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Evaluating short-term morphological changes in a gravel-bed braided river using terrestrial laser scanner

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ABSTRACT

Braided rivers are dynamic and complex environments shaped by the balance of the flow and sediment regimes and by the influence of the riparian vegetation and disturbances such as floods. In particular, the balance between sediment supply and transport capacity can determine the morphological evolution of a river. For instance, aggrading and widening trends are distinctive of reaches where sediment supply is higher than transport capacity. In contrast, incising and narrowing tendencies are dominant. The aim of the present study is to analyze the short-term morphological dynamics and the processes of erosion and sediment deposition along a small reach of a relatively unimpacted gravel-bed braided river (Tagliamento River, northeast Italy) using a terrestrial laser scanner (TLS). The study area is around 23 ha and has been surveyed before after two periods with relevant flood events, two of which were higher than the bankfull level and occurred between September 2010 and September 2011. The very high point clouds density allowed us to derive three high resolution digital elevation models (DEMs) with 0.125 × 0.125 m pixel size. Scan data cloud merging was achieved with an overall high degree of accuracy and resolution (subcentimeter). Topographic data were more accurate for exposed surfaces than those collected in wet areas. A detailed net of dGPS control points allowed us to verify the high quality of the DEMs derived from the surveys (RMSE of about 5 cm). Two DEMs of difference (DoD) were computed, revealing different and consistent episodes of erosion and deposition within the analyzed area, and changes in morphology of channel and bars could also be detected, such as bar edge accretion and bank erosion demonstrating a strong dynamicity of the Tagliamento River. Moreover, a very detailed estimation of the surface roughness in the study area has been carried out, permitting a large-scale analysis of the roughness values distribution. The results of the analysis on the TLS collected data show that along a river with a high natural character (i.e., Tagliamento River), the dynamic processes are also common during low magnitude events.

1. Introduction

Braided rivers are characterized by flowing in at least two alluvial channels, separated by bars and islands as to produce a multithreaded platform (Leopold and Wolman, 1957). These fluvial systems are the most dynamic among alluvial rivers (Brierley and Fryirs, 2005). Braiding, from a hypothetical straight channel, occurs by four different processes: deposition and accumulation of a central bar, chute cutoff of point bars, conversion of single transverse unit bars to mid-channel braid bars, and dissection of multiple bars (Ashmore, 1991). A high morphological complexity arises from the coexistence of several spatial structures, controlled by different spatiotemporal scales interacting in the development of the braided pattern, giving rise to strong fluctuations both in time and in space (Bertoldi et al., 2009). Gravel-bed braided rivers are very dynamic systems and in this context even ordinary flood events can trigger morphologically active processes. Channel evolution is a response to fluctuations and changes of runoff and sediment supply involving mutual interactions among channel form, bed material size, hydraulic forces (Lisle et al., 2000), riparian vegetation (Picco et al., 2012b), and islands (Picco et al., 2012a).

Field studies provided an important insight into braided river mechanics (Ashworth and Ferguson, 1986; Ashworth et al., 1992; Ferguson et al., 1992), but these investigations have suffered from poor spatial and temporal sampling resolution of hydraulic, morphologic, sediment transport, and bed grain size variables (Ferguson, 1993). During the early 1990s, several studies based on field investigations were focused on processes occurring at the chute-bar, or confluence scale (Ashworth et al., 1992; Ferguson et al., 1992; Lane and Richards, 1998). Recent advances in survey equipment and software allowed high resolution digital elevation models (DEMs) to be constructed. This new generation of DEMs is able to represent accurately earth's surface (Tarolli et al., 2009) and offers an excellent opportunity to measure and monitor morphological change across a

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variety of spatial scales (Brasington et al., 2000; Lane and Chandler, 2003; Heritage and Hetherington, 2007; Hicks et al., 2007; Fuller et al., 2009). Coupled with this, the development of topographic survey techniques, i.e., airborne and terrestrial LiDAR (light detection and ranging), electronic distance measuring device (EDM) theodolites, global positioning system (GPS), photogrammetry, and spectrally based bathymetry has led to an increase in the amount of data collected during fieldwork in a riverine environment, offering new insights into fluvial dynamics (Lane et al., 1994; Milne and Sear, 1997; Heritage et al., 1998; Brasington et al., 2000; Heritage and Hetherington, 2007; Marcus and Fonstad, 2008; Fuller et al., 2009). Developments in the methods used to obtain high resolution morphological data sets in river environments include synoptic remote sensing (Lane et al., 2003), CDW (close range digital workstation) photogrammetry at the bar scale (Heritage et al., 1998), photogrammetry in flumes (Ashmore et al., 2000; Lindsay and Ashmore, 2002; Marcus and Fonstad, 2008), total station survey (Fuller et al., 2003, 2009), surveys using real time kinematic GPS (RTK-GPS) (Brasington et al., 2000, 2003), airborne LiDAR (Thoma et al., 2005; Cavalli et al., 2008; Höfle et al., 2009; Cavalli and Tarolli, 2011; Moretto et al., 2012), and terrestrial laser scanner (TLS) (Williams et al., 2011). Among the mentioned techniques, airborne LiDAR (Charlton et al., 2003; French, 2003) offers the possibility to carry out fast and accurate topographic surveys of large areas at a relatively affordable cost. Different authors have shown that, thanks to the advances in the survey technologies, during the last years there was a remarkable increase in spatial extent and resolution related to topographic data acquisition (Lane and Chandler, 2003; Heritage and Hetherington, 2007; Milan et al., 2007; Marcus and Fonstad, 2008; Notebaert et al., 2009; Wheaton et al., 2010a). These advances make monitoring geomorphic changes and estimating sediment budgets through repeat topographic surveys and the application of the morphological method (Church and Ashmore, 1998) a tractable, affordable approach for monitoring applications in both research and practice.

The calculation of difference between subsequent DEMs (difference of DEMs, DoD) is a commonly applied method to analyze and quantify channel change. It allows us to analyze, with a high level of resolution, topographic and volumetric changes during a certain time interval (Brasington et al., 2003; Rumsby et al., 2008) and to identify areas of scour and fill (Lane et al., 2003). The DoDs also allow us to assess changes in sediment storage, to improve sediment budget analysis at the reach scale (e.g., Merz et al., 2006), and to study fluvial processes (Wheaton et al., 2010b). Most of the studies based on the DoD analysis are relative to temporal scales shorter than a decade because of the recent field survey made with improved remote sensing techniques (Heritage et al., 2009). Unfortunately, the computation of DoDs is usually biased by different sources of uncertainty that strongly influence the calculation of depositional and erosional volumes (Wheaton, 2008). In fact, DEMs are affected by errors such as point quality, sampling strategy, surface composition, topographic complexity, and interpolation methods (Lane et al., 1994; Lane, 1998; Wise, 1998; Wechsler, 2003; Hancock, 2006; Wechsler and Kroll, 2006; Wise, 2007). An approach to assessing spatially variable uncertainty in DoDs was presented by Wheaton et al. (2010a,b) and is based on the creation of a fuzzy inference system (FIS) that permits us to combine individually errors of different sources. Heritage et al. (2009) and Milan et al. (2011) also developed a method to assess uncertainty based on the surface roughness. Heritage et al. (2009) and Wheaton et al. (2010a, b) showed that the higher uncertainty values are obtained in areas with higher topographic variability and lower point density. On the other hand, flat areas with high point density featured the lowest uncertainty. The aims of the present research are (i) to recognize and assess the morphological changes occurred over two short periods characterized by ordinary flood events along a subreach of a low impacted gravel-bed braided river (Tagliamento River, Italy); (ii) to develop a novel approach with the fuzzy inference system to improve the change detection analysis using TLS technology; and (iii) to derive surface roughness maps along different geomorphic units from highly detailed surveys.

2. Study area

The Tagliamento River is located in the southern Alps of northeast Italy. Its headwater originates at 1195 m above sea level (asl) and flows for 178 km to the northern Adriatic Sea, thus forming a linking corridor between Alpine and Mediterranean zones. Its drainage basin covers 2871 km^2 (Fig. 1). The river has a straight course in the upper part, while most of its course is braided shifting to meandering in the lower part where dykes have constrained the lower 30 km, so that it is now little more than an artificial channel about 175 m wide. However, the upper reaches are mostly intact, so basic river processes (e.g., flooding or erosion and accumulation of sediment) take place under near natural conditions. A strong climate gradient exists along the length of the river that has great influence on precipitation, temperature, humidity, and consequently vegetation patterns. Because of the climate gradient, the floodplain of Tagliamento is an important biogeograpghical corridor with strong longitudinal, lateral and vertical connectivity, and high habitat heterogeneity, a characteristic sequence of geomorphic types and a very high biodiversity (Tockner et al., 2003).

The hydraulic regime, connected to the climatic and geologic conditions of the upper part, is characterized by flashy pluvio-nival flow conditions (Tockner et al., 2003). The Tagliamento River is considered by different authors as the most intact and natural river in the Alps (Lippert et al., 1995; Müller, 1995; Ward et al., 1999), and it can be considered not only as 'a reference ecosystem for the Alps but also as a model ecosystem for large temperate rivers' (Tockner et al.,

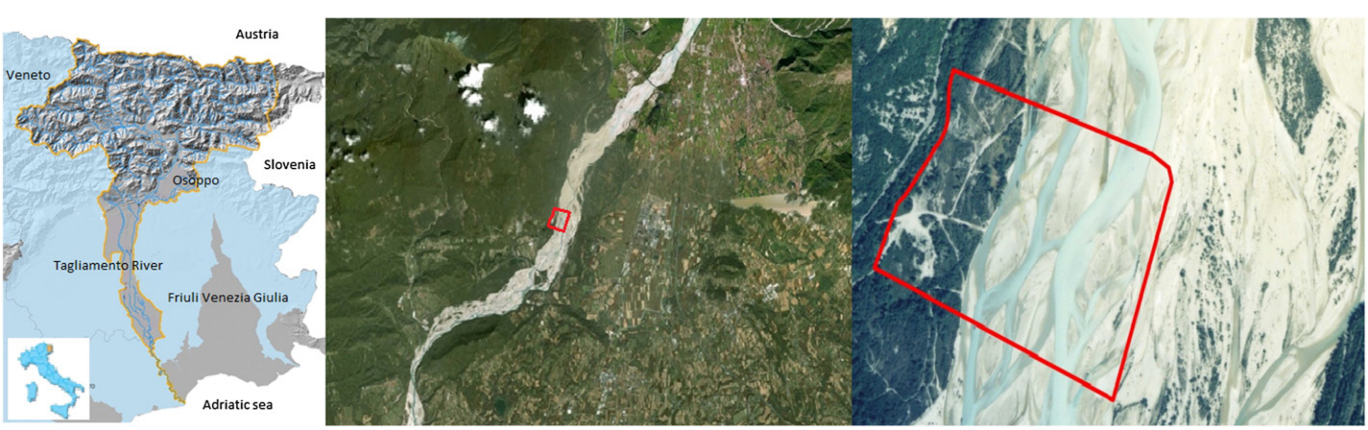

Fig. 1. The Tagliamento River basin (on the left), the study area localization (in the middle), and the entire study area analyzed (on the right). Flow direction is down the page.