in forested areas by studies in Yellowstone National Park, Wyoming (Meyer et al., 1995) and the Huachuca Mountains, southeast Arizona (Wohl and Pearthree, 1991).

Study of the 1988 fires in Yellowstone National Park allowed Meyer et al. (1995) to recognize fire-related sedimentation patterns and then extrapolate this knowledge to older deposits in an attempt to discern the fire-related alluvial chronology of the park. The results of their study showed that forest fires are a major factor in sedimentation from tributaries and that periods of fire-related sedimentation often correlate with warmer temperatures and drought conditions.
Wohl and Pearthree (1991) showed that debris flows originate in the Huachuca Mountains by widespread rilling and slope wash following forest fires. Two known fire-related debris flow events in 1977 and 1988 led to the examination of the fire and precipitation histories for the region. They found that forest fires had a decadal recurrence interval. Although rainfall sufficient to initiate debris flows occurs more frequently, a third factor, sediment availability, is also necessary to produce debris flows in this region.

Debris fan formation and evolution

Mainstem rivers are typically unable to immediately rework all of the deposits delivered by tributary debris flows. Therefore, debris fans develop, build, and evolve in ways that are unrelated to the mainstem river. Hooke’s (1967) work in the laboratory and on alluvial fans in desert regions of California, where the scale of the rivers is much smaller than the scale of the valleys, provides a testable model of fan formation and evolution. This model can be extrapolated to fans formed in a wide range of settings, including the tributary debris fans of the canyon rivers of the Colorado Plateau where the scale of the rivers is approximately equivalent to the scale of the valleys.

Hooke’s (1967) conceptual model begins with an explanation of the depositional characteristics of different types of debris flows. He differentiated between two distinct types of deposits—debris-flow deposits and sieve deposits. Debris-flow deposits are characterized by poorly sorted mixtures of cobbles to boulders imbedded in a fine-grained matrix that forms levees or lobes on the fan surface. Sieve deposits consist of unsorted pebble- to boulder-sized particles, but lack the fines of debris-flow deposits. They also form lobes but do not form levees, and their lobes are characteristically thicker at the
snouts than debris-flow lobes. Sieve deposition occurs as an immediate response to
dewatering caused by infiltration into underlying sediments.

Sieve deposition was tested and observed in the small-scale debris flow models that
Hooke (1967) constructed, but observations of large-scale deposition and channel
formation processes were the most significant results of debris-flow models constructed
by Hooke. He found that, in the short term, debris-fan deposition is localized, but over
longer periods of time, shifting loci of deposition result in a more uniform depositional
sequence on the fan surface. In order for uniform deposition to occur, the debris flow
must periodically transport sediment across the fan surface. This transport occurred in
channels. Hooke has shown that these channels are formed by stream flow rather than
debris flow. In the experiments where only debris-flow processes were used, channels did
not form in the depositional fan.

Hooke’s (1967) experimental evidence that the formation of incised channels in the
head of debris fans is the natural result of alternating stream flow and debris-flow
processes refuted previous assertions that fundamental changes in regime were
responsible for such channel incision (Lustig, 1965). Subsequent debris flows, in Hooke’s
model, are able to exceed the depth of the incised channel and deposit on the fan surface.
In cases where channel incision exceeds the capacity of debris flows to overtop the
channel banks, Hooke hypothesized that down-fan channel deposition eventually results
in backfilling that would allow the flow to overtop the banks. Therefore, he contended
that the state of debris-fan evolution is driven by equalities of depositional rates. If
frequent overbank deposition occurs at the fanhead, incision rates will increase or, conversely, if deposition increases on the distal margin of the fan, incision will decrease.

Hereford and others’ (1996) study of large debris fans in eastern Grand Canyon differentiates between two types of fan deposition—fan-forming debris flows and channelized debris flows. Hereford et al. (1996) determined that many large fans in eastern Grand Canyon consist of large, older, segmented surfaces that they defined as “fan-forming.” These surfaces are interpreted as representing infrequent high magnitude debris flows. Younger debris flows are confined to deeply incised channels that route flows to the distal margin of the fan where they form minor, recently active depositional fans. These fans are described as “channelized” and are thought to be characteristic of periods of high frequency, low magnitude debris flows. Their explanation for the formation of channels on debris fans lies, in contrast to Hooke’s (1967), in the interaction between the tributary debris fan and the mainstem river (Figure 8).

Hooke’s model does not take into account any fan-river interactions because it was based upon alluvial fans in fault-bounded basins. Hereford et al. (1996) contended that local aggradation in the mainstem river channel caused by the deposition of debris-flow deposits from the tributary would increase the base level of the tributary, decrease the gradient of the debris-flow channel, and result in fan aggradation during the next debris flow. Once the mainstem river is able to rework the debris-flow deposits causing the base level to decrease, the debris-flow channel becomes incised into the fan deposits as subsequent debris flows erode the channel to reach the base level.
Figure 8. Schematic illustration of how the ideas of Hooke (1967) and Hereford et al. (1996) can be combined into models of fan evolution. The model assumes that a large fan-shaped feature is present at the mouth of the tributary. Debris flow events occur, depositing material at the head of the fan (A). At time B, deposition at the head of the fan has increased the gradient such that tributary fluvial processes incise a channel into the deposit. The next debris-flow event that occurs at time C will be channeled across the fan surface depositing at the fan toe. The next flow or subsequent flows (D) will aggrade and overtop the channel resulting in a shift in deposition from the toe to the head of the fan. Hereford et al. contend that in a fan-river system (E), the removal of the channelized deposit at the toe of the fan will reduce local base level resulting incision of the channel, hindering channel aggradation that otherwise result in a shift in the locus of deposition from fan toe to fan head.
Hereford et al. (1996) contended that, since the Colorado River is capable of reworking deposits formed by channelized flows, even under controlled flow conditions, debris-flow channels have remained incised and flows have remained channelized. Dating and correlation of surfaces formed by fan-forming flows throughout the canyon (Hereford et al., 1997) indicated that flows of this magnitude have a recurrence interval of approximately 850 years. If so, then fan-forming events, debris flows capable of overtopping the channels, could occur in the next 60 years in Grand Canyon, causing radical changes to the river environment.

The explanation proposed by Hereford et al. (1997) for fan evolution in Grand Canyon pertains only to tributary channel evolution after the channel has already formed, and does not account for channel formation. The combination of Hereford and other’s ideas with Hooke’s model could provide a more comprehensive model of fan evolution and channel development for debris-fan-dominated canyon river systems.

**Debris fan reworking**

Despite the fact that the conditions that initiate debris flows may not be uniform, the depositional features that debris flows create are reasonably similar in their effects upon the mainstem river. A debris flow may form a temporary dam if it reaches the river, and this dam can be reworked to various degrees depending upon the characteristics of the fan (aerial extent, particle size) and the discharge of the river (Webb et al., 1998; Wohl and Pearethree, 1991). Due to current widespread regulated conditions on many western debris-fan-dominated rivers, the ability of the river to rework debris-fan deposits may
have decreased greatly. Reductions in the reworking ability of the river have direct implications on the river environment and, consequently, recreational users.

Graf (1980) made the first attempt to quantify the effect of dam regulation on the stability of rapids on the Green River in the canyons of Dinosaur National Monument. His study used the estimated stability of the largest boulder in each rapid as a proxy for overall rapid stability. He estimated the force of flowing water at both pre- and post-dam discharges and compared it to the calculated resisting forces of the largest boulder in each rapid. Based on these calculations, the percentage of stable rapids in the canyons of Dinosaur National Monument increased from 62% to 93% after the closure of Flaming Gorge Dam. However, Graf’s (1980) assertion that the largest particle in a rapid is representative of the stability conditions of the entire rapid is flawed. In order for this method to provide a reasonable estimate of dam-induced changes, the largest boulder that could be moved under pre-dam conditions should have been determined. In this way, he would have eliminated the potential overestimation of stability caused by the measurement of particles that were immobile under extremely high discharges.

Using Graf’s method, if the largest boulder mobile during pre-dam conditions could not be moved under peak post-dam conditions, then the rapid might be considered stable. Measurement of only the largest boulder also ignores the effect of other boulder sizes on the composition of the rapid as shown by Hammock and Wohl’s (1996) work on Warm Springs Rapid on the Yampa River. For example, a rapid may consist primarily of intermediate-sized (290-725 mm) boulders. Even if the largest boulder is immobile, movement of the smaller particles might reorganize a rapid. In any case, Graf’s method is
difficult to utilize because measuring boulders in the middle of a rapid on the Green River is hazardous, if not impossible.

Kieffer (1985, 1987) considered the constriction of the river at a rapid to be an appropriate measure of its stability. Kieffer defined the constriction as the ratio of the channel width in the rapid to the upstream channel width and determined that, on average, the narrowest part of the channel of the Colorado River in Grand Canyon is in equilibrium with the average flow conditions. In Grand Canyon, this constriction ratio is 0.50 times the mean upstream width. Kieffer’s work at Crystal Rapid attempted to explain the hydraulics of a rapid formed by an erodible debris fan by showing how, at high discharges, erosion of the debris fan regulated velocities in the rapid, thereby maintaining an equilibrium debris-fan configuration. Kieffer’s quantitative model of debris-fan reworking illustrated the evolution from dammed or highly constricted rapids to a stable configuration resulting from reworking by high discharges.

Hammock and Wohl (1996) tested Kieffer’s hypotheses by reconstructing flow conditions at Warm Springs Rapid and using step-backwater modeling to calculate reworking. They found that Kieffer’s model might be limited by her use of only the largest grain size (2 m) to characterize the rapid, similar to the strategy employed by Graf (1980). Hammock and Wohl’s (1996) study showed that the constriction was caused not only by the largest particles, but was the result of the combination of particles in the $D_{50}$ to $D_{84}$ size classes. Similar to Kieffer’s model, they suggest that debris fans are reworked by channel bed erosion that begins at the narrowest point of constriction and proceeds
headward. They also proposed that erosion continues even during moderate discharges, but they did not provide a mechanism to explain this process.

Kieffer (1985, 1987) and Hammock and Wohl (1996) only considered the situation where the debris fans produce a constriction that temporarily dams the mainstem river. Historical photographic evidence from Lava Falls Rapid (Webb et al., 1998) encompass a wider range of constriction scenarios and discharges and thereby provides evidence of reworking that occurs under a wide range of circumstances. They found that reworking occurs during lower magnitude discharges and at lower constriction ratios than those that Kieffer considered “stable.”

Experiments performed during the 1996 Controlled Flood in Grand Canyon allowed researchers to study debris fan reworking at moderate discharges and lower constriction ratios (Webb et al., 1998, 1999; Pizzuto et al., 1999). Webb et al. (1998) revised Kieffer’s model by adding another facet to the reworking process. They contended that boulders are not only transported by direct entrainment in the flow, but that boulders are also mobilized at lower than critical velocities during bank collapse of the face of the debris fan. The results of their experiments show that the majority of the reworking during the moderate discharges of the 1996 Controlled Flood occurred as bank failures. This finding contradicts Kieffer’s (1985) conclusion that high discharges are required for fan reworking. Findings from the 1996 Controlled Flood also provide a mechanism—bank collapse—to explain Hammock and Wohl’s (1996) conclusion that reworking occurred at Warm Springs Rapid during moderate discharges.
Webb et al. (1998) also observed from historical photography at Lava Falls Rapid that, at certain stages in the evolution of a debris fan, high discharges are unable to rework debris fans. They maintained that once fines have been winnowed from a fan and boulders have become sutured in the bed of the river, reworking can no longer occur. Although they do not provide an estimation of the amount of time necessary for suturing to occur, their evidence from Lava Falls Rapid (i.e., lack of reworking of a 1872 deposit by a high discharge in 1884) indicates that suturing could occur in less than 12 years. Thus, a window of opportunity for debris-fan reworking probably exists, and it is during this period that river managers can consider the river’s reworking ability in making decisions about reshaping rapids.

**Stream channel establishment**

Debris-fan reworking following a debris flow is not caused solely by interactions with the mainstem river. As Hooke (1967) has observed, stream flow activity from the tributary can also play an important role in the evolution of debris fans. The study of stream flow activity on debris fans following debris-flow events is valuable not only to debris fan research but also to the study of the origin of channel morphology in steep streams. Channels that form on newly deposited, high gradient debris fans or that are re-established following a debris-flow episode could be used to evaluate existing theories of the origin of stream channel morphology.

The stability and spacing of step-pool sequences in high-gradient streams have been the subject of detailed field study (Judd and Peterson, 1969; Ashida et al., 1984; Grant and Mizuyama, 1991; Wohl and Grodek, 1994). Debate, however, exists in the literature
about the step formation process (Judd and Peterson, 1969; Ashida et al., 1984; Grant and Mizuyama, 1991; Wohl and Grodek, 1994). Since opportunities to observe the formation of natural stream channels are extremely limited, flume studies and observations of periods of reworking during large flood events have been the basis for most theories on the origin of steps.

Step formation had been theorized to be instigated by flow blockage that occurs when bed erosion reaches a particle that cannot be transported (Judd and Peterson, 1969). This factor was also believed to stimulate the formation of a series of downstream steps and pools. Subsequent detailed flume studies using poorly sorted gravels, however, seemed to indicate that steps result from the formation of antidunes in the crests of standing waves (Ashida et al., 1984; Grant and Mizuyama, 1991). Yet Wohl and Grodek (1994) have shown that the antidune model cannot explain the formation of steps in some high gradient streams where the particles that form the steps are never completely submerged by stream flow. Abrahams et al. (1995), recognizing the limitations of the anti-dune model, performed additional flume experiments to test the theory that steps develop with characteristic heights, widths and spacing such that they produce the maximum flow resistance and are therefore the most stable bed configuration.

There seems to be wide agreement in the literature that steps form during high magnitude, low frequency flood events (Whittaker and Jaeggi, 1982; Grant et al., 1990). Chin (1994) attempted to determine the timing and scale of step-pool stability. She found that different scales of steps that exist in the high gradient streams of the Santa Monica Mountains, California are reworked on varying temporal scales, but step-pool sequences
are generally reworked by high magnitude events that occur with a frequency of 5 to 100 years.
CHAPTER 2

METHODS

Debris-Fan Characterization

During summer 1997, reconnaissance surveys were performed at 23 debris fans in Lodore Canyon. Lichen cover and the general characteristics of boulders were also used to classify debris-flow ages as young, intermediate, and old at Zenobia and Mile 233. The general goals of these surveys were to determine which fans had experienced recent debris-flow activity and to identify deposit characteristics that could be used to distinguish fan deposits of different ages. Debris fans were considered recently active if they contained boulders free of lichen. Quartzite boulders were compared for the extent and characteristics of lichen cover. Boulders were defined as fresh if their surfaces were free of any lichen (Figure 9). The lichen were not differentiated in this study, although the morphology of the lichen observed on the boulders varied, probably indicating the presence of several different species. Localized factors that might have affected the growth of lichen were considered insignificant to the relative abundance of lichen growth observed on the boulders on each fan since all of the varieties of lichen observed were pervasive throughout the canyon.

The extent of channelization was also observed on each fan. The existence or absence of a distinct active channel was noted at each site. The youngest channel was determined to be the channel with the most lichen-free boulders, fresh cutbanks, and little or no vegetation in the channel.
Figure 9. Examples of the variation in lichen cover on quartzite boulders on Lodore Canyon fans. Photos A-C represent older, intermediate, and younger boulders, respectively. Photo D shows the initial conditions of newly deposited boulders.
The detailed surficial geology of two fans was mapped in order to characterize the depositional characteristics of Lodore Canyon fans. The debris fan at the mouth of Zenobia Creek was mapped in detail in late October 1997. Mapping of the Mile 233 fan (Grams, unpub.) was field checked and modified in September 1998. Deposits were assigned relative ages based upon the degree of lichen cover on large boulders and vegetative cover on the deposits.

Other debris-fan characteristics were determined using 1997 aerial photographs taken by the U. S. Bureau of Reclamation, the published geologic map of Dinosaur National Monument (Hansen et al., 1983), the USGS 7.5-minute topographic maps of the canyon, and the GIS database of the surficial geology of Lodore Canyon (Grams, 1997). Valley widths throughout the canyon were measured from the break in slope at the base of the canyon walls on each side of the river based on 7.5-minute topographic maps. A measurement was made every 0.8 km beginning at RKM 387.2 and ending at the confluence with the Yampa River to determine the average, minimum, and maximum valley widths for the canyon. In addition, valley widths were measured at the 42 debris fans identified in Lodore Canyon. Values at debris-fan sites were obtained by averaging the upstream and downstream widths measured at the mouths of tributary canyons. Drainage basin areas of the 42 debris fans used in the study were measured from USGS 7.5-minute topographic maps. Fan areas of the corresponding fans were calculated using the existing GIS database.

Attempts to quantitatively test the relation between debris-fan slope and drainage basin slope were hindered by the scale of the debris fans in relation to their drainage
basins. Qualitative estimates of fan slope were determined from a combination of measured topography at some sites and field observations at others.

Constriction ratios were measured from the 1997 aerial photographs at the 23 fans where reconnaissance surveys were conducted. The constriction ratios were calculated using the methods of Kieffer (1985) and Webb et al. (1996). Kieffer (1985) used

$$\frac{w_2}{w_0}$$

(1)

where \(w_2\) is the width at a cross-section in the rapid and \(w_0\) is the width in the upstream pool. The cross section used for \(w_2\) in Lodore Canyon was the narrowest cross section at a discharge of 40 m\(^3\)/s. The upstream width used was the unconstricted width just upstream from the fan. Webb et al. (1996) calculated the constriction ratio \(C_w\) using

$$C_w = [1 - W_{r(ave)}^* (1/W_u + 1/W_d)/2] * 100$$

(2)

where \(W_{r(ave)}\) is the average width of the river channel in the constricted rapid and \(W_u\) and \(W_d\) are the upstream and downstream channel widths, respectively.

Aerial photographs of Lodore Canyon taken in 1938, 1954, 1993, and 1997 were examined in an attempt to determine whether debris flows had occurred on any of the fans in the past 50 years. Thirty-two historical oblique photographs that had been obtained and matched by Grams (1997) were also inspected for evidence of historical debris-flow activity in Lodore Canyon.

**Determining Climate and Fire Histories**

Precipitation data from regional climate stations in the Lodore Canyon area were obtained from the Utah and Colorado state climate offices. The three closest gages are maintained at (1) the Brown’s Park Wildlife Refuge (BPR) located approximately 5 km
north of Gates of Lodore, (2) the Dinosaur National Monument Quarry area (DNMQ) located approximately 30 km southwest of Echo Park, and (3) the Dinosaur National Monument Headquarters (DNM) located approximately 30 km south of Echo Park (Figure 2). The DNMQ station contains the longest record beginning in 1959. The DNM and BPR stations recorded their first full years of data in 1966 and 1967, respectively.

Data from these three climate stations were used as a proxy for precipitation in the Lodore Canyon basins. The regional data are not presumed to accurately reflect the exact amount of precipitation that fell in those basins. The three regional climate stations are located in valleys while the initiation sites of debris flows are located at high elevations in the Lodore Canyon basins.

Precipitation averages and extremes were calculated for each day of the year at each of the three stations using the historical data. The frequency of extreme precipitation was also calculated at the climate stations. For each complete year of record at the DNMQ, DNM, and BPR climate stations, the number of days of precipitation and the number of days when precipitation exceeded 2 cm and 3 cm were calculated.

The occurrence of summer season drought was estimated using the DNMQ, DNM, and BPR climatic data. Drought years were defined for the purpose of this study as years when the total summer rainfall (June, July, and August) did not exceed 65% of the average summer rainfall for the period of record.

The location and occurrence of fires in Lodore Canyon has been mapped and recorded by the National Park Service since 1940. Fire boundaries, as delineated on topographic maps of Dinosaur National Monument, were traced and overlain onto maps containing
outlines of individual Lodore Canyon drainage basins. The Lodore Canyon fire history was also compared to the record of total precipitation and the calculation of drought for each climate station.

**Characterizing the 1997-98 Debris Flows**

The sequence of new debris-flow deposition at each of the four sites was established by observation and detailed mapping of crosscutting relationships both in the debris-flow channel and on the fan surfaces (Figure 10). A geodetic total station was used to measure the area of new deposition at each site. Trenches were also opened at three of the four sites in an attempt to determine the thickness of new deposits (Figure 11). Characteristic particle size distributions of depositional phases for each debris flow were measured using Wolman’s (1954) methodology.

**Calculating Velocity and Discharge**

Peak instantaneous discharges were calculated at two of the four sites using evidence of super-elevation of the debris flow around bends in the channel upstream from the fans. A geodetic total station was used to survey the elevation of high water marks (mud lines) and the corresponding channel cross sections in channel bends. Where possible, two bends were located in each channel. Peak velocity of the debris flow was calculated using Apmann’s (1973) formula:

\[ V = \left[ gR_c h_e / kW \right]^{0.5} \]  

(3)

where \( V \) is peak velocity, \( g \) is gravitational acceleration, \( R_c \) is the radius of curvature around the bend, \( h_e \) is the elevation difference at the bend, \( k \) is a correctional factor, and
Figure 10. Example of cross-cutting relationship of phases on the Wild Mountain debris fan.

Figure 11. Trench 1 located at Mile 233. Base of the debris flow, marked as the top of the alluvial sand, is indicated with an arrow.
W is the effective width of the channel. Peak discharge, Q, is the product of the calculated velocity and the surveyed cross-sectional area, A, at the super-elevation site:

\[ Q = VA. \]  \hspace{1cm} (4)

Assumptions in this method, noted by Webb (1987), indicate that these calculated values are approximations with an error similar to other indirect discharge measurement methods (Costa, 1984).

**Determining Water Content**

Matrix samples collected at three of the four sites were used to determine the approximate water content of each debris flow. The methods of Webb et al. (1989) were used during the reconstitution process. Five to ten kilogram samples were sieved to remove particles greater than 16 mm. Water was added in large quantities initially and then more gradually as the mixture began to exhibit cohesive properties (i.e. form levees), ceased to fractionate and became capable of supporting 16 mm particles. Water was continually added in 10-20 ml quantities until the mixture lost cohesion and was no longer able to support larger particles.

**Measuring the Extent of Reworking by the Green River**

In order to quantify the degree, style, and timing of reworking of the Wild Mountain debris fan by the Green River, a set of baseline measurements was made. Topographic surveys using a geodetic total station, pebble counts employing the methods of Wolman (1954), and detailed field mapping were used to measure the characteristics of the debris fan in late October 1997, approximately 3 weeks after the debris flow occurred. On
March 5, 1998, the topographic survey and pebble counts were repeated along the face of the fan between the elevation of the winter peak flow and the fan surface just beyond the edge of water at 74 m\(^3\)/s. This survey allowed for the determination of the amount of reworking produced by a peak discharge of 97 m\(^3\)/s that occurred between November 3 and December 24, 1997. A map of the change was produced by subtracting the March 1998 topography from the October 1997 topography.

The purpose of the third survey was to determine the amount of reworking attributed to a discharge of 131 m\(^3\)/s that was sustained from May 25 through June 14, 1998. Due to the unusual water year, flows were maintained at a discharge greater than 68 m\(^3\)/s for most of the summer. Repeat measurements were therefore postponed until the Bureau of Reclamation lowered the flows to 47 m\(^3\)/s for a 2-day period during late September. The amount of change measured between March and September 1998 thus reflects the effects of continuous moderate flows in addition to peak power plant capacity discharges. During the September survey, the entire surface of the newly deposited fan and the longitudinal profile of the channel were resurveyed, pebble counts were repeated, and a detailed map of the fan surface was completed.
CHAPTER 3
RESULTS

Canyon-Wide Characteristics of Lodore Canyon Fans

Only a small percentage of Lodore Canyon’s debris fans show evidence of recent debris-flow activity, based on the evidence of fresh boulder deposits and/or unvegetated channels. There are 42 true debris fans in Lodore Canyon, and 23 were examined in the field (Table 1). Eleven of these fans contained evidence of recent deposition (Table 2). Five of those fans are located at the mouths of tributaries that drain the Uinta Mountain Group. The other six active fans also drain portions of the overlying Paleozoic sequence. Although Grams (1997) reported that there are 81 debris fans in Lodore Canyon, only 66 are delineated on his surficial geologic maps. Further examination showed that 24 of the 66 fans are actually talus or other colluvial deposits.

Debris-fan activity could not be adequately determined from historical aerial photographs. Complete aerial photographic coverage of Lodore Canyon exists for 1938 and 1954, yet the combination of the high elevation at which the photographs were taken, the existence of deep shadows concealing portions of the photos, and the lack of stereo coverage made it difficult to discern small-scale changes on debris fans. The only detectable change in fan characteristics was noted on the Zenobia fan. The 1954 photos show no indication of the youngest active channel (Figure 12), but that channel can be clearly delineated on the 1993 and 1997 photos and in the field.
### Table 1. Characteristics of the 42 Lodore Canyon Debris Fans Examined in This Study

<table>
<thead>
<tr>
<th>Debris Fan</th>
<th>River mile</th>
<th>Drainage area (km$^2$)</th>
<th>Valley width (m)</th>
<th>Fan area (m$^2$)</th>
<th>Incised channel</th>
<th>Deeply incised channel</th>
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<td>14,720</td>
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<td>157</td>
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<td>238.2</td>
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<td>181</td>
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<tr>
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<td>0.28</td>
<td>181</td>
<td>37,640</td>
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<td>32,190</td>
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<td>169</td>
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<td>241</td>
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<td>x</td>
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<td></td>
<td>236.1</td>
<td>0.89</td>
<td>169</td>
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<td>234.5</td>
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<td>Debris fan</td>
<td>River mile</td>
<td>Drainage area (km²)</td>
<td>Valley width (m)</td>
<td>Fan area (m²)</td>
<td>Incised channel</td>
<td>Deeply incised channel</td>
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<td>------------</td>
<td>---------------------</td>
<td>------------------</td>
<td>---------------</td>
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<td>133</td>
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<td>1.18</td>
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<tr>
<td>231.1</td>
<td>0.93</td>
<td>108</td>
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<td>230.7</td>
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<td>96</td>
<td>5,360</td>
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<td>230.6</td>
<td>1.75</td>
<td>96</td>
<td>6,030</td>
<td></td>
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<td><strong>Rippling Brook</strong></td>
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<td>3.51</td>
<td>135</td>
<td>13,880</td>
<td></td>
<td>x</td>
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<td><strong>Wild Mountain</strong></td>
<td>229.5</td>
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<td>108</td>
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<td><strong>Limestone Draw</strong></td>
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<td>15.72</td>
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<td>228</td>
<td>0.67</td>
<td>169</td>
<td>14,070</td>
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<td>227.9</td>
<td>0.76</td>
<td>169</td>
<td>15,790</td>
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<td>227.6</td>
<td>3.17</td>
<td>193</td>
<td>44,990</td>
<td></td>
<td></td>
<td>x</td>
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<td>226.3</td>
<td>2.34</td>
<td>145</td>
<td>15,220</td>
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<td><strong>Canyon Average</strong></td>
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<td>150</td>
<td>16,899</td>
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<td><strong>Canyon Minimum</strong></td>
<td>0.10</td>
<td>78</td>
<td>1,950</td>
<td></td>
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<tr>
<td><strong>Canyon Maximum</strong></td>
<td>350.00</td>
<td>265</td>
<td>110,790</td>
<td></td>
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TABLE 2. LIST OF DRAINAGES IN LODORE CANYON CONTAINING EVIDENCE OF RECENT DEBRIS-FLOW DEPOSITION

<table>
<thead>
<tr>
<th>Drainage</th>
<th>River mile</th>
<th>Date of most recent deposition</th>
<th>Date of most recent fire</th>
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</thead>
<tbody>
<tr>
<td>Trailer Draw</td>
<td>238.8 (L)</td>
<td>--</td>
<td>1951*</td>
</tr>
<tr>
<td>Middle Disaster</td>
<td>236.8 (L)</td>
<td>1997</td>
<td>1996</td>
</tr>
<tr>
<td>Zenobia</td>
<td>235.6 (L)</td>
<td>--</td>
<td>1988*</td>
</tr>
<tr>
<td>Mile 233</td>
<td>233 (L)</td>
<td>1997</td>
<td>--</td>
</tr>
<tr>
<td>Hell’s Half Mile (R)</td>
<td>231.8 (R)</td>
<td></td>
<td>1981*</td>
</tr>
<tr>
<td>Rippling Brook</td>
<td>230.5 (R)</td>
<td>1998</td>
<td>1996</td>
</tr>
<tr>
<td>Wild Mountain</td>
<td>229.5 (R)</td>
<td>1997</td>
<td>1996</td>
</tr>
<tr>
<td>Limestone Draw</td>
<td>228.5 (L)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>unnamed</td>
<td>227.6 (L)</td>
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<td>--</td>
</tr>
<tr>
<td>unnamed</td>
<td>227.3 (L)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>unnamed</td>
<td>227.1 (L)</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

* indicates probable link to a mapped fire
-- date of most recent activity not determined
Figure 12. Surficial geologic map in the area of the Zenobia debris fan (see Figure 6 for location). The bold line indicates the extent of the Zenobia debris fan. The youngest channel, indicated by the stippled pattern, is not evident on the 1954 aerial photograph.
The historical oblique photographs taken in Lodore Canyon cannot be used to either substantiate or repudiate activity on any of the debris fans. None of the photos provide a comprehensive view of debris fans or rapids; therefore, it is not possible to determine definitively whether fans have experienced any activity since the first photographs were taken.

In addition to the characterization of fan activity, the degree of channelization of the debris fan surfaces was also observed. Channel morphology characteristics that were observed included size, shape, and depth of channel incision. The largest observed channels were located on the Mile 233, Rippling Brook, and Wild Mountain fans (Figure 6). These channels exceed 2 m in depth, as much as 5 m in width, have steep sides, and trapezoidal cross sections. Elsewhere in Lodore Canyon, the shape of channels is similar to the “swale-like” cross section identified by Wohl and Pearthree (1991) in the Huachuca Mountains. This latter channel type was principally observed on the intermediate or older sections of fans (see below). The majority of the channels on Lodore Canyon fans fall into this category.

Measurements from the 42 Lodore Canyon fans used in this study show a direct correlation between main canyon valley width and the size of debris fans in Lodore Canyon (Figure 13a). The three largest debris fans in Lodore Canyon—Trailer Draw, Buster Basin, and Zenobia—are located in the three widest sections of the canyon (Table 3). Three of the smaller fans—Mile 233, Rippling Brook, and Wild Mountain—are located in narrow sections of the canyon. No relationship, however, exists between drainage basin area and debris-fan area in Lodore Canyon (Figure 13b). While some of
<table>
<thead>
<tr>
<th>Drainage</th>
<th>Valley width (m)</th>
<th>Fan size*</th>
<th>Fan slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailer Draw</td>
<td>250</td>
<td>large</td>
<td>steep</td>
</tr>
<tr>
<td>Buster Basin</td>
<td>275</td>
<td>large</td>
<td>steep</td>
</tr>
<tr>
<td>Middle Disaster</td>
<td>245</td>
<td>large</td>
<td>steep</td>
</tr>
<tr>
<td>Zenobia</td>
<td>260</td>
<td>large</td>
<td>shallow</td>
</tr>
<tr>
<td>Pot Creek</td>
<td>200</td>
<td>large</td>
<td>shallow</td>
</tr>
<tr>
<td>Mile 233</td>
<td>90</td>
<td>small</td>
<td>steep</td>
</tr>
<tr>
<td>Rippling Brook</td>
<td>135</td>
<td>small</td>
<td>steep</td>
</tr>
<tr>
<td>Wild Mountain</td>
<td>135</td>
<td>small</td>
<td>steep</td>
</tr>
<tr>
<td>Limestone Draw</td>
<td>120</td>
<td>small</td>
<td>shallow</td>
</tr>
</tbody>
</table>

| canyon min        | 105              |           |           |
| canyon avg        | 150              |           |           |
| canyon max        | 275              |           |           |

*Large fans are >35,000 m², small fans are <13,000 m².
Figure 13. Relationships between tributary drainage basin area and debris-fan area (a) and between valley width and debris-fan area (b) in Canyon of Lodore.
the larger debris fans form at the mouth of large drainage basins (i.e., Buster Basin and Zenobia), in general, fan area cannot be directly correlated with drainage basin area.

Nearly all of the steep debris fans in Lodore Canyon are located in areas where the drainage basin debouches onto a thick, cliff-forming sequence forming a locally steep tributary drainage slope. Conversely, the low gradient fans typically form at the mouths of drainages that are relatively deeply incised and have low gradients both at the tributary canyon mouth and on average throughout the drainage basin. The low gradient tributaries, such as at Trailer Draw and Buster Basin, are often coincident with large faults (Hansen et al., 1983).

The possible combinations of large-scale fan characteristics can be grouped into four basic categories. Fans are either: 1) large and steep, 2) large and low angled, 3) small and steep, or 4) small and low angled (Table 3) depending primarily upon the combination of local valley width and drainage basin slope at the mouth of the tributary canyon. The principal controlling factor in debris-fan morphology appears to be the geologic characteristics of the particular section of the canyon where the tributary is located rather than the various debris-flow histories of the individual drainages.

**Distribution of Debris-Flow Deposits on Lodore Canyon Fans**

Detailed surficial geologic mapping of two fans in conjunction with field/aerial photographic observations of other fans in the canyon demonstrated that typical debris fans in Lodore Canyon result from a specific sequence of debris-flow deposits. The fans chosen for detailed study include one large, shallow-sloped fan (Zenobia) and one small
steep fan (Mile 233) (see Figure 6 for locations). Both of the fans have experienced recent
debris-flow activity. The most recent debris flow on the Zenobia fan occurred between
1954 and 1993. The Mile 233 fan was aggraded by debris flows in 1993 and 1997. The
Zenobia basin drains only the Uinta Mountain group while the Mile 233 drainage also
contains a portion of the Lodore Formation. Mapping of the surficial deposits on the
Zenobia and Mile 233 fans resulted in the division of debris-fan deposits into three
distinctive ages, although deposit ages were not correlated between the two fans (Figures
12 and 14).

The oldest deposits have low concentrations of boulders on the surface, extensive
vegetation cover (grasses, shrubs, small and large trees), and subdued topography. The
boulders found on these surfaces have extensive lichen cover, in places approaching 90%
(Figure 9). Channels were faint to nonexistent with swale-like cross sections.
Intermediate age deposits had higher boulder concentrations, extensive vegetation cover
(grasses, shrubs, small trees), and steeper topography. Lichen cover on boulders of
intermediate age deposits was less pervasive, but still well developed. Deposits mapped
as intermediate age have distinct, but somewhat subdued, vegetated channels and
bouldery lobes. Deposits classified as youngest have the highest concentration of fresh
boulders, infrequent young vegetation (grass and small shrubs), and steep topography.
The youngest boulders showed little to no evidence of lichen colonization. Distinct
channels and levees with steep sides remain on these deposits.
Figure 14. Surficial geologic map of the Mile 233 debris fan. Striped area depicts extent of 1997 deposits. See Figure 27 for detailed map. X indicates location of view in Figure 53.
At both sites, the oldest deposits occur at the highest elevation. The intermediate deposits apparently filled and overtopped an older channel in places resulting in the diversion of its course toward a lower elevation. Although Zenobia is a much larger fan, the basic pattern of deposition at the two sites was similar. The observed differences in average slope and fan size could not be attributed to differences in depositional patterns between the two sites.

The interface between the debris fan and the Green River is covered by a band of reworked debris-fan deposits and mainstem alluvium at both sites. Although small rapids exist at the constriction caused by the fans, those rapids were formed by the intermediate-aged or older deposits because the youngest deposits did not reach the river in either location.

Although three distinct ages of deposits were observed on a number of Lodore Canyon fans, they are not found on every fan. The youngest deposits were most frequently missing from the fans, but in several cases the entire fan surface exhibited characteristics of older deposits. While the overall fan morphology appears to be controlled by the slope of the tributary canyon, the characteristics of the deposits on each fan appears to be dependent upon the age and frequency of debris-flow deposition from the tributary.

**Timing of the 1997-98 Debris Flows**

During fall 1997 and spring 1998, four debris flows occurred in canyons tributary to the Green River in Lodore Canyon. Depositional evidence and an interview with a river runner indicated that three of the debris flows were initiated during a single storm event
between September 18 and 22; however, documentation of the events was not immediate and the precise date when they occurred cannot be determined. On October 1, 1997, a group of National Park Service employees, rafting on the Green River through Lodore Canyon, encountered the largest of the flows, a new fan-shaped deposit significantly constricting the river at the mouth of Wild Mountain canyon (Tamara Naumann, pers. commun.). William Rice (Colorado State University), a member of a group that was working in the monument, reported that a debris flow had not occurred at the site as of September 21 when he passed the site. He did observe that Zenobia Creek was flooding on September 21 and he provided descriptive evidence of rainfall intensities that suggested that the Wild Mountain debris flow probably occurred on September 22.

The Mile 233 flow was discovered on October 19, 1997. This flow probably also resulted from the September 1997 storm because surficial characteristics of the deposit are similar to those at Wild Mountain. On July 21, 1998, the third 1997 flow was found during an exploratory hike across the Middle Disaster debris fan. This deposit was correlated to the other September 1997 events by its similar deposit characteristics and similar plant species that had colonized the recent deposits (Figure 15).

The Rippling Brook debris flow deposit was observed on September 22, 1998. Although the date of this debris flow is not known, the lack of physical evidence of reworking by the Green River indicates that the fan was deposited after the Spring 1998 peak discharge of 131 m$^3$/s that extended from May 27 through June 16.
Figure 15. Colonization of the coyote tobacco plant (Nicotiana attenuata) on both the Middle Disaster (a) and Wild Mountain (b) debris fans as the basis for correlating the two debris flows.
Regional Climatology

The attempt to correlate recorded precipitation and debris-flow initiation began with the Wild Mountain debris flow because the eyewitness accounts pinpointed the date of the flow. The precipitation data from the DNMQ, DNM, and BPR climate stations showed that a 5-day rainfall event occurred in the region between September 18 and 22, 1997 (Figure 16). Peak daily rainfall exceeded 3 cm on September 19, 1997 at both the DNMQ and DNM stations. The total storm precipitation at the three stations averaged 6 ± 1 cm.

Data from the regional climate stations do not provide conclusive evidence of the timing of the debris flow. However, William Rice recalled that rainfall was continuous on September 20, that there was a break in the weather on September 21, and that there was a resumption of intense rainfall during the night of September 21 through the early morning of September 22. Webb et al. (1998) maintained that storms that cause debris flows in Grand Canyon are distinctive because they characteristically end with a burst of rainfall that triggers each flow. Although the exact timing of the Wild Mountain debris flow has not been documented, the eyewitness accounts of the storm pattern mimics the pattern noted in Grand Canyon.

In order to explore further the precipitation patterns in the Lodore Canyon region, climate data were also examined for the second week of June 1965. On June 10, 1965, a well-documented debris flow occurred in the nearby Warm Springs drainage of the Yampa River Canyon (see Figure 2) (Ellen Wohl, per. commun.). Precipitation data from DNMQ, DNM, and the Maybell, Colorado station were analyzed to determine the
Figure 16. Daily precipitation totals for September 1997 at the DNMQ, BPR, and DNM climate stations.
meterological conditions at the time of the Warm Springs' debris flow. The peak total daily rainfall for this storm of 3.61 cm was measured at the DNMQ gage on June 11, 1965 (Figure 17). Since rainfall data are collected only once per day, this total probably reflects precipitation that fell during the night of June 10 when the debris flow occurred. The much smaller amount of rainfall at the other two climate stations, 0.5 cm at Maybell and 0.8 cm at DNM, indicates that the storm cell was smaller than the one that initiated the September 1997 flows.

Although no general pattern of precipitation could be determined from the limited number of documented debris flows in the region, the magnitude of precipitation that initiated debris flows in Lodore Canyon and the surrounding region is approximately 2-3 cm. Historical data were analyzed to characterize the frequency of these types of storms.

On average, daily rainfall exceeding 2 cm occurs only 0.2% of the time. And daily rainfall of more than 3 cm fell on only 0.06% of the days of record. These frequency calculations indicate that the amount of rainfall that occurred on June 10-11, 1965 and September 19, 1997—in excess of 3 cm—was an extremely rare magnitude in Lodore Canyon and the surrounding region.

Since the frequency of precipitation events totaling between 2 and 3 cm is low in the Lodore Canyon region, precipitation data from the summer of 1998 were examined in an attempt to infer the timing of the 1998 debris flow at Rippling Brook. Both the climatologic data and accounts from a Park Service employee (Tamara Nauman, pers. commun.) who was in Lodore Canyon on June 15-18 indicated intense rainfall during these days. Precipitation equivalent to the rainfall that initiated the 1965 Warm Springs
Figure 17. Daily precipitation totals for June 1965 at the DNMQ, Maybell, and DNM climate stations.
debris flow and the 1997 debris flows occurred in the region during that three-day period, probably initiating the debris flow in the Rippling Brook drainage basin (Figure 18). Rainfall in excess of 2 cm was also recorded during early August 1998 at the DNMQ station, yet neither of the other two stations recorded significant precipitation during those days. Therefore, that storm was unlikely to have triggered the Rippling Brook debris flow.

Fires in Lodore Canyon

During late fall 1997, Marcus Schmidt, a National Park Service employee stated that fires had occurred in the Wild Mountain/Rippling Brook drainages and the Middle Disaster/Zenobia drainages during the summer of 1996. The examination of historical fire records for Lodore Canyon was initiated based upon the discovery of charred wood and/or charcoal on the surface and mixed in the matrix samples from three of the four 1997-98 debris flow deposits. A record of fires in Dinosaur National Monument has been kept by the Park Service since the 1940s. During that time, nine fires larger than 0.8 km² have burned in the drainages of Lodore Canyon. The largest recorded fire burned 26 km² of the Zenobia Basin (Figure 19) during late summer 1988 (Table 4). This fire was initiated by the Park Service as a controlled burn, but was not contained and became a wildfire. Most of the other fires in Lodore Canyon originated from lightning strikes, primarily during the months of July and August.

There have been 6 years of significant wildfires between 1940 and 1998. In 1951, a single fire totaling 17 km² burned a small portion of the Trailer Draw drainage (Figure
Figure 18. Daily precipitation totals for June 1998 at the DNMQ, BPR, and DNM climate stations.
Figure 19. Distribution of fires mapped by the National Park Service in Lodore Canyon from 1940 to the present. No fires occurred from 1940-1949.
TABLE 4. DRAINAGE BASINS BURNED BY LODORE CANYON FIRES FROM 1940 TO THE PRESENT

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</thead>
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<td>1951</td>
<td>--</td>
<td>--</td>
<td>1988</td>
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</tr>
<tr>
<td>Middle Disaster</td>
<td>--</td>
<td>--</td>
<td>1963</td>
<td>--</td>
<td>--</td>
<td>1996</td>
</tr>
<tr>
<td>Zenobia</td>
<td>--</td>
<td>--</td>
<td>1963</td>
<td>--</td>
<td>1988</td>
<td>1996</td>
</tr>
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<td>Pot Creek</td>
<td>--</td>
<td>--</td>
<td>1963</td>
<td>1972</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Hell’s Half Mile (R)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1981</td>
<td>--</td>
</tr>
<tr>
<td>Rippling Brook</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1996</td>
</tr>
<tr>
<td>Wild Mountain</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1996</td>
</tr>
</tbody>
</table>

-- indicates that no fires were documented during the specified years
19). During the 1960s and 1970s, three fires occurred, burning the Pot Creek drainage twice and the Zenobia drainage basin once. In addition to the 1988 prescribed burn, a 5-km² fire burned a limited section of the Trailer Draw drainage in 1981.

Two wildfires burned Lodore Canyon drainages in mid-to-late July 1996. One of the fires burned a portion of the Zenobia drainage basin again, less than ten years after the catastrophic 1988 fire. This fire also affected other nearby drainages (Figure 20). The second 1996 fire originated in the Wild Mountain drainage basin and spread upstream to engulf the Rippling Brook drainage. The Wild Mountain/Rippling Brook fire was actively suppressed by the National Park Service. Helicopters were used to transport an amount of water equivalent to several times the annual rainfall to the site (Marcus Schmidt, 1998 pers. commun.).

When the dates of historical fires were compared to the annual precipitation totals for the three regional climate stations, the correlation between dry years and dry summers in particular was evident (Figure 20). Fire years were always coincident with years that had been calculated as having summer season droughts at one or more of the three climate stations (DNMQ, DNM, or BPR).

**Characteristics of the 1997-98 Debris Flows**

**Middle Disaster debris flow**

The Middle Disaster tributary drains 0.95 km² of quartzitic sandstone with thin interbeds of shale of the Precambrian Uinta Mountain Group. Quaternary colluvium
Figure 20. Total yearly precipitation (triangles) and total summer precipitation (circles) for the DNMQ, DNM, and BPR climate stations. Horizontal line is the average of the values. Dashed lines indicate years when fires occurred in Lodore Canyon. Drought years are indicated by a “D.”
<table>
<thead>
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<th>Location</th>
<th>Valley width (m)</th>
<th>Constriction ratio (methods of Kieffer, 1985)</th>
<th>Constriction ratio (methods of Webb et al., 1996)</th>
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<td>245</td>
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<td>Zenobia</td>
<td>260</td>
<td>0.33</td>
<td>0.50</td>
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<tr>
<td>Ripping Brook</td>
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<tr>
<td>Wild Mountain</td>
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<tr>
<td></td>
<td>canyon avg</td>
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<tr>
<td></td>
<td>canyon min</td>
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</tr>
<tr>
<td></td>
<td>canyon max</td>
<td>275</td>
<td>0.70</td>
</tr>
</tbody>
</table>
overlies the bedrock in approximately 25% of the basin (see Figure 4). Lodore Canyon is approximately 245 m wide at Middle Disaster, 65% wider than the average valley width elsewhere in Lodore Canyon (Table 5). The 44,450-m$^2$ Middle Disaster debris fan constricts the Green River by 60% (Figure 21). The combination of this constriction and a number of large boulders deposited in the river by tributary debris flows produces a rapid located between the well-known Upper and Lower Disaster Falls rapids.

On or around September 22, 1997, periods of intense rainfall probably occurred in the Middle Disaster drainage (see Figure 16). A reconnaissance examination of the upper drainage basin showed no evidence of a failure surface at the head of the debris-flow channel; however, the flow appeared to have been initiated by rilling in the colluvium of the steep upper burned slopes approximately 380 m above the river (Figure 22). Several deep gullies (approximately 0.5 m) headed just below the base of the quartzite cliffs (see Figure 6) coalesced to form a single continuous channel that extends from the upper drainage to the apex of the depositional fan. Erosional evidence indicated that the flow probably gained fine sediment as it scoured a channel and mobilized the toes of colluvial wedges in its path (Figure 23). Depositional levees and lobes composed of particles ranging in size from large boulders (up to 1.8 m) to clay were deposited, perhaps due to the abrupt decrease in slope (from 21° to 9°) at the apex of the fan. The rest of the flow or a subphase appeared to have turned toward the upstream side of the fan by the depositional levees. The debris flow continued downstream from the fan apex where a channel that was carved into the steep fan face diverged into two separate channels and
Figure 21. Large-scale fan morphology of the Middle Disaster debris fan at 38 m³/s (1,420 ft³/s). X indicates locations of velocity/discharge calculations.
Figure 22. Slopes in the upper drainage basin at Middle Disaster burned by one of the 1996 fires.

Figure 23. Scarp behind a colluvial wedge located in the upper channel that was probably eroded during the 1997 Middle Disaster debris flow. Person in center for scale.
then converged again. Below the convergence point, where the slope begins to decrease, overflow lobes were deposited.

Deposition also occurred at the distal margin of the debris fan where it converged with the Green River. At this location, the debris flow appeared to have fanned out to deposit a thick, muddy mixture principally composed of fine particles with few particles larger than cobbles. A deposit containing 40% particles finer than 4 mm and nearly 60% particles in the pebble to cobble range (Figure 24) was also found both in the lower portion of the debris-flow channel and in a lobe at the distal fan margin, where the deposit was more than 67 cm thick (Figure 25). A gravelly deposit was incised into the cobbly lobe. Channels containing this deposit cross the fan on the downstream part of the cobbly lobe as well as upstream from it, and transported gravelly deposits adjacent to the edge of the river.

Field evidence was used to calculate the peak discharge of the flow at two locations (Figure 21) where bends in the debris-flow channel caused the flow to be superelevated, leaving high water marks in the form of levees and mud coatings on trees (Figure 26). Peak discharges ranging from 9-14 m³/s were calculated from the two sites (see Appendix for discharge calculations). Laboratory reconstitution of debris-flow matrix collected from deposits located on the distal edge of the fan exhibited debris-flow properties at water contents of 18-20% by weight.

The following sequence of events for the debris flow was reconstructed using the combined physical evidence. The debris flow was initiated in the upper drainage, where it scoured a channel through the talus and mobilized colluvium. The flow probably
Figure 24. Particle size distribution of the second phase of the 1997 Middle Disaster debris flow. D_{50} is 9 mm.
Figure 25. Surficial geologic map of the distal depositional fan resulting from the 1997 Middle Disaster debris flow.
Figure 26. High-water mudlines (dashed horizontal line) in the lower section of the Middle Disaster debris-flow channel. One of two locations where velocity and discharge were calculated.
continued to gain mass until it reached the apex of the fan, where deposition of the first phases of lobes and levees on the left side of the channel guided the remaining flow toward the steep face of the preexisting fan. Here, the flow began to scour once again, incising a channel across the preexisting debris fan. As the flow neared the river, the regime shifted from erosional to depositional, perhaps due to a local decrease in slope, and fanned out to form a widespread, muddy deposit. A second pulse or flow phase characterized by cobble-sized particles with a sandy matrix probably occurred next, leaving a thick lobe at the distal fan margin. This phase was probably followed by a gravelly pulse of debris flow or a mixture containing a higher concentration of water (i.e. hyperconcentrated flow as defined by Pierson and Costa, 1987, p. 6) that transported material eroded from previous flow phases across the previous deposit. Recessional stream flow was subsequently confined to the incised upstream channel.

*Mile 233 debris flow*

The tributary located at River Mile 233 drains 0.6 km² of Uinta Mountain Group quartzite, shale, and interbedded sandstones and shales of the Lodore Formation (Figure 4). The Mile 233 drainage is located at one of the narrowest points in Lodore Canyon where the valley width is only 90 m (Table 5). The 6,170-m² debris fan constricts the Green River by 45% and forms an unnamed rapid.

Evidence of the sequence of events of the 1997 Mile 233 debris flow was limited to deposits located on the fan surface and a 1954 aerial photograph of the drainage. The 1997 deposits are located at the mouth of a deeply incised channel that existed prior to the debris flow. The location of a fresh lobe overlying the 1993 channel indicated that the
1997 debris flow probably initially followed the course of the 1993 flow. This deposit is mapped as the youngest phase on Figure 14. Subsequent deposition must have been forced to the downstream portion of the fan when the flow filled and overtopped the older channel. A second phase of the flow, characterized by angular, unsorted, matrix-supported particles with abundant fragments of pink, purple, green, and gray micaceous shale, deposited lobes and levees inset into the phase 1 deposits (Figure 27). The third distinctive phase consisting of sand to pebble sized particles appeared to contain material reworked from phase 2 deposits. This third phase formed a fan-shaped feature at the mouth of a channel incised into the phase 2 deposits. The distal fan-shaped deposit of red mud on the sandbar adjacent to the river appeared to be a depositionally continuous sub-phase of the third phase consisting of a much larger proportion of clay to sand-sized particles.

Three trenches dug into the distal deposits (see Figure 27 for location) revealed a 30-65 cm thick sequence of debris-flow and tributary stream-flow deposits, probably deposited by the 1997 debris flow, overlying alluvial sand (Figure 28). The uppermost unit in all three trenches consisted of imbricated gravel in a sandy/clayey matrix. Unsorted, inversely graded matrix-supported deposits containing a higher percentage of clayey matrix (i.e. older debris-flow deposits) underlie the alluvium in two of the three trenches.

The initiation of the September 1997 debris flow at Mile 233 did not occur on bare, burned slopes high in the drainage. Although the July 1996 fire scorched adjacent
Figure 27. Surficial geologic map of the 1997 debris flow at Mile 233. T1, T2, and T3 indicate trench locations. See Figure 12 for larger scale map of the Mile 233 debris fan. X indicates the location of Figure 51.
Figure 28. Detailed stratigraphy of the three trenches located on the distal fan resulting from the 1997 debris flow at Mile 233. See Figure 27 for trench locations.
drainages, none of the Mile 233 basin was affected. A probable path of the flow was determined by following the channel visible on the 1954 aerial photograph. This path headed in a slope forming unit of the Uinta Mountain shale (a subunit of the Uinta Mountain Group) located just below a cliff formed by the overlying Lodore Formation. The flow initiation was probably the results of a failure in this upper portion of the 150-m thick Uinta Mountain Shale that outcrops more than 270 m above the river. Fragments of pink, purple, green and gray micaceous shale characteristic of this unit (Hansen et al., 1983) were abundant in the debris-flow deposits. Intense rainfall, perhaps leading to overland flow pouring from the cliffs, might have entrained material from the shaley unit. Once enough sediment was mobilized, the water flow probably transformed to a debris flow. The water content of the flow was determined by reconstitution of a matrix sample to have been 14-15% by weight. If the debris-flow initiation occurred in the upper portion of the Uinta Mountain Shale, it probably traveled approximately 225 m before it poured over the waterfall at the mouth of the tributary canyon to form the deposits on the surface of the pre-existing fan (Figure 29).

**Rippling Brook debris flow**

Perennial stream flow from the 3-km² Rippling Brook tributary basin drains the Uinta Mountain Group as well as the entire Paleozoic sequence exposed in the downstream part of Lodore Canyon (Figure 4). The 135-m local valley width at Rippling Brook is slightly less than the average of 150 m elsewhere in Lodore Canyon (Table 5). The 13,880-m² debris fan constricts the Green River by 35% and forms a minor rapid (Figure 30). An
Figure 29. Ephemeral waterfall located at the mouth of the Mile 233 tributary drainage. Box elder located in the center of the photograph is approximately 2 m tall.
Figure 30. Large-scale fan morphology of the Rippling Brook debris fan.
approximately 1.5-m deep channel is located the surface of the debris fan from the mouth of the tributary to the Green River.

Although the Rippling Brook drainage burned during the 1996 forest fires and presumably experienced precipitation extremes similar to the other tributaries during late-September 1997, the debris flow from this drainage did not occur until the following spring. The storm that was recorded in the region on June 15-18 was the probable trigger of the debris flow as described previously. Peak total daily rainfall exceeded 2.7 cm at the BPR station and 3.7 cm at both the DNMQ and DNM stations on June 17, 1998 (see Figure 18).

Deposits in the debris-flow channel and on the distal fan at Rippling Brook are a cobbly to bouldery, matrix-supported phase with a low percentage of sandy matrix (similar to the phase 2 deposit at Middle Disaster) (Figure 31). A second phase characterized by pebble- to cobble-size particles with little or no matrix was observed inset into the first deposit on both the upstream and downstream sides. A faint stream-flow channel also existed at the downstream contact of the phase 1 and phase 2 deposits.

The absence of a bouldery, matrix-rich debris-flow phase similar to those found at the mouth of the drainages at Middle Disaster and Mile 233 might be attributed to the location of waterfall-type steps with deep treads at the mouth of the tributary. These steps might have captured any matrix-rich phase that preceded the first phase evidenced on the distal fan. The low matrix content in the two clast-supported deposits on the fan surface indicated that these phases probably contained a higher proportion of water than the debris-flow deposits mapped from the 1997 debris flows and might represent a
Figure 3.1. Surficial geologic map of the distal depositional fan that resulted from the 1998 Rippling Brook debris flow.
hyperconcentrated flow deposit rather than debris-flow deposits. The channel incised the floor of the debris-flow channel between the tributary canyon mouth and the distal fan might have formed during recessional stream flow following the June event, or it could simply be the result of perennial stream flow from the drainage.

**Wild Mountain debris flow**

The 1.82-km² Wild Mountain tributary basin also drains the Uinta Mountain Group and the cliff-forming limestones and intervening sandstones and shales of the Paleozoic section exposed in Lodore Canyon (Figure 4). The valley width at Wild Mountain is 135 m. Almost the entire portion of the 7,489-m² Wild Mountain debris fan downstream from the incised tributary channel is overlain by a large deposit of eolian sand (Figure 32). A deeply incised channel (greater than 1 m deep) crosses the Wild Mountain debris fan, connecting the tributary canyon to the Green River. The Wild Mountain rapid is formed by the 65% constriction at the debris fan.

The debris flow that occurred at Wild Mountain on or around September 22, 1997 deposited a 3,800-m² debris fan at the mouth of the incised channel. The first debris-flow phase deposited large bouldery levees and lobes beginning at the lower end of the incised channel and continuing for several meters downfan of the mouth of the channel (Figure 33). They were the highest elevation deposits and were composed of the coarsest particles, similar to the first phases deposited at Middle Disaster and Mile 233. A large, matrix-rich, fan-shaped feature, spanning approximately one-third of the width of the Green River channel probably resulted from the second flow phase. An inset deposit of a
Figure 32. Large-scale fan morphology of the Wild Mountain debris fan. X indicates location of view in Figure 54.
Figure 33. Surficial geologic map of the distal fan deposit that resulted from the 1997 Wild Mountain debris flow.
third debris-flow phase found on the fan surface consisted of smaller particles—cobble to clay size—and a lower percentage of the clayey matrix. The fourth inset phase contained a much higher percentage of somewhat sorted, imbricated cobbles and clayey matrix and represented stream-flow or hyperconcentrated flow deposits derived from the reworking of earlier phases (Figure 34). The channel carved through the phase 4 deposits was probably the result of recessional stream flow following the debris-flow phases (see Chapter 5 for discussion of stream channel establishment).

On or around September 22, 1997, intense rain falling on steep burned slopes, perhaps leading to overland flow poured off the cliffs of the Round Valley Limestone, probably initiated rilling and slope wash high in the Wild Mountain drainage similar to Middle Disaster. No landslide scarp or other evidence of slope failure was observed during a helicopter reconnaissance survey of the drainage in March 1998, although evidence might have been hidden under moderate snow cover. The debris flow probably reached a water content of 20-22% by weight, determined from flow reconstitution using matrix collected from the site, before it mobilized and suspended boulder-sized particles. The debris flow then continued to entrain sediment as it proceeded toward the river. When the debris flow arrived at the mouth of the tributary canyon, the preexisting channel, more than 1 m deep, incised by stream flow subsequent to earlier debris flows, channeled the peak calculated discharge of 29 m³/s (see Appendix for discharge calculations) toward the river, resulting in the deposition of a large (3,800-m²) fan-shaped feature.
Figure 34. Particle size distribution of the second and fourth phases of the Wild Mountain debris flow. $D_{30}$ of the deposits are <4 mm and 22.9 mm.
CHAPTER 4

REWORKING OF THE WILD MOUNTAIN DEBRIS FLOW

Background

The 1997 Wild Mountain debris flow provided an opportunity to study the potential of the Green River to rework debris fans. The 1997 flow significantly aggraded the fan and narrowed the river channel. The fan was measured in detail prior to the spring 1998 peak discharges of the Green River and following these peak flows. The 1998 peak discharge of the Green River was 131 m$^3$/s, which is the maximum discharge able to pass through the power plant at Flaming Gorge Dam. Thus, it was possible to determine whether this common high discharge was sufficient to rework new debris fans. Prior to the construction of Flaming Gorge Dam, the hydrology of the Green River in Lodore Canyon was dominated by a snowmelt-driven spring peak flow followed by low summer and winter flows (Figure 35). The mean annual pre-dam peak flow on the Green River in Lodore Canyon was 360 m$^3$/s. Since the construction of Flaming Gorge Dam, the average spring peak flood has been reduced in magnitude by 61% to 144 m$^3$/s. The object of this portion of the study was to determine the reworking potential of the Green River at or below the imposed power plant capacity discharges.

Green River Hydrology

The Wild Mountain debris fan was deposited in early fall when releases from Flaming
Figure 35. Peak yearly discharge of the Green River at Greendale, UT. Dashed lines indicate the average peak yearly discharge during the pre- and post-dam eras. Discharges from 1920-1950 were reconstructed using gage station correlation by Schmidt (1994).
Gorge Dam were approximately 50 m$^3$/s (Figure 36). Discharge was increased in October to approximately 83 m$^3$/s and then increased to 97 m$^3$/s during November and December. During January and February, the releases were gradually decreased to a late-winter low of 62 m$^3$/s. In early March, releases were gradually increased again. Discharge reached the power plant capacity release of 131 m$^3$/s in late May. The discharge was reduced from power plant capacity to 50 m$^3$/s in late June 1998, fluctuated between 50 and 73 m$^3$/s for the next 2 weeks, and then was increased to a steady rate of 83 m$^3$/s. In mid-August, the releases were ramped down to 67 m$^3$/s for the remainder of the summer and early fall. On September 21, 1998, the discharge was reduced to 46 m$^3$/s for 2 days to facilitate both the repair of the boat ramp below Flaming Gorge Dam and this survey. Releases were subsequently returned to 67 m$^3$/s.

**October 1997 to March 1998**

The March 1998 topographic survey showed that the winter peak discharge of 97 m$^3$/s did not significantly rework the debris fan (Figure 37). Two cubic meters of net change, a 0.2% reduction in the size of the fan, resulted from erosion of a small, 6-m$^2$ portion of the face of the fan during the period between October 20, 1997 and March 5, 1998. This volume was probably the size of one or two boulders. Comparison of pebble-count data taken along the face of the upstream portion of the fan in October and one from March showed little change in the texture of the surface of the debris-fan deposit in this area (Figure 38).
Figure 36. Average daily discharge released from Flaming Gorge Dam between August 1, 1997 and October 31, 1998.
Figure 37. Map illustrating the amount of erosion (red) and deposition (green) on the Wild Mountain debris fan that occurred between October 20, 1997 and March 5, 1998 when the peak discharge was 97 cubic meters per second.
Figure 38. Comparison particle size distribution measured in approximately the same location along the upstream face of the Wild Mountain fan in October 1997 and March 1998.
October 1997 to September 1998

The results of the September 1998 survey were compared to the October 1997 survey to determine the net change during the entire 11-month study period (Figure 39). The peak flows of 131 m$^3$/s submerged about one third of the surface of the debris fan; therefore, the maximum possible area of erosion was 390 m$^2$ if this part of the fan had been entirely removed. Thirty cubic meters of erosion were measured over an area of 72 m$^2$, a 6% reduction in the area of the debris fan. A 0.23-m high cutbank (Figure 40) was created along the face of the fan. Deposition of 1.3 m$^3$ of sediment occurred on the downstream side of the debris fan where gravel was deposited as a well-sorted, arcuate bar. Material was eroded from the face of the fan, sorted, and in the case of some gravel, deposited approximately 20 m downstream (Figure 41). The gravel bar caused flow separation to occur forming a recirculating eddy where sand was deposited further downstream.

During the March 1998 surveys, three new pebble count transects were established and surveyed adjacent to the edge of the water. In September 1998, these three lines were recounted and compared with the distributions measured in March (Figure 42). The particle size distribution comparisons showed that in two locations along the face of the fan, the median particle size coarsened and in the third location, the percentage of fines decreased.
Figure 39. Map illustrating the amount of erosion (red) and deposition (green) that occurred on the Wild Mountain debris fan between October 20, 1997 and September 21, 1998. The highest intervening discharge was the spring peak power plant capacity flow of 131 cubic meters per second.
Figure 40. A cutbank located along the face of the Wild Mountain fan indicating that approximately 20 cm of erosion had occurred between October 1997 and September 1998.

Figure 41. Arcuate gravel bar located on the downstream side of the newly deposited Wild Mountain debris fan. Person for scale.
Figure 42. Comparison particle size distributions from March 1998 and September 1998 for three pebble count transects. The D50 increased at both of the upstream transects (a and c; bold lines on plan view map of debris fan) and the percentage of fines increased at the downstream transect (b).
Stage Predictions

In addition to direct measurements of change, nearby stage-discharge relations were extrapolated to estimate the area of the fan that would be inundated by high discharges. Therefore, an estimate of the fan area susceptible to reworking at higher discharges was made. Stage discharge relationships determined using cross sections surveyed by Grams (1997) and Martin et al. (1998) for the nearest upstream and downstream cross sections from the Wild Mountain fan were extrapolated to estimate the approximate water surface elevation during a 241 m$^3$/s flow and a 360 m$^3$/s flow (Figure 43).

These estimations suggest that approximately 58% of the newly deposited debris fan would be submerged at a discharge of 241 m$^3$/s, which was the peak release during spring 1997 when the capacity of the by-pass tubes was added to peak power plant operations (Figure 44). The pre-dam average annual peak discharge of 360 m$^3$/s would have submerged nearly 85% of the newly deposited debris fan.
Figure 43. Stage-discharge relationship for the closest established cross sections located upstream and downstream from the Wild Mountain debris fan. These relations were used to estimate the local stage-discharge relationship at Wild Mountain. Cross-sections 25 and 27 are located at RM 230.6 and RM 229.2, respectively. The Wild Mountain debris fan is located at RM 229.5.
Figure 44. Measured and estimated water surface elevations on the newly deposited Wild Mountain debris fan used to estimate the area inundated during discharges equivalent to the 1997 high release and the pre-dam average flood.
CHAPTER 5
STREAM CHANNEL ESTABLISHMENT

Background

The 1997 Wild Mountain debris flow also provided the opportunity to document the reestablishment of the tributary stream channel into the new fan surface. Hooke (1967) documented the role of stream flow in the evolutionary process of depositional fans in his physical model of debris flows, yet the process of stream channel establishment on a natural fan has not been studied in detail.

Recessional stream flow following the 1997 debris flow in combination with subsequent perennial stream flow reworked the existing deeply incised Wild Mountain tributary stream channel located just upstream from the new deposit and cut a path across the newly deposited debris fan. The composition and pattern of debris-flow deposition dictated the location where the stream channel crossed the fan surface. As the debris flow evolved, both the percentage of fines and the average size of the largest particles decreased (see Figure 33) and each subsequent phase formed a surface inset into the previous deposit (see Figure 10). The final phase of recessional stream flow established a braided stream pattern in the lowest elevation, gravelly, hyperconcentrated flow deposit.

Changes in Channel Pattern

Perennial stream flow maintained the braided channel across the fan during the 5-month period between October 1997 and March 1998. During the March 1998 survey, the portion of the pre-debris flow stream channel incised into the older debris fan deposits
was covered with approximately 0.5 m of ice, yet water was still flowing beneath the ice and continuing onto the braided reach on the surface of the new fan. By the third week of July, however, the braided reach had become an incised, actively evolving, meandering channel (Figure 45).

Channel scars adjacent to the July 1998 channel cutting across the fan surface are the result of migration of the meandering channel. These scars provided evidence of the speed at which the channel evolved. Steps had also formed in the longitudinal profile of this reach in places where the stream downcut into coarser particles in the unsorted debris-flow deposit (Figure 46). Similar step-pool sequences are also present in the upstream, pre-debris flow channel. They occur in places where the incising streambed has encountered large particles.

The longitudinal profile of the thalweg of the tributary channel from the edge of water upstream to the second bend in the channel was surveyed in October 1997 and in September 1998 to determine the rate of channel incision. The degree of downcutting was greater in the existing stream channel than in the newly developed channel on the fan surface (Figure 47). The greatest incision was measured in the area of the farthest downstream bend in the channel that predated the 1997 debris flow. The channel incised nearly 1 m in this area as the step-pool sequences became more pronounced. Incision of about 0.5 m was measured in the reach crossing the new fan surface that had transformed from a braided to a meandering channel pattern (Figure 48).
Figure 45. Detailed map of the meandering stream channel that evolved from a previously braided channel on the newly deposited Wild Mountain debris fan.
Figure 46. Various scales of steps on the surface of the newly deposited debris fan (a) and in the channel incised into older debris-flow deposits (b). Lens cap for scale in both photographs.
Figure 47. Longitudinal profile of the thalweg of the tributary stream channel incised into the older debris-fan deposits (right) and continuing across the surface of the newly deposited fan (left) showing the amount of incision that occurred between October 1997 and September 1998.
Figure 48. Comparison longitudinal profiles in the thalwegs of the October 1997 braided channel and the September 1998 meandering channel located on the newly aggraded Wild Mountain debris fan. Arrows indicate locations of steps.
Reworking in the tributary channel was not limited to incision. Upstream from the second bend, the channel was narrower than in the area of the downstream bends. In this reach, steep banks collapsed, in one case bringing with it a mature box elder tree and exposing an older debris flow/sand dune contact.
CHAPTER 6
DISCUSSION AND CONCLUSIONS

Periods of Increased Debris-Flow Activity

The limited amount of data available concerning the dates of debris flows in Lodore Canyon makes it impossible to determine the causes of periods of increased debris-flow activity. However, observations of the 1997-98 debris-flow activity provide the basis for speculation. As in Yellowstone National Park, where a single episode of debris-flow activity alerted researchers to the link between fire and debris flows, the recent events in Lodore Canyon might suggest that a more detailed search for stratigraphic evidence of past fire-related sedimentation events should be initiated.

Reconnaissance surveys of nearly all of the debris fans in Lodore Canyon yielded few signs of recent activity (Table 2). When this inventory is compared to the distribution of fires (Figure 20), the places where recent deposits have been identified are nearly always coincident with the limited number of drainages that have burned in the last 50 years. The exceptions include: 1) the Mile 233 drainage, which contains a thick outcrop of the Uinta Mountain Group shale, and 2) Lodore Canyon drainages located downstream from Limestone Draw where the dominant lithology shifts from the resistant quartzite to alternating layers of sandstone, limestone, and shale.

The possible linkage between fire and debris-flow activity in Lodore Canyon permits speculation about the climatic implications of the observed inactivity of the majority of Lodore Canyon debris fans. In Grand Canyon, researchers have theorized that periods of
increased precipitation, perhaps during cooler periods, are the driving force for episodes of increased debris-flow activity (i.e., fan-forming flows) (Hereford et al., 1997). The occurrence of recent debris flows following forest fires and the correlation between the historical fire record and the timing of droughts in the Lodore Canyon region (see Figure 19) might indicate that drier conditions increase the probability of forest fires and thus could be an important factor influencing debris-flow activity in Lodore Canyon. This factor might suggest that regional climatic differences between the upper and lower Colorado River basins may result in different driving forces of debris-flow activity in the two regions.

Dates obtained from “fan-forming” deposits on the surface of the nearby Warm Springs fan on the Yampa River (Hammock and Wohl, 1996) (see Figure 2 for location) are the only available approximation for periods of increased debris-flow activity in the vicinity of Lodore Canyon. The timing of debris-flow events at Warm Springs does not coincide with Hereford and others (1997) data for Grand Canyon fans (see Figure 7). Only one of Hammock and Wohl’s (1996) five radiocarbon dates is similar to Hereford and others’ (1997) clusters of ages of fan-forming flows calculated from carbonate dissolution pits. However, when the Warm Springs’ data are compared to the dates of fire-related sedimentation at Yellowstone National Park (Meyer et al., 1995), two periods of debris-flow activity are correlative (Figure 49).

Thus, periods of increased debris-flow activity in Lodore Canyon might be explained by climatic fluctuations similar to those that have affected the Yellowstone region. Extensive dating of fire-related sedimentation and correlation of these periods of
Figure 49. Comparative timelines of dates of periods of increased debris-flow activity from the Yellowstone region (top) determined through 14C dating of organic material, from Grand Canyon fans using carbonate pitting relationships (middle), and from the Warm Springs fan on the Yampa River using 14C dating of organic material (bottom). Stippled shading indicates an overlapping time period.
increased activity with the Holocene climatic record suggests that warmer periods provide a greater intensity and inter-annual variability in summer precipitation, which increases the potential for drought, forest fires, and subsequent increased debris-flow activity (Meyer et al., 1995). Applied to the Lodore Canyon region, this would mean that the occurrence of infrequent, intense precipitation events, such as the 1965, 1997, and 1998 events, rather than overall increases in precipitation, favor debris-flow activity.

Initiating Conditions

Frequency and intensity of precipitation and lithology of the drainage basin (i.e., elevation of shale outcrops) have been identified as the most important factors in debris-flow initiation in the Grand Canyon region (Griffiths et al., 1996). Lodore Canyon differs from the southern Colorado Plateau principally because the steep slopes of the drainage basins support more extensive vegetation than in the Grand Canyon region. Therefore, forest fires that remove vegetation, thereby reducing infiltration capacity and cohesion of the soil and exposing steep slopes to intense rainfall, are probably one of the primary factors influencing debris-flow initiation. Yet, not every Lodore Canyon fire results in a debris flow. The comparison between the amount of precipitation that fell during September 1997 and June 1998 and the nearly 50-year record at three climate stations indicates that intense storms are necessary to initiate a debris flow, particularly following a forest fire.

The importance of an additional factor to debris flow initiation equation—sediment availability—cannot be ignored in Lodore Canyon. Wohl and Pearthree (1991) observed
that sediment availability limited debris flows in similar drainages that experienced forest fires in the same year. The occurrence of debris flows in three of the four drainages burned in 1996 suggests that sediment availability was not a limiting factor in those drainages. But a debris flow did not occur in the Zenobia basin even though there had been a fire there in 1996 and eyewitness accounts indicated that the drainage produced a stream flow flood during the September storm.

The absence of a 1997 debris flow might be explained by two factors: (1) some of the freshest looking debris-flow deposits observed during the reconnaissance survey prior to the 1997-98 debris flows were found on the Zenobia fan and (2) the fire record shows that a forest fire occurred in this drainage in 1988. The fresh deposits in the active channel on Figure 12 of the Zenobia fan were possibly the result of a debris flow related to the 1988 fire, and this event might have limited the amount of sediment available to be mobilized in 1997. Although many river users pass by this fan each season, the site is not often explored because it is not an authorized campsite and because it does not have a large, sandy beach downstream. Therefore, a debris flow that aggraded upslope parts of the fan may not have been noticed by river runners.

The occurrence of debris flows in 1997 and other recent debris-flow deposits at Mile 233 are inconsistent with the hypothesis that fires are necessary for debris-flow initiation in Lodore Canyon. No documented fires have burned the Mile 233 drainage during the period of record. The activity in this basin can perhaps be attributed to the 150-m thick outcrop of shale in the Uinta Mountain Group located more than 270 m above the river (see Figure 4). Griffiths et al. (1996) have shown that in Grand Canyon the probability of
debris-flow activity increases where the Hermit Shale occurs more than 100 m above the river. In contrast to Grand Canyon where the Hermit Shale is more extensive, the 150-m-thick shale outcrop in the Mile 233 drainage is an anomaly in Lodore Canyon where discontinuous shale outcrops, 50 m thick or less, are characteristic of the Uinta Mountain Group. Therefore, the increased probability of debris-flow activity caused by failures in the Uinta Mountain Group shale is unique to a small number of Lodore Canyon drainages.

The presence of active deposits on fans located downstream from Limestone Draw probably indicates a shift in debris-flow processes related to the change in predominant lithology in the downstream third of the canyon. Extensive outcrops of the Mississippian Donut Shale and Humbug Formation and the shale of the lower member of the Pennsylvanian Morgan Formation may be an increasingly important factor in debris-flow initiation in the drainages where they are pervasive.

The distribution of the 1997 and 1998 debris flows indicates that forest fires in the Lodore Canyon drainages are an important factor leading to debris-flow initiation. Yet, other factors, such as sediment availability and lithology, particularly the presence and elevation of shale units and the timing of intense precipitation events, probably also play fundamental roles in debris-flow initiation processes.
Fan Morphology

Large-scale

The correlation of large-scale debris fan morphology to variations in local structure and lithology has been examined in limited detail in canyon regions. While Grand Canyon researchers have determined that the aerial extent of debris fans is restricted by the local canyon width (Melis, 1997) (Figure 50), they have not attempted to associate other large-scale fan characteristics to local topography, structure, or lithology. Yet, both Blackwelder (1931) and Bull (1964) observed that fan area and gradient are directly related to the size, slope, and lithology of the drainage basin in semiarid mountain regions and in the San Joaquin Valley.

In Lodore Canyon, the large-scale fan morphology appears to directly correlate with valley width and drainage basin characteristics such as slope and lithology. The relationship between drainage basin size and fan size, however, is complicated by structural geology. While the largest fans do typically occur at the mouths of the larger drainage basins, two of the largest drainage basins in Lodore Canyon—Pot Creek and Limestone Draw—have relatively small fans at their mouths because these drainages enter the canyon in narrow sections. Throughout the entire canyon, there is no distinct correspondence between fan size and drainage basin area (Figure 13).

In the first third of the canyon, where large faults intersect the river at nearly right angles (Jack Springs Fault, Disaster Fault, Zenobia Fault, etc.), the local valley width is the widest and the axes of the tributary drainage basins often follow the faults. However,
Figure 50. Relationship between average channel width (proxy for valley width) and average fan area for debris fans in Grand Canyon. (Data from Meis, unpub.)
drainages such as Pot Creek are located along faults that do not cross the river. In these cases the drainage basins are often large, but the local canyon width is narrower so the fan size is limited by the canyon width (Figure 13). The debris fan-river interactions in canyon-river systems such as Lodore Canyon appear to neutralize the effects of large drainage basins where the canyon is narrow and the river is able to rework a significant portion of the fan material.

**Small-scale**

Each debris fan in Lodore Canyon has been built by more than one debris-flow event or cluster of events. Using a physical model, Hooke (1967) was able to reproduce the process of fan formation. In the short term, he found that debris-flow deposition was localized. Over a longer time period, however, the locus of deposition shifted, resulting in nearly uniform deposition across the fan surface. The detailed surficial geologic maps from Zenobia and Mile 233 illustrate this characteristic shift in depositional loci (Figures 12 and 14).

Observations made at Mile 233, Zenobia, and many other fans in Lodore Canyon also demonstrate that similarities in smaller-scale fan morphology, such as the segmentation of fans into surfaces of different ages, are insensitive to the large-scale morphologic attributes such as fan size and slope. The topography of individual fans appears to be dependent upon the magnitude and frequency of debris-flow deposition. The topography of fans that have not experienced recent debris-flow or stream-flow activity is gentler
than that of the more active fans. The channels or remnant channels are typically swales as opposed to the trapezoidal cross sections observed in the recent channel on active fans.

**Event-scale**

The 1997-98 debris flows offered the opportunity to characterize fresh deposition and enabled the extrapolation of short-term, small-scale deposition to the larger-scale fan morphologies. Researchers in Grand Canyon have developed a classification system of debris-flow hydrographs and resulting event-scale debris-fan morphologies after studying the deposits from over 40 recent debris flows (Melis et al., 1997). They divide debris flows into three categories—Type I, Type II, and Type III—according to the duration of debris-flow, hyperconcentrated flow, and stream-flow processes. Type I flows consist predominantly of debris-flow processes, with limited recessional stream flow. Type II flows are characterized by a complex sequence of debris-flow and hyperconcentrated-flow deposits, typically followed by recessional stream flow. Type III flows begin with a debris flow, but are subsequently overwhelmed by a higher magnitude stream-flow flood that covers and/or reworks the debris-flow deposits. Each fan is also classified as simple or complex depending upon the intricacy of cross-cutting deposition of different phases.

Three of the four 1997-98 debris flows in Lodore Canyon are complex debris fans whose deposits are consistent with Type II flow. Detailed surficial mapping of Middle Disaster, Mile 233, and Wild Mountain debris flows showed multiple debris-flow and/or hyperconcentrated-flow phases probably followed by recessional stream flow that resulted in a complex surficial morphology (see Figures 25, 27, and 33). The Rippling Brook debris flow is interpreted as a multi-phase flow, yet there was no clear evidence of
an initial matrix-rich phase similar to the first phases of the other three flows. Without a more detailed examination of the upper debris-flow channel and the excavation of a trench in the fan, it is impossible to conclusively establish that this debris flow was not a simple Type III flow.

The limited number of documented debris flows in Lodore Canyon makes it difficult to determine if all of the different types of debris flows that have been characterized in Grand Canyon also occur in Lodore Canyon. If the three flow types are dependent upon climatic controls (i.e., storm types) as suggested by Melis et al. (1997), and if the climatic controls are truly different between the upper and lower Colorado River basin, then the event-scale debris-fan morphology in Lodore Canyon might not exhibit the same variety identified on Grand Canyon debris fans.

Fan Evolution

*Theory of fan evolution*

Observations from both natural fans and physical models have established the importance of channel development in the evolution of fan surfaces. Some controversy has developed, however, over the role of regime or climate change in channel formation. Hooke (1967) attempted to refute Lustig’s (1965) assertion that channel incision in alluvial fans resulted from a fundamental change in regime. Hooke based his conclusions on observations from his physical model that showed that alternations between debris-flow and water-flow processes might naturally result in channelization. Hooke did not
agree with the regime-change theory because he considered only the mechanism of the channelization process instead of the driving forces controlling that mechanism.

Hereford and others’ (1996, 1997) work on fans in Grand Canyon, which differentiates between periods of “fan-forming” debris flows and periods of “channelized” debris flows, began to forge a link between Lustig’s proposed regime change theory and Hooke’s channelization mechanism. Hereford et al. attempted to explain the process of “channelized” versus “fan-forming” debris flows and to link the two types of activity to climate.

In order to avoid confusion, it is important to differentiate between the different time scales of channelization and the different processes working at the different time scales. Hooke’s (1967) physical model shows that, in the short term, the formation of channels is not a unique stage in fan evolution; rather it is probably a natural occurrence on all fans. Any fan that is built by debris flows and experiences recessional stream flow will consequently form channels because the water flow that follows the debris flow is able to transport sediment at a shallower slope than that of the debris flow (Hooke, 1967). Evidence of this process was found on all four of the new debris fans in Lodore Canyon.

Hooke’s (1967) explanation of the process of long-term channelization (the persistence of a channel for a geologically significant period of time) is based upon equalities in depositional rate at different locations on the fan. Aggradation at the fan head will drive incision (channel formation). Subsequent debris flows will be contained in the channel and transported to the distal margin of the fan until aggradation at the fan toe allows subsequent debris flows to overtop the channel (see Figure 8). What his theory
is missing is an explanation for the cause of the differences in depositional rate. Perhaps what he is missing is a driving force, such as climate.

Hereford and others' (1996) proposed explanation of the forces driving fan incision in a canyon river system builds upon Hooke's explanation of channelization. The characterization of “fan-forming” or “channelized” flows defined by Hereford et al. (1996) can be used concurrently with the ideas of Hooke (1967) if the terms “fan-forming” and “channelized” are considered to refer to the stage of evolution on a geologic scale. A debris fan would remain “channelized” if the rate of incision resulting from tributary stream flow exceeded the frequency of debris flows. In contrast, the debris fan would be characterized as “fan-forming” if the frequency and/or magnitude of debris flows was high and the locus of deposition was continually shifting so that deposition was also more evenly distributed across the fan surface. These variations probably occur because the forces driving debris-flow initiation (i.e., climate, sediment availability, frequency of fires, etc.) were such that debris-flow magnitudes and/or frequencies were either high or low.

Hereford et al. (1996) expanded the long-term channelization theory further to consider the effects of river reworking on the process of fan evolution. For example, if debris flows occurred at a faster rate than the fluvial incision of the channel on a fan that did not terminate at a river, the channel would eventually fill, and be overtopped by subsequent debris flows, changing the locus of deposition. The two youngest channels on the Zenobia fan in Lodore Canyon provide an example of this process (see Figure 12). The channel located just downstream from the center of the fan, mapped as containing the
youngest deposits, was filled and overtopped by a subsequent debris flow. The flow turned toward the lower elevation, downstream portion of the fan, creating a new locus of deposition. Erosion caused by subsequent recessional stream flow resulted in the formation of the current active channel.

Hereford et al. (1996) proposed that debris-flow deposition in the mainstem river channel would increase the base level of the tributary channel where the distal deposits reached the mainstem river. The act of reworking the deposit would decrease the base level of the tributary channel, thereby instigating further incision without the need for aggradation at the fan head as indicated in Hooke’s model (see Figure 8). Yet Hereford et al. have not shown how aggradation or erosion of debris-flow deposits could control the base level of the tributary stream. If their theory were correct, deposition of a debris fan would have to raise the water surface elevation in the mainstem river. Kieffer (1985) and Webb et al. (1998) showed that the principal effect of debris-fan deposition is the constriction of the mainstem river, and the principal mechanism of reworking is the widening of the constriction caused by the debris flow resulting in a decrease in velocity in the rapid, and not the lowering of bed elevation. Hereford and others’ (1996) general idea that reworking by the river has an effect upon the depositional equilibrium of the fan is probably correct, but it is unlikely that the most important factor is the base level of the tributary.

If debris flows on a canyon river are infrequent enough or small enough to allow the debris fan deposited at the mouth of an incised channel to be reworked by the mainstem river, then the debris-flow channel will not fill. If this process continues for a geologically
significant length of time, then debris flows that occurred on the fan would be considered "channelized." In order for this process to halt, a single large debris-flow event or an episode of debris flows that would aggrade and overtop the channel must occur. If debris-flow magnitudes and frequencies and/or discharges of the mainstem river are dependent upon climate, then it would be logical to conclude that Lustig (1965) was correct in proposing that a fundamental change in climate would be necessary to instigate a shift from "channelized" to "fan-forming" flows.

**Fan evolution in Lodore Canyon**

In Lodore Canyon, the surface morphology of each fan can be subdivided into three distinct categories: 1) fans that have incised channels that intersect the river, and 2) fans with faint channels that do not reach the river, and 3) fans that have no distinctive channel at all (Table 1). There are several possible explanations for these three categories of fan morphology. According to Hooke's (1967) physical model, as long as there are alternations between debris-flow and stream-flow processes, short-term channels can form on the fan surface. If we assume that the four recent debris flows in Lodore Canyon are typical of past debris flows, then the evidence of stream-flow processes following the four new debris flows indicates that Lodore Canyon flows have usually been followed by some degree of recessional stream flow. If this is the case, then why are distinct short-term channels not found on every fan?

The answer to this question most likely lies in the frequency of stream-flow and debris-flow events. The 1997 and 1998 events show that debris flows in Lodore Canyon are initiated by above-average or extreme rainfall events. The magnitude of post-debris
flow, recessional stream flow is probably also of a high magnitude and rare frequency. Yet incision on the lower portion of the Mile 233 fan (Figure 51) shows that a single recessional stream-flow event can cause significant change. However, compared to the existing incised channels in Lodore Canyon fans that are as much as 2 m deep, the incision at Mile 233 seems meager. If stream flow is too rare to continue the incision process, or if the channel is abandoned when a subsequent debris flow fills and overtops it, then the channel will probably stabilize. The oversteepened banks will slump and vegetation will begin to occupy the channel. The fan at Mile 233 shows this process in a “recently” abandoned channel (Figure 52). If the time interval between debris-flow and stream-flow events is great enough, then the channels might gradually disappear. Stable channels can be found on the older portions of nearly every Lodore Canyon fan.

If extreme precipitation in Lodore Canyon is infrequent, then why do any of the fans have deeply incised channels? Some of the incised fans occur at the mouths of streams that are frequently or perennially active. The deeply incised channel (> 1.5 m) at Rippling Brook is one of only two tributary streams denoted as perennial in Lodore Canyon (USGS 7.5-minute quadrangle). This fact alone would appear to be consistent with Hooke’s (1967) model if the long-term channelization was also the result of recessional stream flow alone. Although the channelization probably began as short-term channelization according to Hooke’s processes, the extensive incision observed in Lodore Canyon is probably better explained by perennial stream flow from the drainage and the low magnitude and/or frequency of debris-flow events that could fill and overtop the short-term channel.
Figure 51. Channel incised into 1997 debris-flow deposits by recessional stream flow at Mile 233. Location shown on Figure 27.

Figure 52. Former active channel located on the Mile 233 debris fan (in the "intermediate" deposits) that is characteristic of the evolution of abandoned channels throughout Lodore Canyon. Person in center for scale. Location of view shown on Figure 14.
The deeply incised channel at the Wild Mountain fan provides a case study of this phenomenon. Prior to the September 1997 debris flow, the existing channel was incised to a depth of approximately 1-2 m below the surface of the debris fan, but contained no active stream flow. Although no quantitative comparisons can be made between the depth of incision before and after the debris flow, qualitative observations indicate that the debris flow and recessional stream flow deepened a channel that was previously overgrown with vegetation (Figure 53).

Subsequent to the 1997 debris flow, the Wild Mountain tributary contained perennial stream flow. Surveyed measurements of the longitudinal profile of the channel made 1 month and 11 months after the debris flow showed that the channel continued to incise, with the depth increasing by nearly 0.5 m during that period (see Figure 47). This incision of the channel is attributed to perennial tributary stream flow rather than debris-flow processes because there was no evidence of an additional debris flow. The depth of the incised channel before the 1997 debris flow probably indicates that stream flow from the tributary had been perennial at other times in the history of the debris fan. The 1997 debris flow might have exposed a spring in the tributary canyon that had been covered by colluvium. Or, stream flow from the tributary had continuously flowed in the steep, upstream portion of the tributary channel, but infiltrated the colluvium filling the incised channel when it reached the fan surface. Once the channel was scoured by the debris flow, the stream began to flow on the fan surface, in the incised channel once again.

The Wild Mountain debris fan can be characterized as long-term channelized—debris flows from this drainage are confined to the deeply incised channel and transported to the
Figure 53. View upstream in the Wild Mountain tributary channel in October 1997, following the September debris flow. Person in center for scale.
distal margin of the fan. In order for the stage to shift to fan-forming, the magnitude or frequency of debris flows must increase such that the channel will backfill and overtop.

In Grand Canyon, Hereford et al. (1997) determined that the majority of the fans are in a long-term channelized stage. The fact that the majority of the fans in a region are in approximately the same stage indicates that the long-term channelized or fan-forming stages are the result of an overarching driving force, such as climate, that is synchronous throughout the region. Because only a small proportion of the fans in Lodore Canyon are channelized, the driving force of fan evolution is probably not synchronous between Lodore Canyon and Grand Canyon. Furthermore, the majority of the fans in Lodore Canyon are also not in the fan-forming stage, characterized by extensive surfaces of the same age, probably a result of high frequency and/or high magnitude events (Hereford et al., 1996).

The lack of uniformity of channelization on Lodore Canyon fans suggests that there is another stage of debris-fan evolution in Lodore Canyon. The overall character might best be attributed to a prolonged interval of relative inactivity. This would explain why the majority of the fans have not been active in at least the past 50 years, and perhaps for much longer. The small number of fans in Lodore Canyon that are long-term channelized would not contradict the theory that the fans are in a stable period. If the fan stage had shifted from fan-forming to inactive, then the majority of the fans should exhibit older features characteristic of the fan-forming stage. If, during a time of relative inactivity, perennial stream flow continued to rework the fan surface, eroding a channel on a few fans, then those fans might exhibit the characteristics of long-term channelization.
Debris-Fan Reworking

The repeat topographic surveys from March and September 1998 indicate that the Green River has a limited capacity to rework the newly-deposited Wild Mountain debris fan at or below power plant capacity discharges. Peak winter discharges produced insignificant changes while peak power plant capacity flows were able to effect only minor reworking. Estimates of areas of potential fan submergence at higher discharges show that, in the case of a pre-dam average flood, a fan of this size would probably be almost completely reworked. And, in the case of a more realistic scenario, significant expansion of the area of fan reworking would occur at discharges equivalent to recent high-release events.

The reworking that did occur during the spring peak discharge of 131 m$^3$/s was limited to the face of the fan. The cutbank that formed there indicated that erosion probably occurred through the winnowing of fines and calving of large particles followed by bank collapse similar to reworking processes observed during the 1996 controlled flood in Grand Canyon (Webb et al., 1998).

According to Webb and others’ (1998) conceptual model of fan reworking, low discharges rework the fan and transport material to a new gravel bar in the downstream pool. At Wild Mountain, however, the gravel bar is much closer to the fan than Webb and others’ model predicts. Some of the material eroded from the fan is not being transported to the downstream pool, but rather ends up slightly downstream of the edge of the fan. And, as a consequence of this depositional location, growth of the gravel bar is actually increasing the constriction at the rapid. To explain the processes at this site, an additional
scenario would need to be added to Webb and others’ model to illustrate the range of fan reworking (Figure 54).

At Wild Mountain, minor reworking probably occurs at low discharges. Material is removed from the face of the fan and deposited on a debris bar upstream from the pool. At intermediate discharges, Webb and others’ “low river discharge” scenario might apply with material being transported from the fan and deposited on a gravel bar in the downstream pool. But in this case, this scenario would occur at “intermediate discharges.” It would be difficult to assign discharge values for the boundary between the low and intermediate discharge ranges at this point because the discharge that causes a gravel bar to form in the downstream pool has not been quantified. Only at the highest discharges, perhaps exceeding the pre-dam average flood of 360 m$^3$/s, would the “high river discharges” scenario occur. The newly mobilized debris-flow-derived alluvium would be transported to the upstream margin of the stable debris bar located on the downstream bend.

The location of a stable gravel bar downstream from the Wild Mountain fan and at many other sites throughout the canyon indicates that previous debris-flow deposits on the fans were most likely transported by “high river discharges.” Since no other tributary in Lodore Canyon has had a historic debris flow that deposited a fan in the river, there is no evidence of the intermediate discharge scenario that Webb and others’ model would predict, even though discharges have probably been in the intermediate range since the construction of Flaming Gorge Dam (see Figure 35). The fact that the reworking of the Wild Mountain debris flow, which occurred following the intermediate discharges in the
Figure 54. Schematic diagram of debris fan reworking in Lodore Canyon (adapted from Webb et al., 1998). The low discharge scenario (A) represents flows equivalent to power plant capacity. Intermediate discharges (B) are probably equivalent to the 1997 high release discharge or the 1983 level. The high discharge scenario (C) probably no longer occurs in Lodore Canyon.
post-dam era (flows of 400 m$^3$/s in 1983 and approximately 250 m$^3$/s in 1986 and 1997), did not result in the formation of a gravel bar in the pool downstream from the fan indicates that power plant capacity do not generate features predicted by Webb and others’ (1998) model.

While the current configuration of the Wild Mountain debris fan does not hinder navigation, continued study of the site could provide crucial insight into the debris-fan reworking process at “low discharges.” During one year of low discharges, reworking decreased the constriction at the rapid by eroding the fan face, but it has also slightly increased the constriction where gravel is deposited on the bar. Will sustained low discharges cause further growth of the debris bar as the fan is reworked resulting in greater increases in constriction? Or is it possible that the face of the fan is already stable?

Webb et al. (1998) have determined that the particles on the face of a debris fan become armored and sutured if they are subjected to prolonged low discharges prior to a high discharge event. When this occurs, a subsequent higher discharge event is often unable to mobilize the particles from the face of the fan. With continued observation it might be possible to determine when the Wild Mountain fan might become armored such that subsequent high release events would be unable to rework the fan.

In either case, it is evident from both the preexisting debris fan-gravel bar relationship at fans throughout Lodore Canyon and the current reworking scenario at Wild Mountain, that without high discharge events, reworking of debris fans during a regime of regulated discharges will result in a much different pattern of deposition. The gravel bars that are currently found downstream from the pools below a rapid that have already become
stabilized with the decrease in flood magnitude (Grams, 1997) will be remnant features of
a different hydrologic regime. If intermediate discharge events occur during the window
of opportunity for fan reworking, which at this point remains undefined, the remnant bars
will probably be replaced by gravel bars located in the pools below the rapid. But, if the
debris fan is only subject to low discharges, it is likely that gravel bars will be located on
the downstream edge of the debris fan.

**Stream Channel Establishment at Wild Mountain**

Documentation of the process of stream channel establishment across a newly
deposited debris fan has implications for both debris-fan evolution and stream-channel
development. The channel on the 1997 Wild Mountain debris fan could be likened to a
small-scale model where the evolution of channel planform as it shifted from braided to
meandering, as well as the development of a stepped longitudinal profile, have been
observed and tracked.

Leopold and Wolman (1957) suggested that stream channels transform from
meandering to braided patterns (or vice versa) in accordance with changes in the slope-
discharge relationship. The Wild Mountain surveys show that the average slope of the
stream channel thalweg did not change significantly between October 1997 (0.083) and
September 1998 (0.080) (Figure 48). Therefore, an increase in the discharge of the
tributary stream must have induced the change in channel pattern. The channel
transporting the largest portion of the discharge incised faster than the other channels and
was able to capture the entire flow.
Observations of the development of the step-pool morphology on the newly deposited fan surface at Wild Mountain show that high discharges are not necessary for step formation. There is no direct evidence of high discharges in the newly developed stream channel in the year since its inception.

Physical evidence from the Wild Mountain stream seems to corroborate the Judd and Peterson (1969) model for step origination. The steps that have developed in the immature channel are located where the stream has encountered a particle or group of particles that are significantly larger than the maximum depth of the channel. It is probably too early to discern whether the step-pool sequences will eventually evolve from the random spacing caused by blockage of large particles to a pattern of regular spacing according to the maximum flow resistance model of Abrahams et al. (1995).

**Summary and Conclusions**

Detailed examination of Lodore Canyon debris fans has shown that, while there are basic principles of debris-flow processes and debris fan evolution that are universal, local factors such as climate and geology play a crucial role. The largest debris fans in Lodore Canyon are systematically located at the widest sections of the canyon. Evidence from the 1997-98 debris flows in Lodore Canyon illustrate that the frequency of meteorological events such as drought that leads to fires and the frequency of intense precipitation are principal controlling factors in debris-flow initiation.

Research in Lodore Canyon has shown that the models developed by Grand Canyon researchers in a similar canyon river setting do not always apply. Factors that lead to debris flow initiation, characteristics of individual debris-flow events, reworking
processes of the mainstem river, and processes of fan evolution are not necessarily
correlative between the upper and lower Colorado River basin. Regional climatic
differences and variations in local geology are the principal explanation for the disparity
between the two regions.

The primary role of debris-flow processes as a geomorphic control upon canyon rivers
makes understanding them a necessity for resource managers who have been entrusted
with the task of maintaining controlled river systems located in canyon river settings. Yet,
it would be a mistake to simply concentrate the study of the phenomenon in a single
region such as Grand Canyon or even the Colorado River basin, then generalize and apply
the results to other regions, as is often done in other areas of resource management. The
role of regional climate, local variations in lithology, and other important local
controlling factors need to be examined for each canyon reach.
REFERENCES


### TABLE A1. VELOCITY AND DISCHARGE CALCULATION FOR THE WILD MOUNTAIN DEBRIS FAN

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<td>4966.73</td>
<td>6.16</td>
<td>108.86</td>
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</table>

Area (m²) 6.36

| gravity (m/s²) | 9.80 |
| Rc (m) | 11.86 |
| Δhs | 0.90 |
| k | 1.00 |
| width (m) | 6.16 |
| mean A (m²) | 6.06 |

### Downstream cross section

<table>
<thead>
<tr>
<th>northing (m)</th>
<th>easting (m)</th>
<th>distance (m)</th>
<th>elevation (m)</th>
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Area (m²) 5.76

Note: Correctional factor k is assumed to be equal to 1 following Webb et al. (1989).
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<td>4994.11</td>
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**Upstream cross section**

**Superelevation site**

<table>
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<th>distance (m)</th>
<th>elevation (m)</th>
</tr>
</thead>
<tbody>
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<td>4992.10</td>
<td>0.00</td>
<td>99.74</td>
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<td>4994.57</td>
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</table>

**Downstream cross section**

**Area (m²)**

- 7.57
- 5.68

**Velocity and Discharge Calculation for the Upstream Middle Disaster Superelevation Site**

- **Gravity (m/s²)**: 9.80
- **Re (m)**: 8.68
- **Δhs**: 0.17
- **k**: 1.00
- **Width (m)**: 7.42
- **Mean A (m²)**: 6.63
- **Velocity (m/s²)**: 1.38
- **Discharge (m³/s)**: 9.15

**Note**: Correctional factor k is assumed to be equal to 1 following Webb et al. (1989).
TABLE A3. VELOCITY AND DISCHARGE CALCULATIONS FOR THE DOWNSTREAM MIDDLE DISASTER SUPERELEVATION SITE

<table>
<thead>
<tr>
<th>Northing (m)</th>
<th>Easting (m)</th>
<th>Distance (m)</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
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<td>4993.83</td>
<td>0.00</td>
<td>96.82</td>
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<td>5015.64</td>
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<td>95.09</td>
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<td>97.54</td>
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</table>

**Upstream cross section**

**Area (m²)** 14.01

<table>
<thead>
<tr>
<th>gravity (m/s²)</th>
<th>9.80</th>
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<tbody>
<tr>
<td>Re (m)</td>
<td>15.08</td>
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<tr>
<td>Δhs</td>
<td>0.09</td>
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<td>k</td>
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<tr>
<td>width (m)</td>
<td>10.57</td>
</tr>
<tr>
<td>mean A (m²)</td>
<td>12.79</td>
</tr>
</tbody>
</table>

**Downstream cross section**

**Area (m²)** 11.56

| velocity (m/s) | 1.12 |
| discharge (m³/s) | 14.33 |

Note: Correctional factor k is assumed to be equal to 1 following Webb et al. (1989).