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The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River basin

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ABSTRACT

Prior to the construction of large dams on the Green and Colorado Rivers, annual floods aggraded sandbars in lateral flow-recirculation eddies with fine sediment scoured from the bed and delivered from upstream. Flows greater than normal dam operations may be used to mimic this process in an attempt to increase time-averaged sandbar size. These controlled floods may rebuild sandbars, but sediment deficit conditions downstream from the dams restrict the frequency that controlled floods produce beneficial results. Here, we integrate complimentary, long-term monitoring data sets from the Colorado River in Marble and Grand Canyons downstream from Glen Canyon dam and the Green River in the Canyon of Lodore downstream from Flaming Gorge dam. Since the mid-1990s, several controlled floods have occurred in these canyon rivers. These controlled floods scour fine sediment from the bed and build sandbars in eddies, thus increasing channel relief. These changes are short-lived, however, as interflood dam operations erode sandbars within several months to years. Controlled flood response and interflood changes in bed elevation are more variable in Marble Canyon and Grand Canyon, likely reflecting more variable fine sediment supply and stronger transience in channel bed sediment storage. Despite these differences, neither system shows a trend in fine-sediment storage during the period in which controlled floods were monitored. These results demonstrate that controlled floods build eddy sandbars and increase channel relief for short interflood periods, and this response may be typical in other dam-influenced canyon rivers. The degree to which these features persist depends on the frequency of controlled floods, but careful consideration of sediment supply is necessary to avoid increasing the long-term sediment deficit.

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1. Introduction

The natural flow and sediment supply regimes of many large, canyon-bound rivers in the western U.S. have been dramatically altered by large dams. Large reservoirs trap most, or all, of the sediment supplied from the upstream watershed, and the objective of many reservoir release rules is to achieve a significant amount of flood control. Immediately downstream from dams, the sediment mass balance of the river is typically perturbed into deficit, but the mass balance may be perturbed into surplus farther downstream (Schmidt and Wilcock, 2008). Common geomorphic responses to these perturbations include sediment evacuation under deficit conditions, sediment accumulation under surplus conditions, incision under deficit conditions if the bed material in hydraulic controls can be readily mobilized by typical post-dam flows, and narrowing and/or planform simplification wherever flood magnitude is reduced (Stevens, 1938; Lane, 1955; Williams and Wolman, 1984; Andrews, 1986; Graf, 2006; Schmidt and Wilcock, 2008). Reduction in flood magnitude and increase in base flow magnitude also facilitates vegetation encroachment, which reduces channel capacity and fosters vertical accretion of floodplains and channel narrowing even where total flow is greatly reduced (Dean et al., 2011).

Environmental flows for the purpose of rehabilitating some component of the downstream ecosystem have been prescribed for many regulated rivers (Konrad et al., 2011; Wilcox and Shafroth, 2013). Where rivers have been perturbed into sediment deficit, such as is the focus of this study, the release of controlled floods to rejuvenate simplified aquatic and riparian habitats must be carefully matched with available supplies of sediment that are only available for transport for short periods of time (Webb et al., 1999; Schmidt and Grams, 2011). Political and management priorities have focused increasing scientific attention on the Colorado River in Marble and Grand Canyons downstream from Glen Canyon dam. In this river, controlled floods have been used in an attempt to maintain and rehabilitate sandbars that occur in lateral flow separation eddies. The first of these controlled floods occurred in

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March 1996, and subsequent controlled floods (defined here as being greater than power plant capacity) were released in 2004, 2008, 2012, and 2013. The magnitude of these controlled floods typically ranged from 1200 to 1300 m^3/s, approximately half the magnitude of a pre-dam 2-year flood. Long-term monitoring and short-term processes studies (Webb et al., 1999; Hazel et al., 2006, 2010; Topping et al., 2010; Schmidt and Grams, 2011; Melis et al., 2012) informed development of administrative rules that now allow release of controlled floods whenever downstream fine-sediment supply conditions are sufficiently large (U.S. Department of Interior, 2011).

Environmental flow issues and fluvial processes are similar on other dam-regulated, canyon-bound segments of the Colorado River system. However, no analysis has compared the effects of controlled floods in Marble and Grand Canyons to other canyon-bound river segments of the basin. Here, we present data based on long-term monitoring of the upper Green River in the Canyon of Lodore (hereafter referred to as Lodore Canyon), downstream from Flaming Gorge dam, where five controlled floods of varying magnitude have occurred since monitoring began. Lodore Canyon is a debris fan-affected segment (*sensu* Schmidt and Rubin, 1995) of the Green River and is a small-scale version of debris fan-affected Marble and Grand Canyons (Fig. 1). Measurements from Lodore Canyon are the only other data on bed and bar response to controlled floods in debris fan-affected river canyons. Here, we describe the decadal-scale trajectory of fine-sediment storage and morphologic change in Lodore Canyon, and we discuss this history in comparison to the history of similar features in Marble and Grand Canyons; we emphasize the effects of controlled floods. We also discuss the interflood geomorphic response of the channel bed and sandbars.

1.1. Regional setting

1.1.1. The Green River in Lodore Canyon and the Colorado River in Marble and Grand Canyons

The Green River in the eastern Uinta Mountains flows subparallel to the Laramide Uinta Uplift through a low-gradient collapsed basin in Browns Park and then turns south in Lodore Canyon through the eastern dome of the Uinta uplift (Fig. 1) (Hansen, 1986). Precambrian quartzitic rocks dominate the bedrock in Lodore Canyon. The canyon is ~28 km long, and only small, ephemeral tributaries enter the canyon. The largest tributary has maximum peak discharges less than 3 m^3/s (USGS gage 09235800) and is subject to extensive upstream diversion. Thus, streamflow in Lodore Canyon is nearly identical to the flow released from Flaming Gorge dam. Reach-averaged slope is 0.0029, average channel width is 60 m, and average width-to-depth ratio is 34 (Grams and Schmidt, 1999).

The Colorado River in Marble Canyon is established in Paleozoic sedimentary rocks (Fig. 1) and flows subparallel to the Laramide Kaibab uplift. Farther downstream, the Colorado River encounters a mixture of sedimentary and basement igneous and metamorphic rocks at river level. The delineation between Marble and Grand Canyons is generally considered to occur at the confluence with the Little Colorado River (Fig. 1). Tributaries that enter the Colorado River downstream from Glen Canyon dam typically contribute minimal streamflow except during short-duration summer monsoon rainstorms or during periods of snowmelt in larger basins. Reach-scale geomorphology of the Colorado River in Marble and Grand Canyons varies as a function of river level geology, with average channel slope ranging from 0.001 to 0.0023, average channel width ranging from 55 to 120 m, and width-to-depth ratios of 7 to 27 (Schmidt and Graf, 1990; Melis, 1997).

High local relief in these canyons results in steep tributary valleys where debris flows deliver boulders into the mainstem valley and constrict the channel (Howard and Dolan, 1981; Larsen et al., 2006). Hydraulic interactions with debris fans control reach-scale channel geometry, resulting in upstream pools, bouldery rapids, and downstream zones of flow recirculation where fine sediment is deposited as eddy bars; Schmidt and Rubin (1995) termed this assemblage of channel units the fan–eddy complex (Fig. 2). Where flood control is imposed by large dams, very coarse sediment in rapids is rarely entrained and the bed cannot be incised (Graf, 1980; Kieffer, 1985). The bed material outside of rapids is composed primarily of sand, gravel, and cobbles,

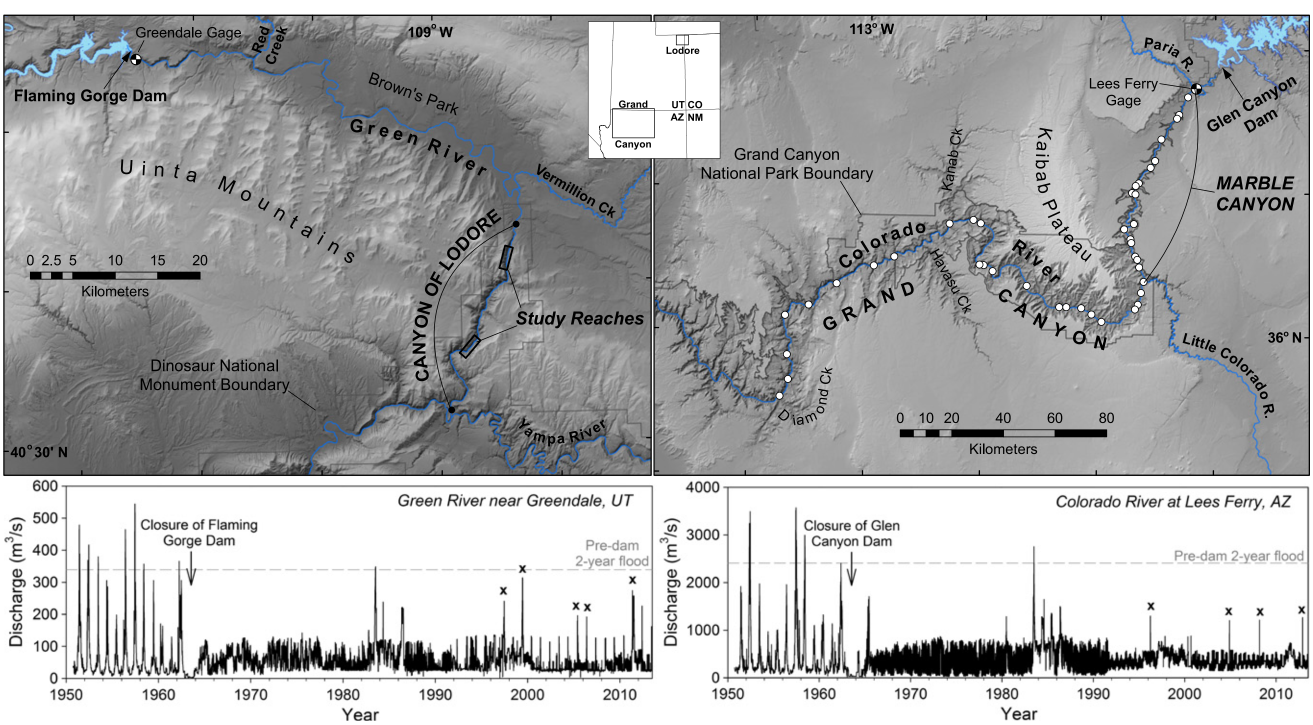

Fig. 1. Maps of the Green (top left) and Colorado (top right) Rivers indicating study reaches (white dots for the Colorado River) and upstream dams. Below each map are instantaneous flow hydrographs for years 1951–2012 (bottom); only mean daily flow was available for the Greendale gage during the period 1951–1986, 1990, and 1992–1993. X's indicate controlled floods discussed in the text.