Geomorphology 114 (2010) 326–337

Contents lists available at ScienceDirect

Geomorphology

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

Observations on sediment mobility in a large gravel-bed river

Luca Mao [a,*], Nicola Surian [b]

[a] Department of Geography, University of Hull, Cottingham Road, Hull, HU67RX, UK
[b] Department of Geography, University of Padova, Via del Santo 26, 35123, Padova, Italy

ARTICLE INFO

Article history:
Received 21 April 2009
Received in revised form 29 July 2009
Accepted 30 July 2009
Available online 7 August 2009

Keywords:
Bedload
Painted sediments
Partial transport
Travel distance
Tagliamento River

ABSTRACT

This study investigates sediment mobility in a large gravel-bed river (Tagliamento River, northeastern Italy). Field data were used to identify the morphological effectiveness of a range of flows (floods with recurrence interval <1 to 3.5 year) and for a detailed analysis of the partial transport condition. The analyses were carried out on three cross sections where a number of areas representative of different morphological units (main and secondary channels, low and high bars, islands) were painted. Grain size of the painted area was measured using a photographic method. Monitoring of bed mobility during the study period supplied new photographs of the painted areas, measurements of size and travel distance of the mobilized particles, and estimate of flow depth after each flood event.

Our analyses have shown that with dimensionless shear stress around 0.073 (17 N m^{-2}), the morphological effect over the painted areas was primarily partial transport; while with stresses >0.1 (25 N m^{-2}), the bed experienced full mobility, i.e., all the painted particles were transported or totally buried. Full sediment mobility was observed on lower morphological units (i.e., main and secondary channels) under floods with very high frequency (*RI*<1 y), whereas on the low bars full mobility occurred under floods with a recurrence interval slightly >1 year. Instead, fine deposition and partial transport conditions were observed on the higher bars even after the largest of the monitored floods (*RI* = 3.5 y).

The analysis of the partial transport condition relies on more than 3500 measurements of particle travel distance (travel distances range from a few centimetres up to 22 m). The transported particles were generally finer than the painted sediments, and the analysis of the sediment transport ratio revealed that partial transport occurred under equal-mobility conditions for particles finer than 32 mm and under size-selective mobility for coarser fractions. This appears to be corroborated (for *D*<32 mm) by the insensitiveness of particle transport distance to particle sizes, even if the exponent (≈1) of the relationship between the dimensionless shear stress and the maximum transported diameter would suggest that all fractions are transported under equal-mobility conditions.

1. Introduction

Sediment transport is an essential component of river dynamics; responsible for the erosion and creation of bed forms, and lateral–vertical channel changes, especially in wide and complex gravel-bed river systems. The threshold for particle entrainment needs to be quantified in order to estimate the bedload sediment transport. However, such threshold is complex to quantify and subject to a number of variables (Buffington and Montgomery, 1997). Moreover, even if small particles are more easily entrained because of their small dimensions in comparison with coarser fractions, in the nearly ubiquitous case of bed surface composed by heterogeneous alluvium the coarser grains are more easily transported if surrounded by finer grains because they are more exposed to entraining forces (Andrews, 1983). Based on this evidence, Parker et al. (1982) introduced the equal-mobility theory. The latter states that the threshold conditions for transport are independent of grain size, in contrast to size-selective transport conditions. Though some bedload measurements (Parker et al., 1982; Andrews, 1983; Marion and Weirich, 2003) show that the equal-mobility was the predominant transport mode during near-bankfull and lower flow events, other studies (Ashworth and Ferguson, 1989; Wathen et al., 1995) have emphasized the size-selective nature of the gravel transport approaching equal mobility only during the highest flows.

A further complication in a mixed-size bed is due to the condition of partial transport (Wilcock and McArdell, 1993, 1997), during which some surface sediments in a certain area remain immobile during a transport event. A certain grain size is in a state of partial transport if only a percentage of surface grains of that size are transported (Wilcock and McArdell, 1997). On the contrary, if all the surface grains of a certain size are transported, the condition has been defined as a state of full mobility (Wilcock and McArdell, 1997). Later on, Haschenburger and Wilcock (2003) redefined the partial transport

* Corresponding author. Tel.: +44 1482465349; fax: +44 1482466884.
E-mail address: L.Mao@hull.ac.uk (L. Mao).

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doi:10.1016/j.geomorph.2009.07.015

condition relative to the bed as a whole instead of a certain grain size. Therefore, the partial transport condition can be identified in a portion of the river bed where some grains remain immobile (regardless of their diameter) while others are transported. Using magnetically tagged stones in a small gravel-bed river, they showed that (as flow increases) areas of partial transport become larger at the expense of inactive areas and fully active areas (all grains in motion) replace areas with partial mobility.

In wide gravel-bed rivers, the transport of sediments is very difficult to measure accurately with bedload traps or samplers because of the high heterogeneity of sediment sizes and complex channel topography (i.e., different morphological units). This is especially true during flood events, when most of the bedload transport occurs (Ryan and Dixon, 2008). Also, because bedload samplers are normally handled from bridges, the high spatial variability of bedload transport and the sporadic movements of coarse fractions are difficult to quantify (Ferguson et al., 2002; Hassan and Ergenzinger, 2003). For this reason, tracers have been used in the field to measure travel distance of single particles (Church and Hassan, 1992; Hassan et al., 1992; Pyrce and Ashmore, 2003), incipient motion (Wilcock et al., 1996), downstream particle size fining (Ferguson and Hoey, 2002), and particle motion over large timescales (Ferguson et al., 2002). Displacement of tracers, if combined with a measure of active layer of the bed (estimated with scour chains and cross section resurveys), has been also used to calculate bedload transport (Wilcock, 1997; Liébault and Laronne, 2008).

Various types of sediment tracers have been used in both fluvial and costal environments (Hassan and Ergenzinger, 2003), ranging from painted particles (Leopold et al., 1966; Laronne and Carson, 1976; Petit, 1987; Hassan et al., 1992; Lenzi, 2004), passive magnetic tracers (Ashworth and Ferguson, 1989; Ergenzinger et al., 1989; Church and Hassan, 2002), radio transmitting particles (Ergenzinger et al., 1989; Habersack, 2001), and passive integrated transponders (Lamarre et al., 2005). The painted particles have been extensively used as it is a simple and inexpensive technique allowing the use of a large number of particles and having no limitations on the minimum grain size. On the other hand, the recovery rate is usually low, especially for the smallest particles (Laronne and Carson, 1976), and cannot be feasibly employed to track bedload transport of high magnitude floods and over long periods (Schmidt and Ergenzinger, 1992; Hassan and Ergenzinger, 2003).

This paper reports on a field study conducted on the Tagliamento River (northeastern Italy), a large gravel-bed river where various portions of the bed were spray painted in summer 2006 to gain information on sediment mobility. Flood events of higher magnitude occurred during the following months, allowing the assessment of the increasing morphological effects (from the deposition of fine sediments to the entrainment and transport of painted particles and to the complete erosion of the bed surface layer) on various morphological units (main and secondary channels, low and high bars, islands). Coupling these observations on painted sediments with an analysis of aerial photos (the photos were taken in seven different dates within a period of 10 years) a range of formative discharge was defined for the different morphological units (Surian et al., 2009). Floods with recurrence intervals less than 1 y, 1.1 y and 4–5 y turned out to be formative for channels, low bars and high bars respectively. This companion paper aims to a detailed analysis of sediment mobility (e.g., threshold of motion, travel distance of particles), focusing in particular on the partial transport condition which has been investigated rarely with field-collected data.

2. Study area

The study was conducted in the Tagliamento River, located in the Friuli region in northeastern Italy (Fig. 1). The Tagliamento River has a length of 178 km and a drainage basin of 2580 km^2. Being one of the few European gravel-bed rivers still retaining a highly dynamic nature and ecomorphological complexity from a relatively low human impact (Tockner et al., 2003), the Tagliamento River has been extensively studied as to its ecological properties (Langhans and Tockner, 2006; Tockner et al., 2006); dynamic habitat changes (Van der Nat et al., 2003); invertebrate communities (Arscott et al., 2005; Paetzold et al., 2005); and large woody debris, riparian vegetation, and island dynamics (Gurnell et al., 2001; Gurnell and Petts, 2006; Zanoni et al., 2008).

The mean annual precipitation in the Tagliamento basin is highly variable depending on the position in the basin (Tockner et al., 2003), but ranges around 2000 mm. The Tagliamento River is characterized by a flashy pluvionival flow regime, which results from both alpine and Mediterranean, snowmelt and precipitation regimes. At the Pioverno gauging station (basin area of 1880 km^2), which is the only one with a reliable stage–discharge relationship (period 1932–1973), the maximum and the mean discharges were 4050 and 81 m^3 s^{-1}, respectively (Surian et al., 2009). In the present study, for the description of the analyzed flood events we refer to the Madrisio station, which is located between the surveyed cross sections (without major tributaries joining the Tagliamento between them) and which provides stage measurements at 30-min intervals.

The montane portion of the Tagliamento basin (which features a steep, coarse-bedded stream network) generates a braided, gravel-bedded, and highly dynamic river corridor with a moderate slope (between 0.01 and 0.002 m m^{-1}) for about 90 km. In this reach, the active channel width is up to 2 km, with multiple active channels divided by bare gravels and vegetated islands (Tockner et al., 2003; Zanoni et al., 2008; Surian et al., 2009). The braided reach is followed by a sinuous-meandering, single-thread channel reach where the channel width is about 100-200 m and the bed and bank material is much finer (fine gravels, sand, and silt). In its terminal reach, from Latisana to the mouth, the Tagliamento River eventually flows in a highly confined and artificial channel.

The study has been conducted on three cross sections located in the braided and sinuous-meandering portions of the Tagliamento River (Fig. 1). Two cross sections were measured in the braided reach where the active corridor width ranges from 580 to 850 m and the slope is between 0.002 and 0.004 m m^{-1}. The dynamics of the river in this reach are relatively natural because the levees for flood control are about 1.8 km apart, although other structures (two bridges and some bank protection structures) have some influence on lateral channel mobility. The third section was measured in a sinuous-meandering reach (Fig. 1). The average slope of this reach is about 0.001 m m^{-1}. As in the braided reach, the river dynamics are relatively natural because the main levees are far apart (1.2–1.4 km), although some bank protection are present.

3. Methods

3.1. Cross section survey and identification of morphological units

Two of the measured cross sections (named 130 and 136) are located in the braided reach, and one (section 102) is in the sinuous-meandering reach (Fig. 1). Their locations replicate the position of the monumented cross sections measured since 1970. The cross sections were surveyed in June–July 2006 with a total station (Fig. 2).

Morphology of the active channel along each cross section was classified into one of the following units: main channel (MC), secondary channel (SC), low bar (LB), high bar (HB), and island (I). Table 1 provides images and a brief description for each of them. The field recognition of those units is not always straightforward but was based on a combination of elevation, bed material, and vegetation cover criteria. The use of vegetation is justified by the strong relations between vegetation characteristics (e.g., species and density) and fluvial landforms (e.g., Hupp and Osterkamp, 1996; Gurnell et al., 2001; Gurnell and Petts, 2006; Hupp and Rinaldi, 2007).