Geomorphology 253 (2016) 225–238

Contents lists available at ScienceDirect

Geomorphology

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

Development of sediment slug upstream from the Czorsztyn Reservoir (southern Poland) and its interaction with river morphology

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ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 21 September 2015
Accepted 22 September 2015
Available online 25 September 2015

Keywords:
Sediment storage
Sediment slug
Dam reservoir
Base-level rising

ABSTRACT

The effects of base-level rising upstream of dam reservoirs on in-channel sedimentation and interaction of the stored sediments with the gravel-bed channel morphology have received little attention so far. Previous studies, however, suggested that the feedback mechanism between in-channel sedimentation and bank erosion may affect channel morphology. Here, the pattern of the bar area, bank erosion, and morphology of the gravel-bed Dunajec River upstream from the Czorsztyn Reservoir (CR), constructed in 1997 in southern Poland were analyzed from aerial images (1982–2012) and LiDAR data (2013). In the part of the post-dam period with a large flood, the average bar area increased significantly in the backwater section, and at some distance upstream, and then extended in the upstream direction at an average rate of above 40 m/y, reaching 2.2 km upstream from the CR in 2012. The bar area variation was 40% and 77% explained by local bank erosion in the periods of large and low to moderate floods, respectively. The sum of bank erosion from the post-dam period explained 80% of the variation in the present width/depth ratio, significantly increased in the backwater section. The results showed that the large floods in 1997, in conjunction with backwater inundation, initiated intensive bank erosion and bar growth. Subsequently, in the period with low and moderate floods, the localized bar-bank interaction, connected with the flow divergence around the deposited bar, led to localized bank erosion and additional bar growth promoting bend development. These processes, propagating in the upstream direction, were facilitated by the existence of a large amount of easily remobilized sediment stored in the floodplain connected with the sedimentation zone from the end of the nineteenth century. Bend development was controlled by valley confinement causing downstream bend translation in the narrower valley-confined section and its extension in the wider unconfined section of past sediment storage. The results obtained from this site-specific location imply that the occurrence of similar past sediment storage zones of easily remobilized coarse sediments may favor intensive bank erosion and bar growth during large floods, and in the case of low transport competence backwater zones of gravel-bed rivers where the remobilized sediments cause localized bar growth; it may promote morphologically effective bar-bank interaction in the period with low and moderate floods.

1. Introduction

Dam construction in a river valley causes the upstream base level to rise, which can influence water and sediment transport in the river channel, leading to its morphological adjustment (e.g., Leopold et al., 1964; Maddock, 1966; Lusby and Hadley, 1967; Leopold and Bull, 1979; Van Haveren et al., 1987; Bhowmik et al., 1988; Klimek et al., 1990; Xu, 1990, 2001a,b; Łajczak, 2006; Xu and Shi, 1997; Evans et al., 2007; Skalak et al., 2013; Csiki and Rhodes, 2014; Liro, 2015). Despite the large increase in the number of large dams all over the world in the last century from about 400 to 50,000 (ICOLD, 1988, after Brandt, 2000 and ICOLD, 2007, after Kummu et al., 2010) and their widely recognized downstream effects on channel depositional forms (e.g., Brandt, 2000; Petts and Gurnell, 2005; Grant, 2012), relatively less is known about the development of in-channel sediment storage zones upstream from these structures (Leopold et al., 1964; Knighton, 1998) and the interaction of stored sediments with the gravel-bed channel morphology. However, the sediment storage zones upstream from low-head dams (e.g., Evans et al., 2007; Csiki and Rhodes, 2014) and large dam reservoirs (e.g., Skalak et al., 2013; Liro, 2015) are typically larger than several channel widths and exist in a river channel over a time period above the event scale. The similar, large, spatial-temporal scale depositional forms, or form assemblages associated with the disequilibrium in fluvial systems, are termed by Nicholas et al. (1995) as *sediment slugs*. The slugs may be generated through riverbed or bank erosion (*endoslugs*), or they may be formed by sediments from sources external to the river (*exoslugs*); furthermore, they may be associated with minor (*macroslugs*) or major (*megaslugs*) channel changes, or a major valley-floor adjustment (*superslugs*) (Nicholas et al., 1995). For example, in single-thread, gravel-bed rivers the process-form interaction between deposited bars and channel banks may lead to

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http://dx.doi.org/10.1016/j.geomorph.2015.09.018
0169-555X/

bank erosion (Nicholas et al., 1995; Wathen and Hoey, 1998; Klösch et al., 2015) and result in an increased local channel instability leading to the increased remobilization of floodplain sediments (Jacobson and Gran, 1999), causing channel widening or shallowing (Hoey, 1994; Wathen and Hoey, 1998; Klösch et al., 2015) and bend initiation (Leopold et al., 1964). This bar-bank interaction, in turn, may increase the magnitude of the initial sediment forms (Wathen and Hoey, 1998; Klösch et al., 2015). The over-widened channel with the large bars itself may act as a barrier to sediment transport from the upstream reaches (Hooke, 2003; Fryirs, 2013), and further sediment may be added to its tail resulting in the upstream extension of sedimentation zones in the river channel (Schumm et al., 1984 after Fryirs, 2013). The temporal development of sediment slugs is related to large floods, whereas spatially they are related to the location of past sediment storage in a river valley and to the valley confinement (Hoey, 1994). This implies that the sediment slugs that occurred upstream from a dam reservoir may interact with the local channel morphology, and effects of this interaction may be controlled by floods and by the evolution of the channel and the local valley history, influencing the location of the past sediment storage section and its lateral connectivity with the present channel. Therefore, an analysis of the large-scale in-channel sedimentation forms in gravel-bed rivers upstream from large reservoirs can be useful for the reconstruction of the spatial reach of backwater disturbances in the bedload transport during floods and for analyzing potential linkages between bedform deposition and the related changes of channel morphology (e.g., Nicholas et al., 1995; Wathen and Hoey, 1998). Such an analysis may also detail the information on coarse sediment deposition in the reservoir delta topset that may proceed in the upstream direction (Łajczak, 2006).

A special opportunity for such an analysis exists for the gravel-bed Dunajec River channel upstream from the Czorsztyn Reservoir (CR) constructed in 1997. This channel section has unique database of the aerial images taken in the pre-dam (1982, 1994) and post-dam (2003, 2012) periods at very similar and low river discharges (5.9, 5.7, 4.7, and 9.9 m^3/s, respectively), the LiDAR digital elevation model (2013) and the historical map (1869–1887). This allows a detailed reconstruction of the pattern of in-channel sedimentation upstream from the CR and its morphological effects in the broader context of the local geomorphic history of this specific site, where the sediment storage section existed at the end of the nineteenth century, now, providing the large amount of sediments stored in floodplains that may be easily remobilized by bank erosion. Previous studies conducted in this study area documented significant channel widening during the period with a large flood in 1997 and hypothesized that it may have been an effect of the intensive in-channel deposition and bank erosion caused by backwater effects during the large flood (Liro, 2015). However, a pattern of the development of this in-channel sedimentation zone was not reconstructed, and the potential relationship between in-channel sedimentation and bank erosion and their morphological effects were not quantified. This study goes deeper and aims at quantifying the previously speculated feedback mechanism between in-channel sedimentation and bank erosion and its influence on channel morphology. My specific objectives are the following:

- to reconstruct the temporal and spatial pattern of in-channel sedimentation upstream from the CR,
- to quantify a potential relationship between the bar area and local bank erosion and between bank erosion and channel morphology, and
- to assess the present morphological changes connected with the development of the in-channel sedimentation zone upstream from the CR.

I hypothesize that the trajectory of the temporal-spatial development of the in-channel sedimentation zone upstream from the CR is interrelated with the bar-bank interaction effects and that the present channel morphology in this section may be explained by the effects of these interactions.

2. Study area

2.1. Dunajec River

The analysis was conducted on a 4.5-km-long reach of the single-thread, gravel-bed Dunajec channel upstream from the CR in Polish Carpathians (Fig. 1). The Dunajec River catchment upstream from the CR has an area 1147 km^2 (Sroczyński, 2004) with the elevation ranging from about 600 m asl in the Orawa-Nowy Targ basin to 2655 m asl in the Tatra Mountains (Fig. 1). The catchment consists of resistant metamorphic rocks, granitoids, and less resistant limestones, dolomites, and flysch rocks (Zawiejska and Krzemień, 2004). The hydrological regime of the Dunajec River is controlled by the high-mountain part of the catchments (Kundzewicz et al., 2014), with annual precipitation ranging up to 1700 mm (Niedźwiedź and Obrębska-Starklowa, 1991) and a low retention potential of the bedrock, which facilitates the generation of maximum annual discharges equaling 251.5 m^3/s in 1970–2012, typically occurring during the spring and summer (Kundzewicz et al., 2014).

From the late nineteenth century to the first decades of the twentieth century the Dunajec in the Orawa-Nowy Targ basin had a wide, shallow, active bar-braided channel (Krzemień, 1981; Zawiejska and Krzemień, 2004; Wyżga et al., 2012). Wyżga et al. (2012) indicated that this morphology resulted from the absence of engineering work and that high agricultural and pastoral pressure in the largely deforested catchment, which facilitated high sediment flux during large floods, promoted rapid reworking of the active channel zone and prevented vegetation expansion on the channel bars and on the floodplain. From the mid-twentieth century, the Dunajec River underwent significant narrowing and deepening, and its channel changed from multithread to single-thread (Zawiejska and Wyżga, 2010). This was likely from the river engineering work conducted here from the 1960s to the 1990s (Krzemień, 1981; Zawiejska and Krzemień, 2004), gravel mining, particularly intense in the 1950s and the 1960s (Dudziak, 1965), as well as from the reduction of sediment supply from the catchment caused by environmental and land use changes (Kopacz and Twardy, 2006; Wyżga et al., 2012). No tributaries are in the study section, and the small stream and the erosional-denudational valley on the left side of the valley do not input coarse sediment into the river channel (Fig. 1B). In the part of the study section situated within the inundated backwater, and at some distance upstream, large cut banks and channel bars were mapped in 2014 with a high peak within the segments located at 1.4–2.4 km upstream from the CR (Figs. 1B and 3). A wide, multithread channel existed in this section at the end of the nineteenth century (Figs. 1B and 7), and its extent and past morphology are presently visible in the floodplain relief (Fig. 1B) testifying to the large amount of gravel sediment storage in this section from the end of the nineteenth century. An analysis of aerial photos indicate that the backwater (up to 1.5 km upstream from the CR, see Section 3.1) and at some distance upstream (up to 2.4 km upstream from the CR) channel widening is more than two times greater during a large flood than in the above section (Liro, 2015). The present channel slope of the studied river section changes markedly at the place corresponding to the intersection of the normal water level at the CR (529 m asl) and the channel bed profile at 0.65 km upstream from the CR, from 0.00085 to 0.00405. The channel banks in the studied section are built of a thick bottom gravel layer (1.5–2 m) and a thin upper fine overbank deposit layer (up to 1 m) (Fig. 3). Only up to 0.1–0.2 km from the CR is the fine overbank deposit layer thicker (up to 2.5 m). The banks are covered with riparian forest dominated by willows and planted spruce (Figs. 3 and 7). The riparian forest canopy is less dense in the wider valley floor section (1.4–2.4 km upstream from the CR) than in the upstream. In 2012 the young willow