Debris-fan reworking during low-magnitude floods in the Green River canyons of the eastern Uinta Mountains, Colorado and Utah

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ABSTRACT

The magnitude and frequency of tributary debris flows and the historical range of main-stem river discharges are the main factors that create and modify rapids in the Colorado River system. Monitoring of two recently aggraded debris fans in the Green River canyons of the eastern Uinta Mountains shows that main-stem floods with magnitudes between 40% and 75% of the predam 2 yr flood cause significant reworking of fan deposits. Cutbanks formed at fan margins during both small and large flows, indicating that lateral bank erosion is an important reworking mechanism. Armoring of the debris-fan surface limited the degree of reworking by successive floods, even when subsequent flood magnitudes were similar to those that caused significant reworking. Peak discharges increased the width of the reworked zone, decreased fan constrictions, and lowered the water-surface elevation of the ponded backwater. Contrary to predam geomorphic evidence, monitoring indicated that eroded material from recently aggraded debris fans was deposited in bars adjacent to the downstream parts of both fans. This change in the organization of the fan-eddy complex has the potential to alter the location of recirculating eddies and associated areas of fine-grained sediment deposition and storage.

Keywords: eastern Uinta Mountains, debris flows, floods, debris-fan reworking.

INTRODUCTION

Debris flows are widespread in the Colorado Plateau. In the canyons of the largest rivers, debris flows from tributaries are one determinant of the geomorphic organization of the main-stem channel, because debris flows deliver coarse sediment (Webb et al., 1989; Melis et al., 1994) that creates rapids (Kieffer, 1985; Webb et al., 1988; Hammack and Wohl, 1996) that constitute the keystone of the fan-eddy complexes that are the essential geomorphic attribute of these rivers (Schmidt and Rubin, 1995; Grams and Schmidt, 1999). Despite the significance of the interaction between main-stem streams and tributary debris flows, the characteristics of debris-flow blockage of the main channel and subsequent reworking by main-stem floods are not well understood, and conceptual models of this interaction are based mostly on data from the Grand Canyon. Studies of reworking of debris flows are few and have reached conflicting conclusions as to whether large- (Kieffer, 1985) or small-magnitude floods (Webb et al., 1999; Pizzuto et al., 1999) are sufficient to significantly rework these deposits.

The construction of large dams in the Colorado River basin had dramatic impacts on the hydrology of downstream reaches (Andrews, 1986; Topping et al., 2003). Whereas the alteration of downstream hydrologic regimes was purposeful and expected, corresponding downstream geomorphic changes were largely unanticipated (Schmidt et al., 1998). One of the unanticipated geomorphic changes has been decreased reworking of debris-flow deposits in rapids owing to decreased flood magnitudes (Graf, 1979, 1980; Howard and Dolan, 1981; Kieffer, 1985; Webb, 1996). The combination of increased stability of boulders in rapids, narrower channel constrictions, and continuing debris-flow inputs has the potential to alter the geomorphic template on which the aquatic ecosystem is organized and to create navigation difficulty for recreational boaters.

The goal of this study was to document the reworking of two recently aggraded debris fans in the Green River canyons of the eastern Uinta Mountains. We repeatedly surveyed the debris fans over 6 and 4 yr periods to determine the magnitude of reworking and the resultant geomorphic arrangement associated with a range of main-stem flood magnitudes.

PREVIOUS STUDIES OF REWORKING

Kieffer (1985) developed a conceptual model of debris-flow reworking derived from a study of Crystal Rapid in the Grand Canyon during unprecedented high postdam flows in 1983. Kieffer's model was based on estimates of velocity and tractive forces estimated to be required to erode large debris-flow boulders. According to Kieffer (1985), reworking takes place only during very large discharges when supercritical flow occurs and large tractive forces exist in the constricted flow field. As the channel widens because of erosion of large boulders, velocity and tractive forces decrease below the threshold required for transport, and reworking ceases.

Webb et al. (1999) found that the 1996 controlled flood in the Grand Canyon, with a discharge that was 60% of the predam 2 yr flood, caused significant reworking of many recently aggraded fans. This flood was moderately high by postdam standards (Schmidt et al., 2001) and reduced both the area and volume of fan deposits and left a coarse armor layer on the distal margins of debris fans. Webb et al. (1999) showed that the greatest magnitude of reworking occurred on fans that had been most recently aggraded by debris flows. Fans whose surfaces had been aggraded decades earlier and had already been inundated by prior floods were not significantly reworked in 1996, because those fan surfaces were already armored.

The mechanism by which lower-magnitude floods rework debris-flow deposits is primarily bank failure. Pizzuto et al. (1999) monitored transport of clasts from debris-fan surfaces during the controlled flood and observed (1) entrainment of individual clasts from the fan surface and (2) bank failure of debris-flow deposits owing to lateral bank erosion, which imparted an initial motion to large clasts that were not otherwise entrained. Pizzuto et al. (1999) observed that erosion primarily occurred during the initial 4 h of the flood, and reworking ceased as the surface became armored. Most tagged particles removed from the debris fan were deposited in the pool immediately downstream from the rapid and did not reach the expansion gravel bar farther downstream (Pizzuto et al., 1999).

On the basis of these observations, Webb et al. (1999) presented an alternative model to that of Kieffer (1985) that emphasizes the role of lower-magnitude flows. Webb et al. (1999) stated that the locus of deposition for particles eroded from debris fans differs between large- and small-magnitude floods. In large flows typical of the predam regime, material eroded from debris fans was deposited at the expansion bar downstream from the pool, but reworked material is deposited immediately downstream from the rapid during small floods.

GREEN RIVER IN THE CANYONS OF THE EASTERN UINTA MOUNTAINS

The Green River has established its course through the eastern end of the Uinta uplift in Colorado and Utah, forming three spectacular

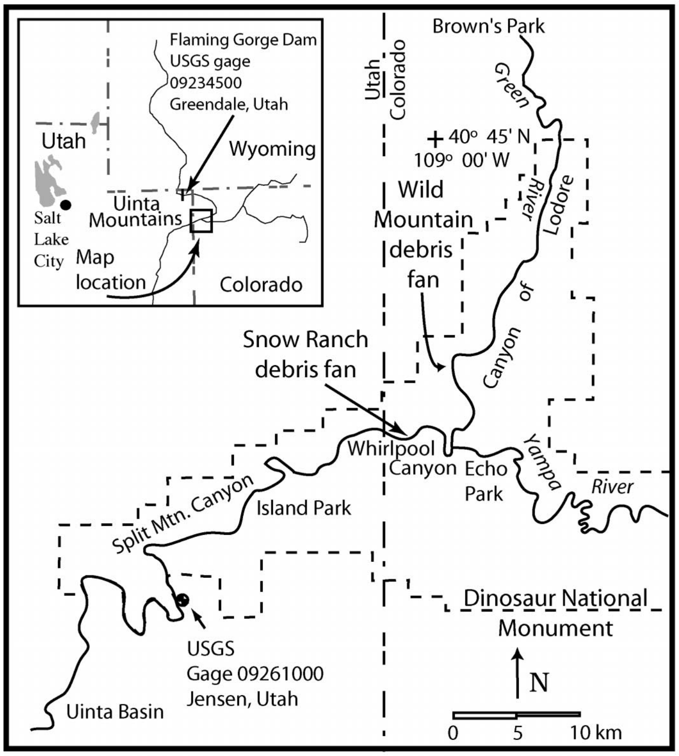

Figure 1. Study area map and locations of study debris fans.

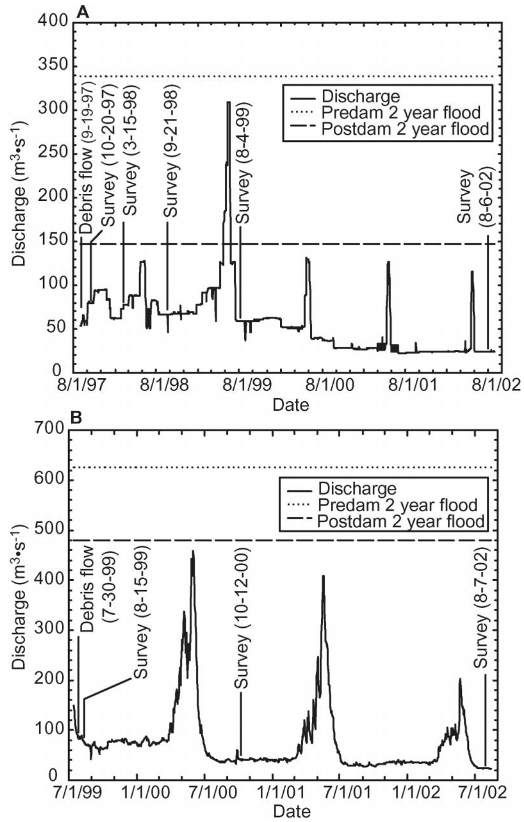

Figure 2. A: Hydrograph showing discharge at Greendale, Utah, predam and postdam 2 yr floods, and timing surveys in Canyon of Lodore. B: Hydrograph showing discharge at Jensen, Utah, predam and postdam 2 yr floods, and timing of surveys in Whirlpool Canyon.

canyons: the Canyon of Lodore, Whirlpool Canyon, and Split Mountain Canyon (Fig. 1). These canyons contain abundant debris fans that, along with river-level geology, control the longitudinal profile, cross-section geometry, and location and style of alluvial deposition (Grams and Schmidt, 1999). The debris fans create 96 fan-eddy complexes where 72% of the alluvium and 89% of the gravel in the valleys are stored (Grams and Schmidt, 1999).

The hydrology of the Green River was historically dominated by large spring snowmelt runoff. Operation of Flaming Gorge Dam, located 68 km upstream from the Canyon of Lodore (Fig. 1), has significantly decreased the frequency and magnitude of flood discharges. The 2 yr recurrence flood at Greendale, Utah (U.S. Geological Survey [USGS] gage 9234500), has decreased 57%, from 339 $m^3 \cdot s^{-1}$ to 147 $m^3 \cdot s^{-1}$ (Fig. 2A) (Grams and Schmidt, 2002). The influence of Flaming Gorge Dam is diminished downstream from where the unregulated Yampa River joins the Green River (Fig. 1). The 2 yr recurrence flood in Whirlpool Canyon, measured at Jensen, Utah (USGS gage 9261000), has decreased 23%, from 626 $m^3 \cdot s^{-1}$ to 480 $m^3 \cdot s^{-1}$, since completion of the dam (Fig. 2B) (Grams and Schmidt, 2002). The reduction in the frequency of large floods has had fundamental effects on the alluvial geomorphology of the canyons, causing significant channel narrowing through vertical accretion of inset floodplains (Grams and Schmidt, 2002).

Since 1997, 15 debris flows have aggraded debris fans in the Canyon of Lodore and Whirlpool Canyon (Martin, 2000; Larsen, 2003). Several of these debris flows deposited significant amounts of sediment in the Green

TABLE 1. DEBRIS-FAN REWORKING RESULTS

Survey date	Maximum discharge since previous survey ($m^3 \cdot s^{-1}$)	Volume eroded since previous survey (m^3)	Volume deposited since previous survey (m^3)	Fan-margin grain size D_{16}, D_{50}, D_{84} (mm)	Gravel-bar grain size D_{16}, D_{50}, D_{84} (mm)	Constriction ratio*
Wild Mountain						
10/20/97	N.A.	N.A.	N.A.	<4, <4, <4	N.A.	0.25
3/15/98	95	2	0	<4, 18, 50	N.A.	0.25
9/21/98	128	30	1.3	4, 28, 85	30, 65, 110	0.26
8/4/99	309	320	36	50, 160, 380	17, 32, 65	0.33
8/6/02	130	0	1	<11.3, 160, 380	12, 32, 65	0.33
Snow Ranch						
8/15/99	N.A.	N.A.	N.A.	<2, 8, 35	N.A.	0.26
10/12/00	459	323	126†	N.D.	N.D.	0.37
8/7/02	408	10	10	30, 110, 220	30, 60, 120	0.37

Note: N.A. = not applicable; N.D. = Not measured.
*Measured at baseflow. Constriction prior to debris flow at Wild Mountain was 0.42; that at Snow Ranch was 0.62.
†Volume does not include estimated 200–300 m^3 of material deposited downstream of the initial survey boundary.

River, aggrading rapids and riffles. Our focus is on two of these debris flows. The Wild Mountain debris flow was initiated in the Canyon of Lodore during a September 1997 rainstorm and deposited ~2100 m^3 of material onto the 0.01 km^2 debris fan and in the Green River. On 30 July 1999, the Snow Ranch debris flow deposited ~4300 m^3 of material on the distal margin of the 0.02 km^2 debris fan and in the Green River in Whirlpool Canyon.

METHODS

Topographic surveys of the Wild Mountain and Snow Ranch fans were conducted soon after the initial debris flows, and subsequent surveys were made following significant changes in main-stem flow. These surveys were used to determine the volume of the initial debris flows that were reworked, and the magnitude of reworking was related to the peak discharge of each intervening survey period (Table 1). Only fan areas with overlapping survey data and sufficient point density from different survey dates were used to calculate changes in fan volume. Because of potential error associated with surveying an irregular surface, only elevation changes of >0.2 m were used to calculate changes in fan volume.

In addition to calculating volume changes, clast counts (Wolman, 1954) were repeated to evaluate grain-size changes in the reworked zone of the fan and on downstream gravel bars composed of reworked material. We used survey data collected at the Wild Mountain fan during the 1999 peak flow to calculate unit stream power, ω, as

$$\omega = \gamma Q S W^{-1}, \quad (1)$$

where γ = specific weight of water, Q = discharge, S = the water-surface slope through the rapid, and W = the constricted channel width. We used γ = 9810 N/m^3 in our calculations. Constriction ratios, the ratio of the upstream channel width to the channel width at the constriction (Kieffer, 1985), were measured using aerial photographs and surveys.

RESULTS

Reworking of the Wild Mountain Debris Fan

The threshold of significant reworking of the aggraded Wild Mountain debris fan was between 0.4 and 0.9 times the predam 2 yr flood. Between September 1997 and June 1999, flows did not exceed the maximum capacity of the Flaming Gorge Dam power plant (130 $m^3 \cdot s^{-1}$ or 40% of the predam 2 yr flood), and <1% of the original deposit was reworked. However, ~15% of the 1997 debris-flow deposit was removed by flows of 309 $m^3 \cdot s^{-1}$, ~90% of the predam 2 yr flood (Fig. 3). This June 1999 flood was the second largest since completion of Flaming Gorge Dam.

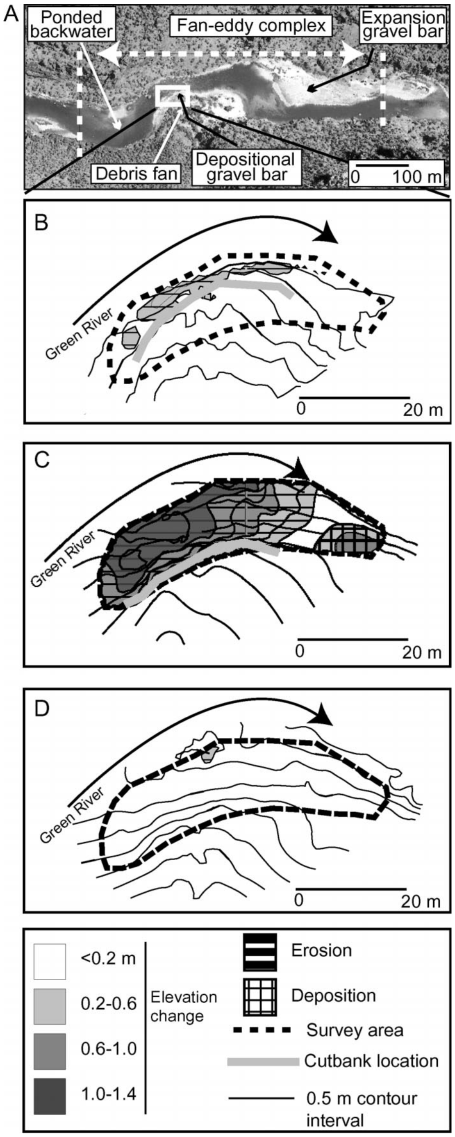

Figure 3. A: Aerial photograph of Wild Mountain debris fan taken in July 2001, showing fan-eddy complex and location of survey maps. B: Reworking at Wild Mountain associated with peak discharge of 131 $m^3 \cdot s^{-1}$ between October 1997 and September 1998. During this time, erosion was restricted to distal margin of fan. C: Reworking at Wild Mountain associated with peak discharge of 309 $m^3 \cdot s^{-1}$ between September 1998 and August 1999. Significant volume of material was removed from fan surface and deposited in gravel bar directly downstream. D: Little volume change occurred at Wild Mountain between August 1999 and August 2002.

The unit stream power during the June 1999 discharge was 1962 $W \cdot m^{-2}$, and there was 10 m of lateral bank retreat that widened the constriction ratio from 0.25 to 0.33 (Table 1). Fan reworking caused the stage vs. discharge relationship for the ponded backwater upstream from the rapid to decrease 0.2 m (Fig. 4), because the backwater effect of the constriction was decreased.

Erosion occurred primarily on the upstream distal margin of the fan (Fig. 3). As a result

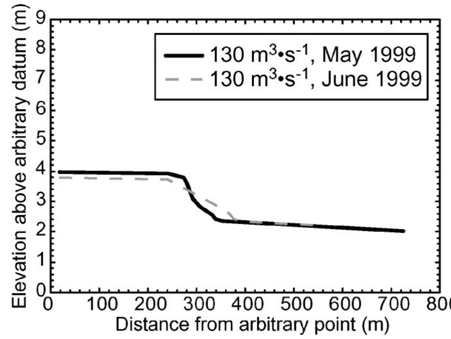

Figure 4. Water-surface profile at Wild Mountain showing 0.2 m stage decrease in upstream pool at discharge of 130 $m^3 \cdot s^{-1}$ due to reworking that occurred between May and June 1999.

of coarsening of the fan surface during the 1999 flows (Table 1), no reworking occurred during subsequent smaller floods (Fig. 3). The eroded material was deposited in a small gravel bar attached to the downstream end of the fan. During this study, this gravel bar increased in volume by 36 m^3 (Fig. 3).

Reworking of the Snow Ranch Debris Fan

Significant reworking of the aggraded Snow Ranch debris fan was caused by flood discharges that were 75% of the predam 2 yr flood. Spring floods in 2000 reached a peak discharge of 459 $m^3 \cdot s^{-1}$ (Fig. 2B) and eroded 8% of the volume of the original deposit. The following spring, peak discharge reached 65% of the predam 2 yr flood, but very little reworking occurred (Fig. 5).

The fan surface was significantly armored by the 2000 flood (Table 1), and reworking resulted in as much as 20 m of lateral bank retreat on the middle and downstream parts of the fan (Fig. 5). The lateral erosion widened the constriction ratio of the fan from 0.26 to 0.37 (Table 1). Between 40% and 100% of the material eroded from the debris-fan surface was deposited directly downstream from the fan, forming an elongated gravel bar that lengthened the constriction by 35 m (Fig. 5).

DISCUSSION AND IMPLICATIONS

These results show that debris fans in the eastern Uinta Mountains can be reworked by discharges less than the predam 2 yr flood. A threshold of fan reworking may exist: flows as low as 75% of the predam 2 yr flood caused significant reworking, whereas discharges of <40% of the predam 2 yr flood did little reworking.

In the Canyon of Lodore, geomorphically effective floods are nevertheless rare, because they exceed the capacity of the Flaming Gorge Dam power plant. Such floods only occur when water releases from bypass facilities and maximum capacity power plant releases occur simultaneously. Downstream from the confluence of the Yampa River, these discharges oc-

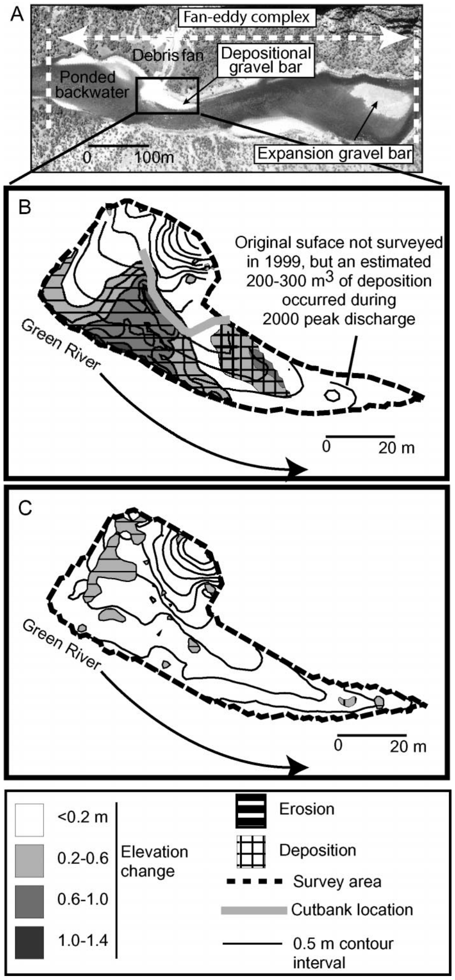

Figure 5. A: Aerial photograph of Snow Ranch debris fan taken in July 2000 showing fan-eddy complex and location survey area. B: Reworking at Snow Ranch associated with peak discharge of 459 $m^3 \cdot s^{-1}$ between August 1999 and October 2000. Large volume of material was eroded from fan and deposited in gravel bar downstream from fan. C: Little reworking occurred at Snow Ranch between October 2000 and August 2002; during this interval, peak discharge was 408 $m^3 \cdot s^{-1}$.

cur more frequently due to inflow from unregulated tributaries.

These results indicate that lateral bank erosion is an important process in reworking. Once significant reworking has occurred, subsequent smaller floods accomplish little geomorphic work, presumably due to armoring of the fan surface. Our data do not support the conceptual model of Kieffer (1985), who suggested that large floods are required for reworking; our results are consistent with those of Webb et al. (1999), who suggested that low-magnitude floods are an important influence on the geomorphology of debris fan–dominated, bedrock-influenced canyon rivers.

The depositional fate and transport distance of eroded material from the fans in our study are inconsistent with (1) field evidence that indicates that material eroded from debris fans was deposited on expansion gravel bars during the predam flow regime (Grams and Schmidt, 1999) and (2) findings from the controlled flood in the Grand Canyon, where reworked material was transported to the pools immediately downstream from rapids (Figs. 3 and 5). Of the total material removed from the fans at Wild Mountain and Snow Ranch, 10% and 40%–100%, respectively, moved less than one channel width, and was deposited directly downstream from the fans as adjacent gravel and cobble bars (Figs. 3 and 5). This location represents a significant change in the organization of the fan-eddy complex and has the effect of lengthening the fan constriction and increasing the water-surface slope downstream from the fan. These effects have the potential to alter the location and/or presence of recirculating eddies and associated backwater habitats and fine-grained sediment deposits.

Because debris flows will continue to aggrade fans throughout the Colorado River system, resource managers may need to consider strategies to rework these deposits in order to maintain the predam geomorphic organization of the main channel and its associated aquatic habitats, as well as maintaining navigable rapids for recreational boaters. The results from this study indicate that controlled flood releases designed to rework debris-flow deposits would have the greatest impact if (1) they occur soon after debris-flow emplacement and coincide with naturally occurring floods in unregulated tributaries and (2) they are not preceded by small floods that armor the fan surface. By proper timing of controlled floods, fan reworking can be accomplished by flows that exceed normal power plant operations, but that are within the operational range of Flaming Gorge and Glen Canyon, the largest dams of the Colorado River Storage Project.

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