Catena 153 (2017) 143–156

Contents lists available at ScienceDirect

Catena

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

Dam-induced base-level rise effects on the gravel-bed channel planform

Maciej Liro [1]

Department of Geomorphology, Institute of Geography and Spatial Management, Jagiellonian University in Krakow, Poland

ARTICLE INFO

Article history:
Received 19 July 2016
Received in revised form 12 December 2016
Accepted 7 February 2017
Available online 16 February 2017

Keywords:
Dam reservoir
Base-level rise
Channel narrowing
Fine sediment deposition
Backwater

ABSTRACT

Little is known on the planform evolution of gravel-bed rivers in base-level raised backwater zones upstream from dam reservoirs. The general model of river channel response to base-level rise predicts a decrease in river sinuosity. However, the observations of channel adjustments in the reservoir backwater document a narrower and more sinuous channel developed as a result of fine sediment deposition and vegetation expansion. Here, the long-term aerial photo-based observations (1963–2015) of two gravel-bed rivers of different initial channel pattern (the Dunajec and its tributary, the Smolnik) located in the base-level raised zone of the Rożnów Reservoir in the Polish Carpathians were analyzed. The results show that the initially multi-thread river in backwater was significantly narrowed and its sinuosity increased (*phase 1*), which was followed by the stabilization of channel planform (*phase 2*). However, in the initially single-thread river only *phase 2* occurred. The rate of channel narrowing observed on the initially multi-thread river was positively related to the initial channel width ($R^2 = 0.90$, $p < 0.0001$) and bar width ($R^2 = 0.81$, $p < 0.0001$). The increase in sinuosity was higher in the previously wider channel section and did not occur in the valley-confined zones of the single-thread river. The results are conceptualized in a two-phase conceptual model, which hypothesizes that the trajectories of the long-term planform adjustments of gravel-bed river in backwater are controlled by the initial river morphology which creates accommodation space for fine sediment deposition and associated vegetation expansion.

1. Introduction

Because of significant disturbances to water and sediment transport (Maybeck, 2003; Vörösmarty et al., 2003; Nilsson et al., 2005; Syvitski et al., 2005), dam reservoir construction is one of the most important factors shaping the river valley landscape in the Anthropocene (Syvitski and Kettner, 2011). Despite the large number (>50,000) of large dams (>15 m) operating all over the world (ICOLD, 2007, after Kummu et al., 2010) and the numerous studies documenting the river geomorphic response to these disturbances (e.g., Leopold et al., 1964; Maddock, 1966; Lusby and Hadley, 1967; Leopold and Bull, 1979; Petts, 1979; Van Haveren et al., 1987; Bhowmik et al., 1988; Klimek et al., 1990; Xu, 1990; Xu, 2001a,b; Xu and Shi, 1997; Brandt, 2000; Grant et al., 2003; Petts and Gurnell, 2005; Graf, 2006; Łajczak, 2006; Evans et al., 2007; Grant, 2012; Skalak et al., 2013, 2016; Csiki and Rhodes, 2014; Wiejaczka and Kijowska-Strugała, 2014; Bao et al., 2015; Liro, 2015a, 2016; Raška et al., 2016; Tang et al., 2016), the long-term planform adjustments of gravel-bed rivers in the base-level raised zone of backwater upstream of dam reservoirs are still poorly understood. As a result of precisely defined spatial and temporal extent of the base-level rise, river backwater sections serve as natural field-scale laboratories for reconstructing the channel planform adjustment to the base-level rise, allowing to test the existing models of river planform response to the base-level rise (e.g., Schumm, 1993, 2005; Xu and Shi, 1997; Xu, 2001a), and thus may supplement existing knowledge of the fluvial response to base-level change in general (Blum and Törnqvist, 2000).

The general model of river planform response to the base-level rise assumes that valley slope decrease as a result of the base-level rise-induced sediment deposition, and the river should decrease its sinuosity to maintain the channel gradient necessary to transport sediment load (Schumm, 2005; Fig. 16.3, pp. 153). Contrary to this assumption, observations of fine-grained bed wandering braided or meandering rivers in the base-level of the raised backwater zone document that a narrower and more sinuous channel develops here from a wider, initially multi-thread channel (Xu, 1990, 2001a; Xu and Shi, 1997). This morphology is developed because of the significant deposition of fine sediments and associated vegetation expansion in side channel and on channel bars in backwater (Xu and Shi, 1997) that increase the height and erosional resistance of banks (Xu, 1990, 2001a). Recently Alibert et al. (2011) showed that the river width and sinuosity in the base-level raised section of a semi-alluvial, sandy-pebbly, single-thread river may be stable over time. Schumm (1993) noted that lateral channel confinement (e.g., resulting from valley morphology or the presence of bank structures) is one of the most important factors determining a river's ability to adjust its planform to a base-level change. Specifically, he stressed that, in the case of a laterally confined channel, the vertical

E-mail address: maciej.liro@gmail.com.

[1] Present address: Institute of Nature Conservation, Polish Academy of Sciences, Kraków, Poland, al. A. Mickiewicza 33, 31–120 Kraków, Poland.

http://dx.doi.org/10.1016/j.catena.2017.02.005
0341-8162/

adjustment without a lateral shift may be the only option for channel adjustment to the base-level change (Schumm, 1993; pp. 283).

There is a lack of long-term studies of gravel-bed channel planform adjustments in the base-level raised backwater zone of a dam reservoir, which may allow for verifying the above state-of-the-art in this type of channel. Previous studies on gravel-bed river channel changes in dam reservoir backwater highlighted the role of large floods and intensive in-channel deposition which may have significantly contributed to the channel widening in the early stages of adjustments (up to 20 years since the dam construction) (Liro, 2015a, 2016). However, the observations of later stages of gravel-bed channel adjustments in backwater are still lacking. There is also a lack of studies analyzing flood effects in the course of these adjustments. Furthermore, the dynamic interaction between river morphology and vegetation expansion in gravel-bed rivers has recently been documented in numerous works (for review see Corenblit et al., 2007, 2015; Gurnell et al., 2012; Gurnell et al., 2016; Bätz et al., 2016). In reservoir backwater, the interaction between fine sediment deposition and vegetation expansion was assumed to significantly control channel morphological adjustments (Xu and Shi, 1997). The influence of initial river morphology on the trajectories of these adjustments has not been quantified so far. However, the initial morphology of a river channel in a fluctuating backwater zone may be an important factor controlling the places of fine sediment deposition and further vegetation expansion and the associated trajectories of channel changes in these zones.

To narrow the mentioned gaps in the knowledge of gravel-bed river adjustments in backwater, this paper uses an aerial-photo-based reconstruction (1963–2015) of the river planform from the unique field-scale laboratory, served by two (initially single- and multi-thread) gravel-bed rivers located within the base-level raised zone of the backwater of the same reservoir (the Rożnów Reservoir (hereinafter “the RR”)) constructed in 1941 in southern Poland. The studied sections of these two rivers are situated within the upper part of a delta deposited in the reservoir, where reservoir-induced water level fluctuations occur. The specific objectives and hypotheses (Table 1) of the study are:

- to test the existing models of channel changes in backwater (predicting channel narrowing (H1), and an increase in sinuosity (H2) in backwater as a long-term planform adjustment to dam-induced base level rise (Xu, 1990; Xu and Shi, 1997, Fig. 8, pp. 109)) in gravel-bed rivers, and to compare the obtained results with the predictions from the general model of fluvial response to base level-rise formulated by Schumm (1993, 2005).
- to quantify the influence of initial channel morphology on the course of these adjustments (H1, H2). I hypothesize that a river's ability to narrow its channel in backwater depends on the initial channel width and bar area that provide accommodation space for fine sediment deposition and vegetation expansion on it (H3).
- to explore the morphological effects of large floods on the trajectory of channel planform adjustments in backwater. I hypothesize that morphological effects of large floods (e.g., widening) will be smaller in the lower part of backwater than in its upper part because of higher backwater inundation during floods in this place (H4), which decreases the river flow energy and the ability to cause bank erosion.

Table 1
Hypotheses tested in this study.

H1. Long-term, dam-induced base-level rise promote channel narrowing, and
H2. It's sinuosity increasing.
H3. River ability to narrow its channel in backwater depends on the initial channel width and bar area that provide accommodation space for fine sediment deposition on channel bars and vegetation expansion on it.
H4. Morphological effects of large floods (e.g., widening) will be smaller in the lower part of the backwater than in its upper part because of higher backwater inundation during floods in this place, which decrease the river flow energy and the ability to cause bank erosion.

This study highlights the importance of dam-induced base-level rise for gravel-bed channel morphodynamics, and presents a two-phase model which conceptualizes gravel-bed channel changes upstream from a dam reservoir hypothesizing that initial river morphology is a key factor controlling observed morphological adjustments, and explaining the different trajectories of adjustments between single- and multi-thread gravel-bed rivers.

2. Materials and methods

2.1. The Dunajec and the Smolnik rivers

The study was conducted on two not channelized sections of gravel-bed rivers of different sizes and different initial channel patterns, flowing into the same dam reservoir (the RR), operating since 1941 in the Polish Carpathians. The larger Dunajec River was initially single-thread, whereas the smaller Smolnik River (a tributary to the Dunajec) (Fig. 1A, B) was initially multi-thread. The Dunajec River upstream from the RR drains an area of 4865 km^2 (Sroczyński, 2004), rising in the high-mountain Tatra massif with elevations up to 2655 m asl, and average annual precipitation of up to 1700 mm (Niedźwiedź and Obrębska–Starklowa, 1991). This river's catchment consists of resistant metamorphic rocks, granitoids and less resistant limestones, dolomites, and flysch rocks (Klimaszewski, 1937; Unrug, 1957; Zawiejska and Krzemień, 2004).

The Smolnik River drains an area of 61.5 km^2, with elevations up to 900 m asl, and average annual precipitation reaching up to about 900 mm (Niedźwiedź and Obrębska–Starklowa, 1991). The river's catchment covers mainly the Beskidy middle-mountains underlain by sandstone-shale flysch rocks, and partly the bottom of an intermontane basin filled with gravel and sand-silt deposits.

The average maximum annual discharge of the Dunajec River at the Nowy Sącz gauging station equals 950 m^3/s (the period 1921–2014), and that of the Smolnik River at the Kłęczany gauging station is 116.1 m^3/s (the period 1971–1996) (Fig. 2), with both gauging stations being located above the study reaches upstream from the reservoir backwater influence. The largest floods (defined as those with at least 10-year recurrence interval) on both rivers typically occur between May and August. The Dunajec supplies a considerable amount of suspended load to the RR, particularly in July and June (up to 451,000 tons per month in 1971) (Klimek et al., 1990). The mean annual supply of suspended material during the years 1961–1980 was about 300,400 tons, reaching its maximum (750.000 tons) in 1965 (Klimek et al., 1990).

In the late 19th century the Dunajec River was characterized by a multi-thread channel pattern. Since the end of the 19th century channelization works have been conducted on the Dunajec upstream from the studied section (Zawiejska and Wyżga, 2010). These interventions caused channel narrowing, bed degradation and simplification of the channel pattern. However, due to a considerable catchment sediment supply at that time, connected with environmental conditions and high agricultural and pastoral pressure in the largely deforested catchment (Wyżga et al., 2012, 2016), these works were ineffective and the channel recovered its multi-thread pattern in the mid-20th century (Zawiejska and Wyżga, 2010). In the 1960s new channelization works began and gravel mining activities were intensified causing narrowing of the channel and its deepening by up to 2 m. They also resulted in the channel pattern transformation from the multi-thread to a single-thread one (Zawiejska and Wyżga, 2010). These changes were favoured by a reduction in the sediment supply from the catchment resulting from environmental and land use changes (Kopacz and Twardy, 2006; Wyżga et al., 2012, 2016). An analysis of historical maps, aerial photos and channel regulation projects from the last century, as well as a field inspection showed that channelization works were similarly undertaken on the Smolnik River (upstream from the study site), favouring incision of its channel.