Sedimentary Geology 363 (2018) 181–199

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Invited Review

Variability in eddy sandbar dynamics during two decades of controlled flooding of the Colorado River in the Grand Canyon

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ARTICLE INFO

Article history:
Received 21 July 2017
Received in revised form 2 November 2017
Accepted 3 November 2017
Available online 10 November 2017

Editor: J. Knight

Keywords:
Sandbars
Fan-eddy complex
Controlled floods
Sediment transport
River morphology
Grand Canyon

ABSTRACT

Sandbars are iconic features of the Colorado River in the Grand Canyon, Arizona, U.S.A. Following completion of Glen Canyon Dam in 1963, sediment deficit conditions caused erosion of eddy sandbars throughout much of the 360 km study reach downstream from the dam. Controlled floods in 1996, 2004, and 2008 demonstrated that sand on the channel bed could be redistributed to higher elevations, and that floods timed to follow tributary sediment inputs would increase suspended sand concentrations during floods. Since 2012, a new management protocol has resulted in four controlled floods timed to follow large inputs of sand from a major tributary. Monitoring of 44 downstream eddy sandbars, initiated in 1990, shows that each controlled flood deposited significant amounts of sand and increased the size of subaerial sandbars. However, the magnitude of sandbar deposition varied from eddy to eddy, even over relatively short distances where main-stem suspended sediment concentrations were similar. Here, we characterize spatial and temporal trends in sandbar volume and site-scale (i.e., individual eddy) sediment storage as a function of flow, channel, and vegetation characteristics that reflect the reach-scale (i.e., kilometer-scale) hydraulic environment. We grouped the long-term monitoring sites based on geomorphic setting and used a principal component analysis (PCA) to correlate differences in sandbar behavior to changes in reach-scale geomorphic metrics. Sites in narrow reaches are less-vegetated, stage changes markedly with discharge, sandbars tend to remain dynamic, and sand storage change dominantly occurs in the eddy compared to the main channel. In wider reaches, where stage-change during floods may be half that of narrow sites, sandbars are more likely to be stabilized by vegetation, and floods tend to aggrade the vegetated sandbar surfaces. In these locations, deposition during controlled floods is more akin to floodplain sedimentation, and the elevation of sandbar surfaces increases with successive floods. Because many sandbars are intermediate to the end members described above, high-elevation bar surfaces stabilized by vegetation often have a more dynamic unvegetated sandbar on the channel-ward margin that aggrades and erodes in response to controlled flood cycles. Ultimately, controlled floods have been effective at increasing averaged sandbar volumes, and, while bar deposition during floods decreases through time where vegetation has stabilized sandbars, future controlled floods are likely to continue to result in deposition in a majority of the river corridor.

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1. Introduction

Debris fan-affected canyons, where the geomorphic organization of the channel is structured into fan-eddy complexes (sensu Schmidt and Rubin, 1995), occur wherever debris flows initiated in high relief tributaries reach the main valley and partially block the channel (Webb et al., 1988; Schmidt et al., 1995; Webb, 1996; Larsen et al., 2004, 2006; Andrews and Vincent, 2007; Mueller et al., 2014). Where large amounts of fine sediment are transported by the main channel, such as by the Colorado River in the western United States, fine-grained bars occur in the zones of flow recirculation (eddies) that occur in the lee of debris fans (Howard and Dolan, 1981; Rubin et al., 1990; Schmidt, 1990; Schmidt and Graf, 1990; Grams and Schmidt, 1999). Hereafter, these bars are referred to as eddy sandbars or sandbars, because they are primarily composed of sand. Prior to the construction of large dams, eddy sandbars in the debris fan-affected canyons of the Colorado River were typically expansive during base flow (Dolan et al., 1974; Kearsley et al., 1994). Immediately downstream from many of these dams, these sandbars were extensively eroded, because the large reservoirs completely trapped the fine sediment flux and perturbed the downstream fine sediment mass balance into deficit (sensu Schmidt and Wilcock, 2008), such as in Marble Canyon and Grand Canyon downstream from Glen Canyon Dam. In some debris fan-affected canyons, especially in Grand Canyon National Park,

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https://doi.org/10.1016/j.sedgeo.2017.11.007
0037-0738/Published by Elsevier B.V.

eddy sandbars are of recreation value and provide ecosystem services (Turner and Karpiscak, 1980; Kearsley et al., 1994; Stevens et al., 1995; Korman et al., 2004; Kaplinski et al., 2005; Grams et al., 2010; Sankey et al., 2015; East et al., 2016).

Beginning in the early 1990s, reservoir operations at Glen Canyon Dam were adjusted in an effort to reverse progressive sandbar erosion. Mitigation measures included reduction in the magnitude of daily hydropeaking and release of controlled floods (Webb et al., 1999). Because both strategies reduce the revenue earned from hydropower production (U.S. Department of the Interior, 1995, 2016), public policy deliberations require an understanding of the tradeoff between the cost of lost hydropower revenue and the benefit of increased sandbar frequency and size in Grand Canyon National Park. Thus, there is a need to describe the "average" response of eddy sandbars to specific mitigation measures, such as the release of a specific controlled flood.

In Grand Canyon National Park, where a comprehensive monitoring program has been in place for >25 years, measurements have demonstrated that there is large variability in eddy sandbar response to controlled floods (Schmidt and Graf, 1990; Beus and Avery, 1992; Hazel et al., 1999, 2010; Schmidt and Grams, 2011; Mueller et al., 2014), making it difficult to assess the effectiveness of each flood. A general model characterizing sandbar response to controlled floods has remained elusive, and the purpose of this paper is to propose such a model. This paper analyzes 26 years of monitoring data, and distinguishes different geomorphic settings that are dominated by different characteristic responses to floods. The model proposed here is applicable to other debris fan-affected rivers whose eddy sandbars are a valued resource and are threatened by sediment deficit conditions and a reduction in flood magnitude.

2. Background

2.1. Sandbars in the Grand Canyon

Debris fan-affected canyons are common in the Colorado River basin (Schmidt and Rubin, 1995). At base flow, the longitudinal profile through these canyons is characterized by a series of long pools interspersed with steep drops where debris fans impinge on the channel (Leopold, 1969). Fluvial sand deposits occur at all elevations along the river corridor, from the river bed up to the elevation reached by the highest pre-dam floods, and the area of sand deposits typically increases downslope. Eddy sandbars within the active channel occur predominately in zones of recirculating current downstream from debris fans (Howard and Dolan, 1981; Schmidt, 1990; Schmidt and Graf, 1990; Melis, 1997; Grams and Schmidt, 1999; Vincent and Andrews, 2008; Mueller et al., 2014).

Schmidt and Rubin (1995) proposed the term fan-eddy complex for the sequence of hydraulic and geomorphic features centered on each debris fan. Upstream from each fan, stream flow is typically ponded in a hydraulic backwater (Kieffer, 1985). Downstream, the channel narrows and accelerates in the cascading flow of a rapid that is adjacent to or crosses part of the debris fan. Downstream from each debris fan, the channel widens, and the main flow separates from the banks, and sandbars are deposited near the points of flow separation and reattachment (Schmidt and Graf, 1990) (Fig. 1; Supplementary Fig. S1). Eddy sandbars may also be deposits that mantle the upstream part of a debris fan, where flow recirculates upstream from a constriction. The proportion of each recirculation zone filled by an eddy sandbar is controlled by factors such as the geometry of the debris fans that create flow recirculation and control the degree of stage change with discharge. For example, the length of the recirculation zone and location of the reattachment point tend to migrate downstream with discharge, but the distance of downstream migration may be restricted by downstream debris fans in some eddies (Schmidt, 1990). While all eddy sandbars show clear evidence of recirculating flow, the main recirculation zones may have an overprint of waves that propagate from the tailwaves of the rapids (Bauer and Schmidt, 1993).

Historically, seasonal snowmelt from the Rocky Mountains caused an annual flood in May and June (Howard and Dolan, 1981). Upon recession from this flood, large eddy sandbars became emergent downstream from most debris fans in Marble Canyon and Grand Canyon. Marble Canyon is the debris fan-affected canyon between Lees Ferry, 25 km downstream from Glen Canyon Dam, and the Little Colorado River 100 km downstream (Fig. 2). Grand Canyon begins at the Little Colorado River and extends 350 km downstream. Large floods scoured most of the river corridor's riparian vegetation, and large, barren eddy sandbars would be emergent from late summer to the following spring (Webb, 1996). The pre-dam 2-year flood was approximately 2350 m^3/s, and the largest observed flood was approximately 5950 m^3/s (Topping et al., 2003). Tributary flash floods during the summer and fall season of the North American monsoon delivered large quantities of fine sediment (sand, silt and clay) to the Colorado River

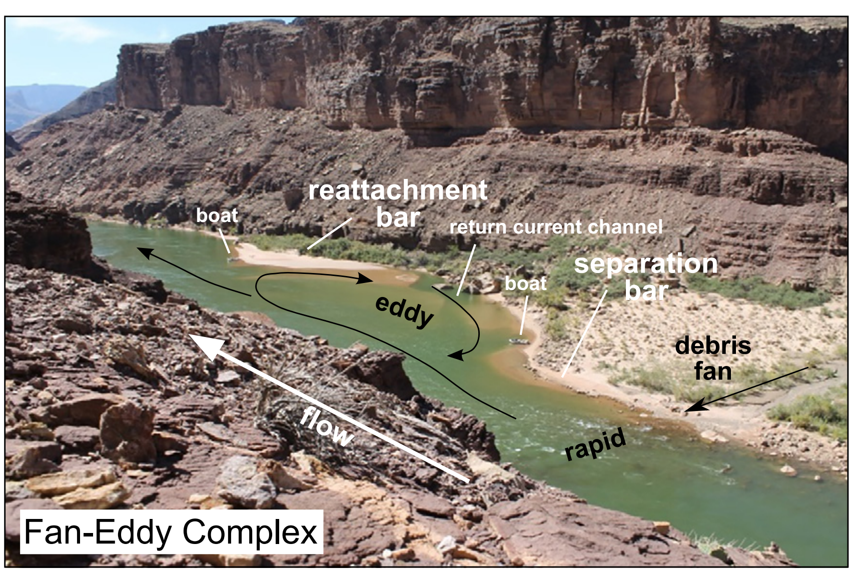

Fig. 1. Characteristics of a typical fan-eddy complex near river mile 65 in Grand Canyon, Arizona, U.S.A. Boats shown are approximately 5 m in length. Discharge is approximately 250 m^3/s in this image. Photograph by Paul E. Grams, U.S. Geological Survey, 2012.