Using a Terrestrial Laser Scanner to assess the morphological dynamics of a gravel-bed river

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Abstract Braided rivers are dynamic and complex environments shaped by the balance of the flow, sediment regimes and the influence of the riparian vegetation. The balance between sediment supply and transport capacity determines the morphological evolution of a river. The aim of the study is to analyse the short-term morphological dynamics and the processes of erosion and deposition along a sub-reach of a low impacted gravel-bed braided river (the Tagliamento River, Italy) using a Terrestrial Laser Scanner (TLS). The device used is a pulsed TLS able to collect up to 50 000 points per second at a spatial resolution up to one point per mm^2. The study area is around 23 ha and has been surveyed before and after significant floods of recurrence interval approx. 15 years and 12 years. The differences of the two DEMs (DoD) computed revealed consistent episodes of erosion and deposition within the analysed area, showing a strong dynamic of the Tagliamento River.

Key words difference of DEMs (DoD); Terrestrial Laser Scanner (TLS); fluvial systems; morphological changes; Tagliamento River, Italy

INTRODUCTION

Braided rivers are characterized by a highly dynamic response to both natural and human-induced changes in their drainage basins (Comiti *et al.*, 2011). Starting from a hypothetical straight channel, braiding involves four different processes: deposition and accumulation of a central bar, chute cutoff point bars, conversion of single transverse unit bars to mid-channel braid bars, and dissection of multiple bars (Ashmore, 1991). High morphological complexity arises from the coexistence of several spatial structures and gives rise to strong fluctuations both in time and in space (Bertoldi *et al.*, 2009). Gravel-bed braided rivers are very unstable and even “ordinary” flood events can result in active morphological processes. Channel evolution is a response to runoff and sediment supply involving various interactions among channel form, bed material size, hydraulic forces (Lisle *et al.*, 2000), riparian vegetation (Moretto *et al.*, 2012a,c) and fluvial islands (Picco *et al*., 2012a,b).

Field studies have provided an important insight into braided river mechanics (Ashworth & Ferguson, 1986; Ashworth *et al.*, 1992; Ferguson *et al.*, 1992), but these investigations have often suffered from poor spatial and temporal sampling resolution of hydraulic and morphological variables such as sediment transport and bed grain size (Ferguson, 1993). During the early 1990s, several studies based on field investigations focused on the processes occurring at the chute-bar or in confluence scale (Ashworth *et al.*, 1992; Ferguson *et al.*, 1992; Lane & Richards, 1998), possibly reflecting the difficulties in obtaining data sets over larger spatial ranges (Milan *et al.*, 2007).

Recent advances in spatial analytical equipment and software allowed high-resolution Digital Terrain Models (DTMs) to be constructed. This new generation of DTMs accurately represents landform surface variability and offers an excellent opportunity to measure and monitor morphological change across a variety of spatial scales (Brasington *et al.*, 2000; Lane & Chandler, 2003; Fuller *et al*., 2005; Heritage & Hetherington, 2007; Hicks *et al.*, 2008). Coupled with this, the development of topographic survey techniques, i.e. airborne and terrestrial LiDAR (light detection and ranging), EDM theodolites, GPS, photogrammetry, has led to an increase in the amount of data collected during fieldwork, offering new insights into fluvial dynamics (Lane *et* *al*., 1994; Milne & Sear, 1997; Heritage *et al*., 1998; Brasington *et al*., 2000; Fuller *et al*., 2005, Heritage & Hetherington, 2007). 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 & Ashmore, 2002), total station survey (Fuller *et al*., 2003, 2005), surveys using real-time kinematic global positioning systems (RTK-GPS) (Brasington *et al*., 2000, 2003), airborne LiDAR (Thoma *et al*., 2005; Cavalli *et al*., 2008; Hofle *et al*., 2009; Moretto *et al*., 2012b) and Terrestrial Laser Scanner (TLS) (Williams *et al*., 2011). RTK GPS technology permits around 3000 observations per day to be obtained, which allowed Brasington *et al*. (2003) to achieve a survey density of 12–17 pts m^{-2} on the River Feshie. 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. Wheaton *et al*. (2010a) show recent advances in ground-based, boat-based and remotely-sensed surveying technologies, and the rapid acquisition of topographic data is now possible at spatial resolutions and extents previously unimaginable (Lane & Chandler, 2003; Heritage & Hetherington, 2007; Milan *et al*., 2007; Marcus & Fonstad, 2008; Notebaert *et al*., 2009). These advances make monitoring geomorphic changes and estimating sediment budgets through repeat topographic surveys and the application of the morphological method (Church & Ashmore, 1998) a tractable, affordable approach for monitoring applications in both research and practice.

The aims of the present research are to recognize a response dynamic along a sub-reach of a low impacted gravel-bed braided river (the Tagliamento River) and to analyse the morphological changes occurring after ordinary flood events in a short period using Terrestrial Laser Scanner (TLS) technology.

STUDY AREA

The Tagliamento River is located in the southern Alps of northeast Italy. It originates at 1195 m a.s.l. and flows for 178 km to the northern Adriatic Sea, thereby forming a link corridor between the Alpine and the 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 it is now little more than an artificial channel about 175 m wide. However, the upper reaches are more-or-less intact, thus the basic river processes, such as flooding and the erosion and accumulation of sediment, take place under near-natural conditions. A strong gradient exists along the length of the river which has a big influence on precipitation, temperature, humidity and consequently vegetation patterns. Because of the climate gradient, the floodplain of the Tagliamento is an important biogeographical corridor with a strong longitudinal, lateral and vertical connectivity, high habitat heterogeneity, a characteristic sequence of geomorphic types and very high biodiversity (Tockner *et al*., 2003).

The hydraulic regime of the Tagliamento River is characterized by irregular discharge and high sedimentation load, due to the climatic and geological conditions of the upper part. The river is considered as the last morphologically intact river in the Alps, and therefore constitutes an invaluable resource, not only as a reference ecosystem for the Alps, but also as a model ecosystem for large temperate rivers. In fact the extensive vegetated islands and gravel bars are key indicators of its natural conditions, while engineering work for flood control or navigation has eliminated such features in most European water courses.

An area of about 23 ha, located along a piedmont stretch of the Tagliamento River in a flood-plain called *Campo di Osoppo,* near the village of Forgaria nel Friuli (Udine province), has been surveyed (Fig. 2).

This floodplain consists of a sedimentary layer with pronounced granulometric variability (from fine sand to large pebbles). In this stretch, the river has a braided channel configuration with a significant presence of side bars, longitudinal bars and islands. The islands have been colonized by stands of willow trees of maximum age 5–7 years.

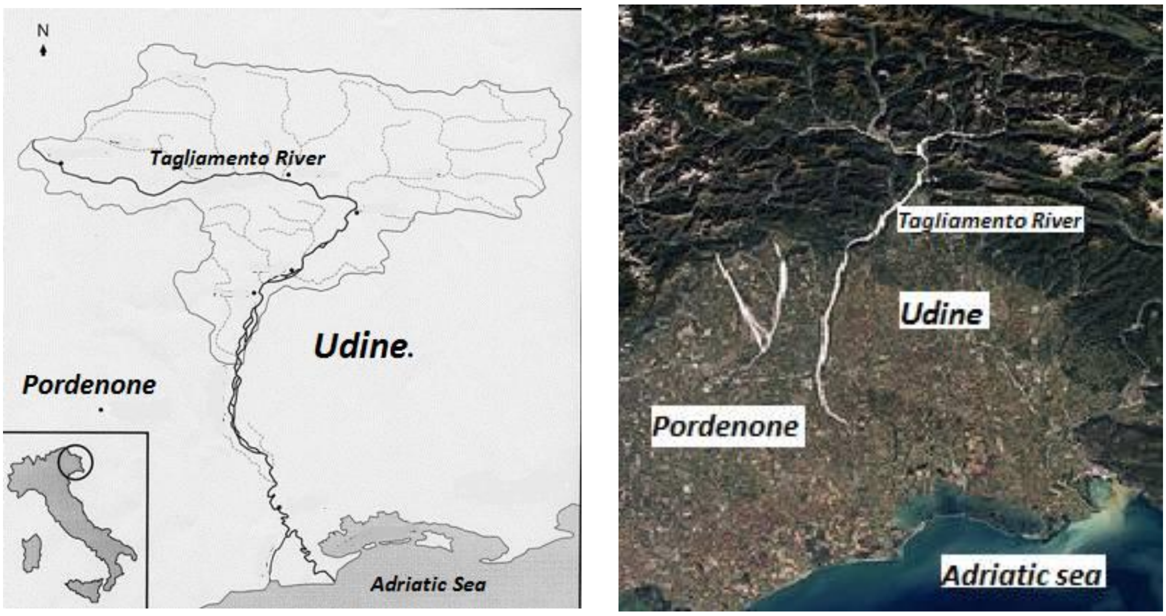

Fig. 1 The Tagliamento River basin.

Fig. 2 The study area location (left) and the entire study area analysed (right).

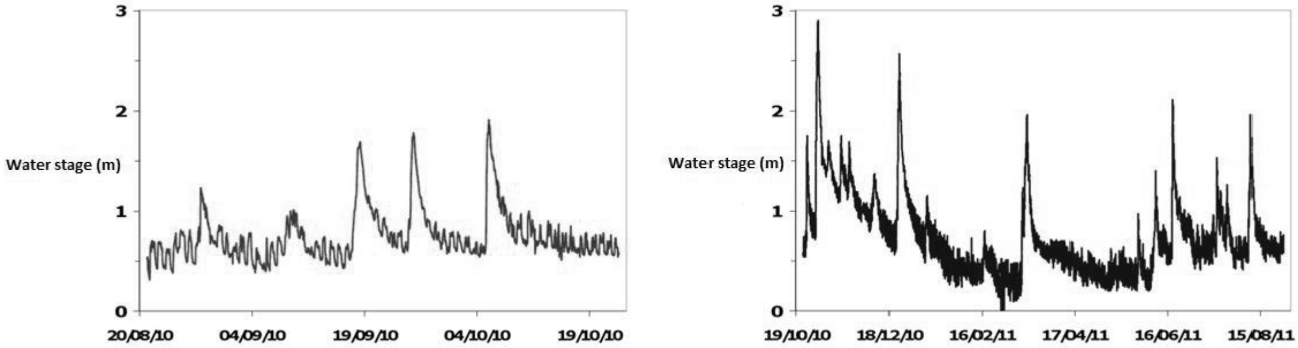

Fig. 3 Flood events occurred during the study period along the Tagliamento River; three significant events during the first period (left) and five during the second period (right).

Flood events along the Tagliamento River were recorded during the study period. Between the first two scan acquisitions there were three significant floods with return intervals (RI) of around 12 years, while between the second and the third scan acquisition there were five different flood events, two with RI of around 15 years and the other three with RI of around 12 years (Fig. 3).

MATERIALS AND METHODS

Three surveys of the study area were carried out using a Leica ScanStation2 TLS. The TLS used is a pulsed one with a high-speed bi-axial compensator, characterized by precision of 6 mm on position and 4 mm on distance (for 100 m scan radius), maximum range of 300 m, a scan speed up to 50 000 points per second, and maximum scan density less than 1 mm. The number of scan stations depends directly on the complexity of the area, the presence of vegetation, LW accumulations and strong topographic gradients. A single survey requires about 4–5 working days. Individual scans were registered, georeferenced and filtered through removing vegetation and LW from raw data. The main characteristics of the three data acquisitions are listed in Table 1.

Table 1 Main characteristics of data acquisition.

Survey	Period	Duration	No. of scans	Point density (radius distance)	Scan radius	Scan area	No. of points (filtered cloud)
T1	August 2010	5 days	21	Grid 0.05 m × 0.05 m	Variable, from 70 to 120 m	25.6 ha	19 million
T2	October 2010	5 days	38	Grid 0.05 m × 0.05 m	Variable, from 70 to 120 m	23.3 ha	28.5 million
T3	September 2011	4 days	27	Grid 0.05 m × 0.05 m	150 m	23.3 ha	51.5 million

Point clouds were imported into ArcGIS 10 (ESRI, 2011) and processed to obtain the DTM of the surveyed area. The average density of point clouds allow us to create DTMs with a cell size of 15 cm. The error analysis yielded the following mean values: 0.055 m on DTM T1 (August 2010), 0.062 m on DTM T2 (October 2010) and 0.026 m on DTM T3 (September 2011). The analyses of volumetric changes were done using a plug-in for ArcGIS software called Geomorphic Change Detection (GCD) (Wheaton *et al*., 2010a,b). The GCD calculates positive and negative volumetric changes, net changes and surfaces of variation, and provides DoD (Difference of DTM) maps showing the spatial pattern of the morphological changes. The method uses fuzzy logic inference on the values of three parameters (slope, roughness and survey point cloud density) to obtain a level of uncertainty. The uncertainty is then applied back to the DoD to discriminate the variations. An important step in the method is to define the rules of the fuzzy inference system. It was necessary to change the default rules when processing the TLS survey data using this method. The input classes were adapted to the range of our data, Slope: low 0–10%, medium 5–20%, high 15–1000%; Roughness: low 0–0.008, medium 0.002–0.256, high 0.064–1.0; Point density: low 0–1 pt/m^2, medium 1–36 pt/m^2, high 36–10 000 pt/m^2.

Roughness was derived directly from the DTMs following the approach developed by Cavalli *et al*. (2008). Relation rules were based on default values but assigning greater importance to high density of point clouds. Output uncertainty classes were set according to the following considerations: low class as error on point clouds (maximum average registration error), medium class according to the maximum average error of the DTM, high class as the height of the lower bars in the riverbed, extremely high class as the height of the highest deposits. Therefore, our classes were set: low 0–0.007 m, medium 0.005–0.08 m, high 0.07–0.5 m, and extremely high 0.45–1.5 m.

RESULTS

Difference of the DEMs (DoD)

The fuzzy interference system analysis resulted in a series of raster of uncertainty associated with each of the three scans (Fig. 4). The uncertainty is relatively high (0.08 to 0.5 m class) within the channels, especially for the floodplain on the right-hand side, which has not been affected by morphological changes from one scan to the others. The areas belonging to channels and bars are characterized by medium to low uncertainty. As expected, the areas with particularly low

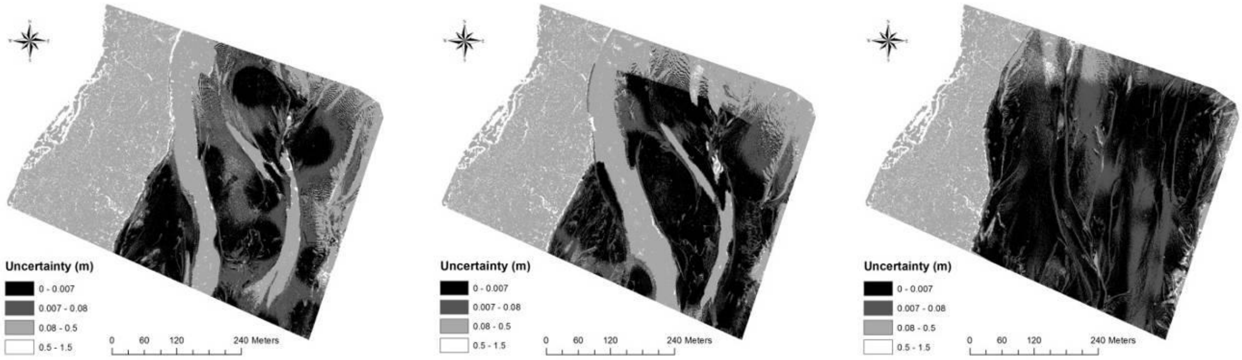

Fig. 4 Uncertainty levels derived from the fuzzy interference system for T1 (left), T2 (middle) and T3 (right).

uncertainty are located where the density point is higher than or close to the points where the laser scanner was placed. The levels of maximum, minimum and standard deviation uncertainty are quite comparable for the three scans, at about 0.99, 0 and 0.21 m, respectively.

The DoD obtained using the fuzzy approach by comparing T1 and T2 shows considerable changes, especially near the floodplain and within the active channels (Fig. 5). As shown by the graph relating volume changes to vertical adjustments, erosion has been the most important process between T1 and T2. The DoD obtained by comparing scans T2 and T3 (Fig. 6) reveals that erosion and deposition processes were quite balanced, and also in volumetric terms. Table 2 presents a synthesis of the volumetric variations calculated using the fuzzy interference system analysis. The averaged vertical elevations of the DoD indicate a dominance of erosion in T1–T2 (–0.62 m) and a dominance of deposition in T2–T3 (+0.23 m). Equally, the volumetric net change is negative in T1–T2 (–80 662.6 m^3) and T1–T3 (–54 672.9 m^3), and positive in T2–T3 (34 887.2 m^3). Maximum and minimum erosional changes are related to T1–T2 (83 655.3 m^3) and T2–T3 (35 537.5 m^3), whereas maximum and minimum depositional changes are related to T2–T3 (70 424.8 m^3), and T1–T2 (35 537.5 m^3), respectively. The maximum extent of areal change occurred between T1 and T2, occupying the half of the entire surveyed surface (120 557 m^2).

Bank erosion

The considerable erosion experienced by the right bank of the main channel is definitely the most relevant morphological change that occurred during the study period. In order to investigate in detail the erosion process between the surveys, four cross-sections were chosen from the DTMs of

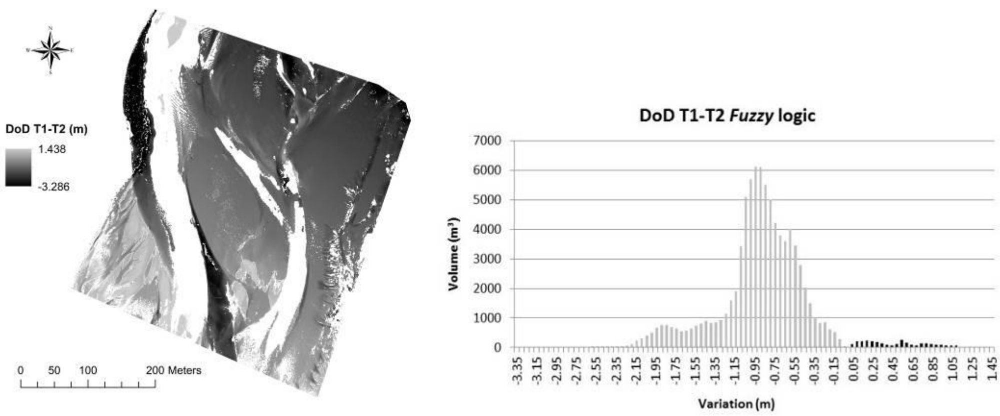

Fig. 5 DoD obtained comparing T1 with T2 (left), and volume changes associated with ranges of elevation of the D0D T1–T2 (right).

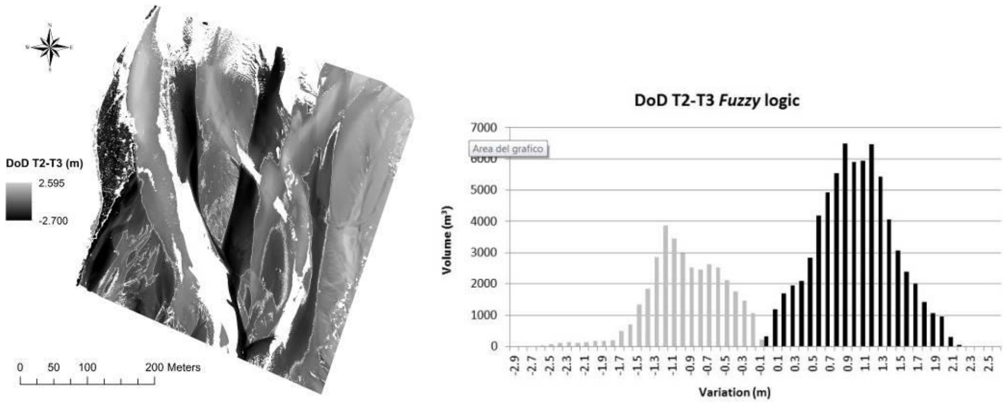

Fig. 6 DoD obtained comparing T2 with T3 (left), and volume changes associated with ranges of elevation of the DoD T2–T3 (right).

Table 2 Summary of T1–T2 and T2–T3 DoDs obtained using the interference system analysis.

Parameter	T1–T2	T2–T3
Maximum deposition (m)	1.44	2.6
Maximum erosion (m)	–3.29	–2.7
Average vertical change (m)	–0.62	0.23
Standard deviation of DoD (m)	0.46	0.82
Volume of deposition (m^3)	2 992	70 424
Volume of erosion (m^3)	83 655	35 537
Volume change (m^3)	–80 662	34 887
Area with deposition (m^2)	10 391	91 442
Area under erosion (m^2)	120 557	57 328

the three scans (Fig. 7). Along section DA (Fig. 8), from T1 and T2 the bank suffered 20 cm of erosion (2 m deep) and the channel experienced 0.5 m of deposition. The scan taken at T3 shows that along the DA the bank experienced a further 20 m of erosion with 2 m depth (portion a). In the cross-section DB (Fig. 8) the erosion on the right bank was even more obvious (35 m long, 1.9 m deep, portion b), whereas in the channel there was 0.5 m of sediment deposition. The tendency was reversed between T2 and T3 in the section DB. The erosion extended a further 35 m, but sediment deposition of 0.5 m depth occurred along the whole eroded portion b of the section. The section DC shows approx. 20 m of 1-m-deep erosion (portion a) between T1 and T2, which increases to 60 m between T2 and T3 (portion a), but sediment deposition occurred on the previously eroded area (portion b). The cross-section DD was relatively stable between T1 and T2, has up to 1.5 m deep, 60 m long erosion between T2 and T3 (portion a of the section).

DISCUSSION AND CONCLUSIONS

The goals of the present paper were (i) to analyse morphological changes in a 23 ha portion of the Tagliamento River, assessing erosion and deposition processes, and (ii) to quantify the bank erosion activity. The main issue related to the collected data has been the relatively low point density obtained along the wetted areas, due to the laser scanner's difficulty in recognizing the submerged areas. Various authors (Heritage & Hetherington, 2007; Milan *et al*., 2007) showed that the elevations of wetted areas as surveyed by TLS are affected by significant errors. Cavalli & Tarolli (2011) and Lollino *et al*. (2008) show that, in some cases, the use of bathymetric LiDAR or sonar could solve the issue. Due to the very shallow water (>1 m) in the study reach of the Tagliamento River, the bathymetric LiDAR could not detect the channel bed. Instead, bathymetric mapping (Williams *et al*., 2011) could have served this use. In this study, after the TLS surveys,

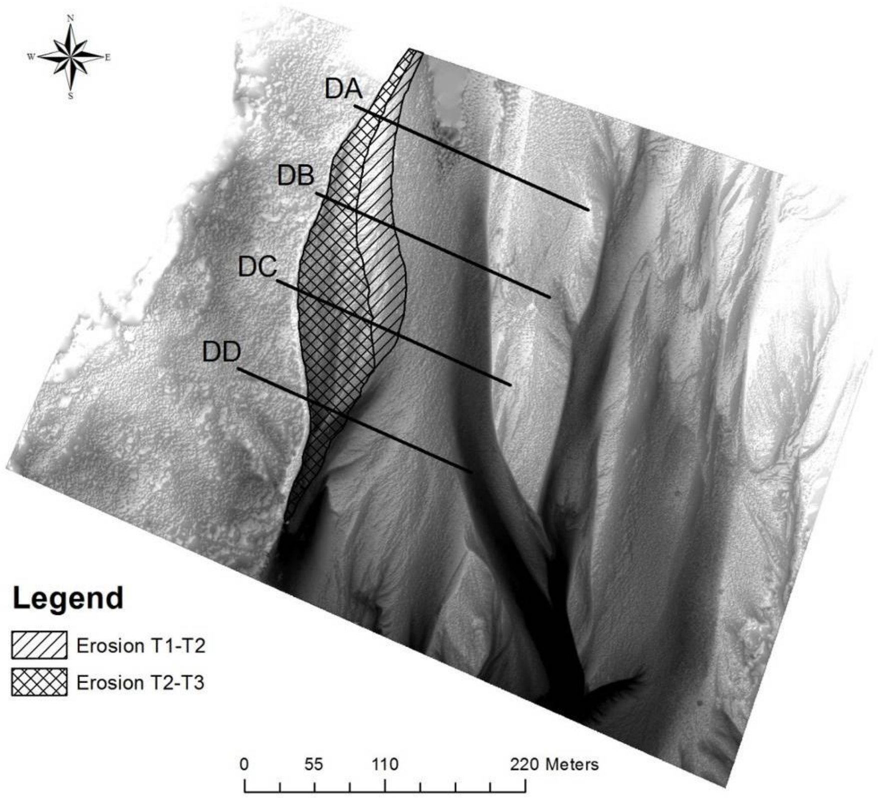

Fig. 7 Cross-sections selected to study bank changes. The flow is from north to south.

some points were collected (241 points for T1 and 2219 points for T2) in the wetted areas using a DGPS in order to complete the survey. However, due to the lower spatial density of points in the wetted areas, the final cell size of the DTM was chosen to be 15 cm. The lower point density in the wetted areas implies higher levels of uncertainty along the water stage lines (see Fig. 4). Thanks to the calibrated fuzzy analysis and the GCD plug-in (Wheaton *et al.*, 2010a,b), it was possible to analyse in detail the morphological variations before and after the flood events. A clear difference between the DoDs (T1–T2, and T2–T3) was observed, with a dominance of erosional processes occurring during the first study period, and a consistent but lower depositional tendency during the second period. This evidence allows better understanding of the processes ongoing in the Tagliamento River, which are particularly dynamic and active. Erosion and deposition occurred at the patch scale over the whole study area. Clear and consistent erosion was observed only along the right bank. During the first study period (T1–T2) the bank erosion was lower than during the second study period (T2–T3), likely due to the initial resistance of the bank to erosion and bending. Also, in the upper part of the bank there was dense riparian vegetation of some trees and a few shrubs that certainly helped to stabilize the bank. After the vegetation was removed, the bank was more easily eroded during the second study period. According to various authors (i.e. Simon & Collison, 2002; Van de Wiel & Darby, 2007; Picco *et al.*, 2012c), the role of vegetation in mediating the morpho-dynamics of wide river systems is very important, because the type and size of riparian vegetation play a crucial role in increasing bank strength against erosion.

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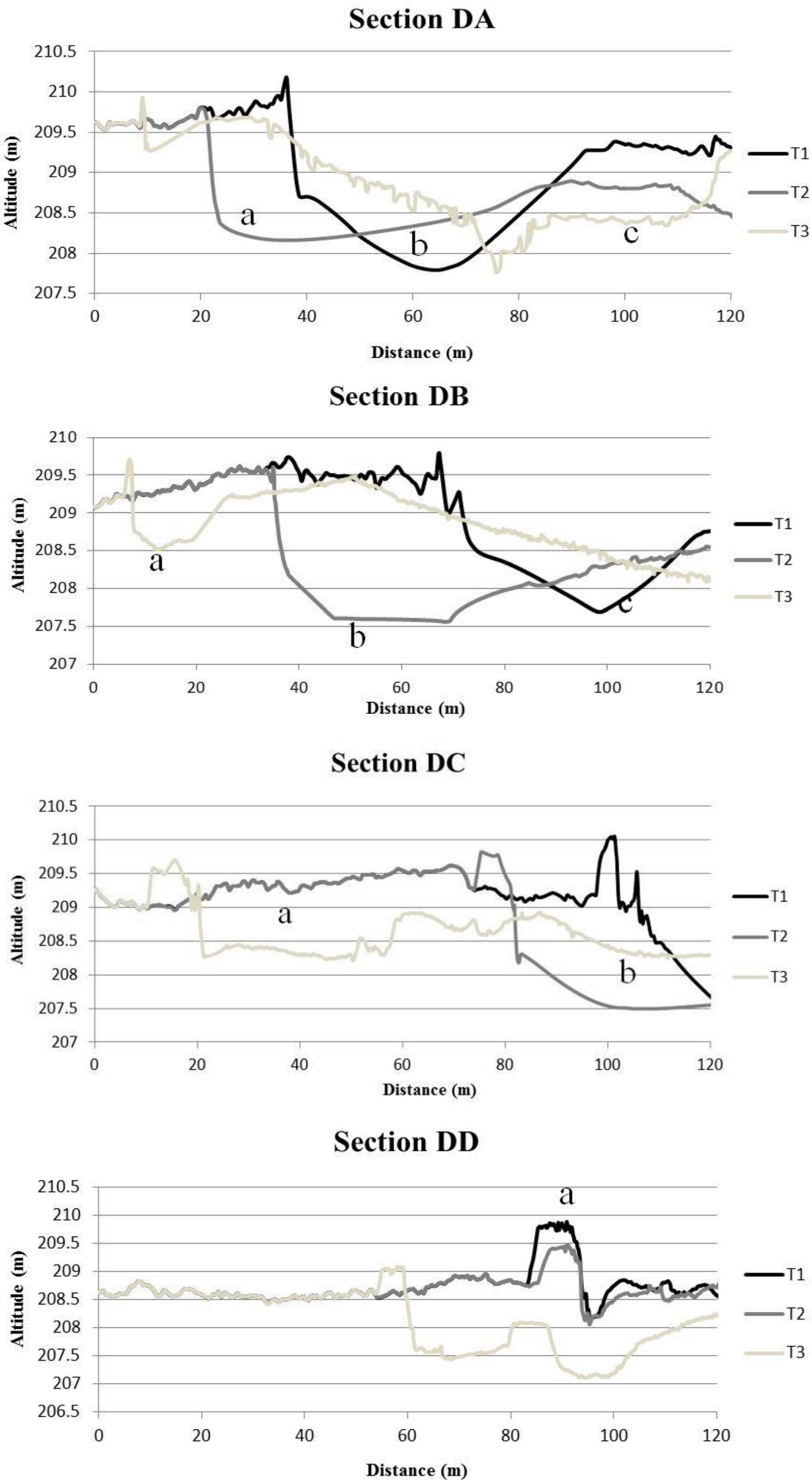

Fig. 8 Temporal changes experienced between the scans by the cross-sections selected as shown in Fig. 7.

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