Journal of Agricultural Engineering 2013; volume XLIV(s2):e15

Evaluation of short-term geomorphic changes along the Tagliamento river using LiDAR and terrestrial laser scanner surveys

R. Rainato,[1] L. Picco L,[1] M. Cavalli,[2] L. Mao L.,[3] F. Delai,[1] D. Ravazzolo,[1] M.A. Lenzi[1]

[1]Department of Land, Environment, Agriculture and Forestry, University of Padova, Italy; [2]CNR-IRPI, Padova, Italy; [3]Department of Ecosystems and Environment, Pontificia Universidad Catolica de Chile, Santiago, Chile

Abstract

In the recent years a change in the predominant morphology of several river environments has taken place, consisting in a reduction of the braided pattern in favor to wandering or straight configurations. This evolution seems to be due, according to the scientific community, to anthropic causes and, in particular, to the alteration of flow regimes as well as the reduction of sediment transport. Braided rivers are characterized by two or more active channels, separated by bars and fluvial islands and normally feature a high morphological dynamism. This dynamism is the result of the interaction among different elements as sediment supply, flow regime and in-channel and perifluvial vegetation. These factors have a fundamental role in the erosion and deposition processes which are the basis of the morphological changes. The aims of this study are the assessment of the short period geomorphic and volumetric changes occurred along a reach of the Tagliamento River and the comparison between the results obtained from LiDAR (Light Detection and Ranging) and TLS (Terrestrial Laser Scanner) data. The Tagliamento river is a natural gravel-bed river located in the NE of Italy, characterized by a relatively low degree of human disturbances. The analyses were carried out considering two different scales (a reach of about 430 ha and a sub-reach of about 25 ha) and were based on two subsequent datasets in order to investigate the short-term geomorphic changes due to eight significant floods. The surveys were performed using two different datasets derived from LiDAR and TLS technologies and used to analyze the reach and sub-reach respectively. The short-term estimates of geomorphic and volumetric changes were performed using DEMs of Difference (DoD) based on a Fuzzy Inference System. The results have confirmed the high dynamism of the Tagliamento river, estimating a prevalent deposition at reach and a predominant erosion at sub-reach levels. Finally, a comparative qualitative assessment of the output derived from the different data sources was performed, showing little differences between the two survey methods that proved to be both precise and reliable.

Correspondence: Riccardo Rainato, Department of Land, Environment, Agriculture and Forestry, University of Padova, Italy.
E-mail: riccardo.rainato@studenti.unipd.it

Key words: geomorphic changes, gravel bed braided river, LiDAR, Tagliamento River, Terrestrial Laser Scanner.

Acknowledgements: this research was founded by both the Italian National Research Project PRIN20104ALME4-ITSedErosion: "National network for monitoring, modelling and sustainable management of erosion processes in agricultural land and hilly-mountainous area"; and The EU SedAlp Project: "Sediment management in Alpine basis: Integrating sediment continuum, risk mitigation and hydropower",83-4-3-AT, in the framework of the European Territorial Cooperation Programme Alpine Space 2007-2013.

Journal of Agricultural Engineering 2013; XLIV(s2):e15
doi:10.4081/jae.2013.s2.e15

Introduction

Rivers are exposed to changing environmental conditions over multiple spatial and temporal scales, with the imposed environmental conditions and response potential of the river modulated to varying degrees by human activity and our exploitation of natural resources (Buffington, 2012). The watershed features that control river morphology include topography, sediment supply, discharge (Lisle *et al.*, 2000) and vegetation (Picco *et al.*, 2012). Among the various fluvial morphologies, the braided rivers represent very dynamic systems, in which even ordinary flood events can trigger morphologically active processes. Braided gravel-bed rivers are defined as streams which flow in multiple and migrating channels across an alluvial gravel bed, containing numerous and changing bars, ponds and islands (Gray & Harding, 2007). This fluvial pattern is localized mainly in the piedmont areas, where the proximity of mountains brings large amount of coarse sediment supply, as well as rapid and frequent variations of flow discharge, and thus braided gravel bed rivers present high amounts of energy which makes them respond dynamically to any change (Picco, 2010).

Also in the field of study of fluvial geomorphology a valuable aid is represented by the recent advances in survey equipment and software, that allow the production of high-resolution Digital Elevation Models (DEMs). This new generation of DEMs offers an excellent opportunity to measure and monitor morphological changes across a variety of spatial scales (Heritage & Hetherington, 2007). Coupled with this, the development of topographic survey techniques, *i.e.* airborne and terrestrial LiDAR, GPS, photogrammetry, has led to an increase in the amount of data collected during fieldwork in riverine environments, offering new insights into fluvial dynamics (Brasington *et al.*, 2000). These advances allow the monitoring of geomorphic changes and the estimation of sediment budgets through the application of the morphological method (Church & Ashmore, 1998). This method, in the last decades, has been expanded to include the use of repeat topographic surveys from which DEMs could be built and differenced to produce DEMs of Difference (DoD) (Wheaton *et al.*, 2010). In fact, as shown by different authors (Brasington *et al.*, 2003; Rumsby *et al.*, 2008), a DoD may provide a high resolution, spatially distributed surface model of topographic and volumetric changes through time.

The aims of the present research are the assessment of the short period geomorphic and volumetric changes occurred along a braided reach of the Tagliamento River, and the comparison between the results obtained from LiDAR and TLS data.

Study area

The Tagliamento river is a gravel-bed river, located in the North-Eastern Italy. It originates at 1195 m a.s.l. and flows for 178 km from the Alps to the northern Adriatic Sea. Its catchment covers 2871 km^2. 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 last 30 km. 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 (Picco *et al.*, submitted). A strong climate gradient exists along the length of the river which has a big influence on precipitation, temperature, humidity and consequently vegetation patterns. Another peculiarity of the Tagliamento river is the fact that within its catchment are located very rainy areas, where the annual precipitation can reach 3100 mm per year. The precipitation regime, as well as the temperatures, present a north-south gradient. Following this trend the first ranges from 3100 to 1000 mm per year, while the mean annual temperatures varies from 5 to 14°C. The upper part of the catchment (Carnian and Julian Alps) receives very intensive rain-storms, resulting in severe erosions; torrential rainfalls, steep slopes and extensive sediment sources that, in turn, generate high floods and massive sediment transport rates (Tockner *et al.*, 2003). In this sense, it is important to note as more than 70% of the basin is located in the Alpine area. The study areas, a braided reach of about 430 ha (Figure 1), inside which it was identified a sub-reach of about 25 ha, are localized at the end of the mountain basin, near to the village of Forgaria nel Fiuli (UD).

During the study period significant flood events were recorded (Figure 2). Between August 2010 and September 2011, for 8 times the water stage has exceeded 1.6 m. The events of November 2010 (2.90 m) and December 2010 (2.57 m) were significant with a recurrence interval (R.I.) of around 3 years.

Materials and methods

As said the surveys analyses were carried out considering two different scales. The reach has been detected by two airborne LiDAR flights, carried out in August 2010 and April 2011 (adopting orthometric elevations, estimated vertical error ± 0.20 m) (Picco *et al.*, 2013). The datasets produced by LiDAR surveys (called L2010 and L2011) were filtered using the software Terrascan, developed by Terrasolid. This step was necessary in order to obtain the ground points, necessary for the creation of the DEMs. For this purpose the filtered datasets were imported into ArcGIS 10.1 (ESRI). After the filtering was reached a mean point density of 2/m^2 for L2010 and a value of 2.66/ m^2 for L2011. These density values allowed us the adoption a cell size of 0.50×0.50 m, for the DEMs derived from LiDAR surveys (Figure 3).

The sub-reach was detected via TLS surveys, carried out in August 2010 and in September 2011, using a Leica ScanStation2. During the 2010 survey (T10), the sub-reach presented a low discharge level, while

Figure 1. The Tagliamento river basin (on the left), the reach localization along the main course (in the middle), and the entire reach of about 430 ha (on the right).

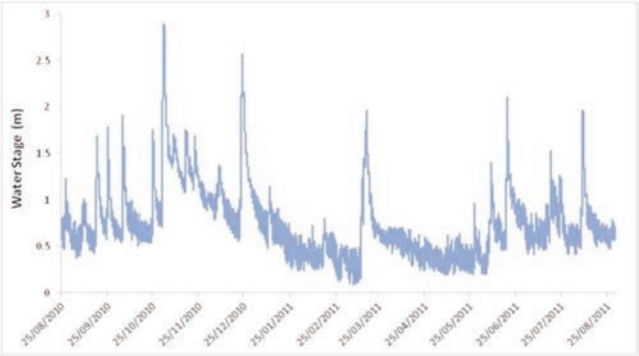

Figure 2.The flood events occurred during the study period along the reach, on the Tagliamento river.

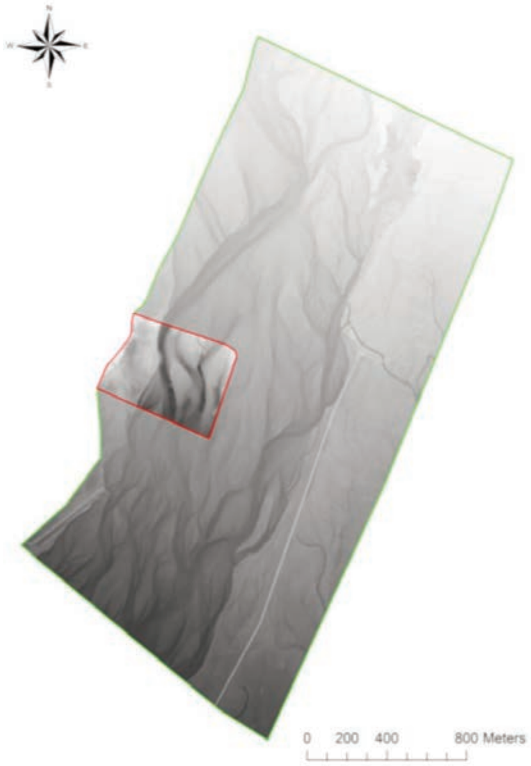

Figure 3. DEM of the study areas in 2010. In red is delimited the sub-reach (25 ha), while in green the reach (430 ha).

during the 2011 investigation (T11) the channels were nearly dry. In the first case, 241 points were measured, within the active channels, using a differential Global Position System (dGPS) in order to collect ground data given that the TLS data is not accurate for the submerged areas (Milan *et al.*, 2007). The individual scans were registered, georeferenced and filtered. These operations were performed using the software Cyclone 7, developed by Cyra Technologies Inc. Also in this case, the filtered point clouds were imported into ArcGIS 10.1, and were integrated with points collected with dGPS along the submerged areas (only for T10). After the integration a mean point density of 68.46/m^2 for T10 and 201.91/m^2 for T11 was reached. In this case, the mean density values allowed us the adoption a cell size of 0.15×0.15 m (Figure 3). Root mean square error (RMSE) analysis was conducted to define the DEM vertical accuracy using a series of dGPS data (vertical quality lower than 0.02 m) as control points. The errors were computed as the difference between the control point elevation and the cell elevation value in the DEM. The RMSE analysis resulted in the following values: 0.052 on DEM T10 and 0.048 on T11 depicting the high accuracy of the surveys. In addition, the average vertical error analysis resulted in the following values: 0.055 m on DEM T10 and 0.026 m on DEM T11.

The availability of subsequent surveys, concerning the same study areas, allows to analyze the geomorphic changes. To perform this type of analysis, we have used the Geomorphic Change Detection 5.1.0 (GCD) software (http://gcd.joewheaton.org). This is a plug-in that can be utilized in ArcGIS environment and allows the monitoring of geomorphic changes through the creation of DoD, in other words through the comparison of repeat and subsequent DEMs. In the case of the present study a not simplistic difference between DEMs but an *ad hoc* Fuzzy Inference System (FIS) was developed to estimate the DEM uncertainty. This FIS (Table 1) was also used in other works (Picco *et al.*, submitted) concerning this study area, and uses as inputs: slope, point density and roughness. For the detailed explanation of GCD software we refer to Wheaton *et al.* (2010). After defining the spatial variability of the uncertainty, the DoDs were recalculated and thresholded at a 95% confidence interval, also using the Bayesian updating method, that re-elaborate the DoDs on the basis of the spatial coherence of erosion and deposition units.

Results

The first result concerns the geomorphic variations occurred within the entire reach. The DoD obtained (Figure 4) from the comparison between the L2011 (April 2011) and the L2010 (August 2010) shows the changes occurred in about 8 months. In the DoD are shown in red the areas prone to erosion, while in blue the surface prone to deposition. We can observe that the most part of the geomorphic changes occur within the active channel areas, without significant variations in the perifluvial zones. The most important erosion phenomenon, from the point of view of extent and incision degree, occurs as bank erosion. This type of scour affects the floodplain areas, as we can observe especially in the middle of the sub-reach, along the main channel, on the right side.

In the upper part of reach other erosions take place, in this case due to the development of some new secondary channels. A significant aggradation occurred along the course of the main channel, on the right side. Here are located the maximum values of deposition. Others considerable depositional phenomena take place downstream, where the channels have deposited in the central part, eroding the lateral floodplain through bank erosions.

Table 2 shows the main results obtained from the comparison between L2011 and L2010. The *Total Net Volume Difference* (+ 145898 m^3) highlights how, in the study reach, there was a prevalent trend of deposition, during the study period. Nearly all values concerning erosion and deposition do not show large differences. For example the *Total Area of Erosion* features the value of 1135232 m^2, a result very similar to the *Total Area of Deposition* that is 1584695 m^2. Also the volumetric results, in particular the percentages, are quite similar with 43% of *Erosion* and 57% of *Deposition*. According to this trend, also the

Table 1. FIS rules used in this work.

ROUGHNESS	SLOPE	DENSITY	UNCERTAINTY
low	low	high	LOW
medium	low	high	LOW
high	low	high	LOW
low	medium	high	LOW
medium	medium	high	LOW
high	medium	high	AVERAGE
low	high	high	LOW
medium	high	high	AVERAGE
high	high	high	AVERAGE
low	low	medium	LOW
medium	low	medium	AVERAGE
high	low	medium	AVERAGE
low	medium	medium	AVERAGE
medium	medium	medium	AVERAGE
high	medium	medium	HIGH
low	high	medium	AVERAGE
medium	high	medium	HIGH
high	high	medium	HIGH
low	low	low	HIGH
medium	low	low	HIGH
high	low	low	EXTREME
low	medium	low	HIGH
medium	medium	low	HIGH
high	medium	low	EXTREME
low	high	low	EXTREME
medium	high	low	EXTREME
high	high	low	EXTREME

Table 2. Results of comparison L2011-L2010.

Maximum positive variation (m)	3.56
Maximum negative variation (m)	-3.06
Average variation (m)	0.05
Standard deviation	0.53
Total Area of Erosion (m^2)	1 135 232
Total Area of Deposition (m^2)	1 584 695
Total Volume of Erosion (m^3)	468 223
Total Volume of Deposition (m^3)	614 121
Total Volume of Difference (m^3)	1 082 343
Total Net Volume Difference (m^3)	145 898
Percent Erosion (by volume)	43%
Percent Deposition (by volume)	57%

Average Variation takes a value of 0.05 m, very close to zero. However, meaningful is the assessment of the *Total Volume of Difference* equal to 1082343 m^3.

The geomorphic changes occurred within the sub-reach were analyzed through two DoDs. The first one was produced by comparing high-resolution DEMs (T11-T10), in other words using the maximum resolution (0.15 m) offered by TLS surveys. The further DoD (T11_05-T10_05) was made by comparing the same data acquisition, but producing DEMs with lower resolution (0.50 m), as in the case of the LiDAR DEMs. These two DODs, characterized by different resolutions, are shown in Figure 5. In both comparisons we can clearly identify the erosion and depositional phenomena, taking place in approximately 12 months between the two data acquisitions. First of all we can observe as the erosion phenomena occur in two main areas: along the main channel an extended and deep bank erosion affects the contiguous floodplain on the right side (maximum values of erosion), and in the middle of the sub-reach, due to the creation of two new secondary channels. The depositional phenomena were concentrated on the left side, where was situated a vegetated bar, and along the course of the main channel, where a wide aggradation has taken place.

Table 3 shows the main results obtained from the comparison between T11-T10, T11_05-T10_05 and, in the last column, the percentage difference between these two results. First of all, we can observe how both the DoDs have estimated a prevalence of erosion within the sub-reach, with values of *Total Net Volume Difference* of -68351 m^3 and -68604 m^3 respectively. In the results of T11-T10 this trend is also confirmed by the considerably higher value of the *Total Volume of Erosion* (96638 m^3) in respect to the *Total Volume of Deposition* (28287 m^3). Also the extension of the areas affected by the phenomena, are in line with these results, with the *Total Area of Erosion* equal to 148186 m^2, while the *Total Area of Deposition* amounting to 75333 m^2, nearly a 2/1 ratio (1.97). Other results according to this trend is the *Average Variation* that accounts for -0.31 m, featuring a negative value. All the results obtained from the comparisons T11_05-T10_05 are in line with the values seen before. It is interesting to note how the percentage difference achieves a maximum value of 12.58%, as in the case of the *Total Area of Deposition*, while in other cases the difference is always maintained below 10%. Very significant is the estimate of the *Total Net Volume Difference* that differs by only 0.37%.

Table 3. Results of comparison T11-T10, T11_05-T10_05 and the percentages differences between them.

Maximum positive variation (m)	1.74	1.68	-3.45
Maximum negative variation (m)	-2.96	-2.94	-0.68
Average variation (m)	-0.31	-0.34	9.68
Standard deviation	0.68	0.70	2.94
Total Area of Erosion (m^2)	148 186	136 036	-8.20
Total Area of Deposition (m^2)	75 333	65 856	-12.58
Total Volume of Erosion (m^3)	96 638	95 806	-0.86
Total Volume of Deposition (m^3)	28 287	27 202	-3.84
Total Volume of Difference (m^3)	124 924	123 008	-1.53
Total Net Volume Difference (m^3)	-68 351	-68 604	0.37
Percent Erosion (by volume)	77%	78%	1.00
Percent Deposition (by volume)	23%	22%	-1.00

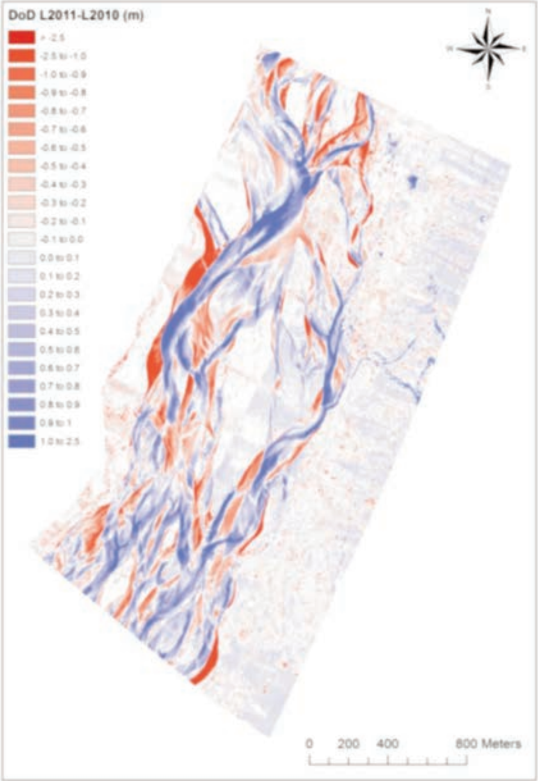

Figure 4. DoD relative to the comparison L2011-L2010.

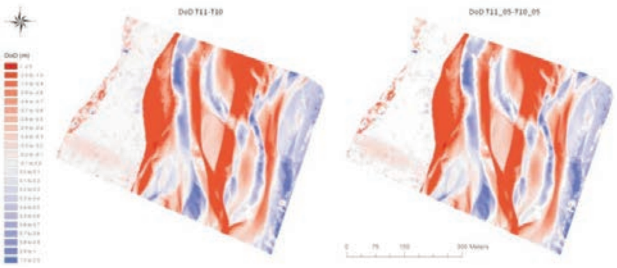

Figure 4. DoD relative to the comparison L2011-L2010.

Discussion

The analysis carried out showed how the floods events occurred during the study period have caused consistent geomorphic variations along the study areas. The DoD obtained from the comparison between L2011 and L2010 has analyzed the changes along the entire study reach, estimating a positive budget (+ 145898 m^3) However, this trend is weak given that there was no prevalent phenomena: a sort of balance between erosion and deposition has taken place. The analysis carried out by comparing the TLS surveys allowed us to study in detail the changes that took place within the sub-reach. In this study area it is observed a clear prevalence of erosion phenomena with a value of *Total Net Volume Difference* of -68351 m^3, in the comparison T11-T10, and -68604 m^3 in T11_05-T10_05. The formation of two new secondary channels, in the middle of the sub-reach, has certainly influenced these results. But a key role can be attributed especially to the extended and deep bank erosion which affected the contiguous floodplain, on the right side. Concerning the third comparison (T11_05-T10_05) that calculates the difference between low-resolution DEMs (0.50 m) the volumetric data were compared with the results obtained by T11-T10 (resolution 0.15 m). This comparative relation (Table 3) allowed to high-light as the percentages difference never exceed the 12.6%, with the most of the differences that were maintained below 10%. Analyzing individually the results, we can observe how the use of a cell size of 0.50×0.50 m has caused a reduction in the values of *Maximum Negative Variation* (-0.68%) and *Maximum Positive Variation* (-3.45%), in other words a sort of flattening of this punctual values. Differences of more than 8% are related only to the *Average Variation* (9.68%), the *Total Area of Erosion* (-8.20%) and the *Total Area of Deposition* (-12.58%). In this case, the lower resolution caused an underestimation of the areas affected by erosion and depositional phenomena.

Conclusions

The aims of this study was the assessment of the short period geomorphic and volumetric changes occurred along a reach of the Tagliamento River and the comparison between the results obtained from LiDAR and TLS data. Regarding the latter aim a comparative assessment of the output derived from the different data sources was performed, showing little differences between the two survey methods that demonstrated, anyway, to be both precise and reliable. The comparison between different resolution DoDs has shown that even the lower resolutions (0.50 m) allow to obtain significant results, with differences that at most have reached 12.58%, if compared to those obtained by higher resolutions (0.15m). This prove how, in this context, also the use of medium resolutions permits a correct assessment of geomorphic changes, and in particular of volumetric variations. On the other hand the use of high resolutions is confirmed as essential for a correct analysis of specific parameters, as roughness. The GCD method, used in this study, thanks also to the use of an *ad hoc* FIS has proved to be an efficient tool that allows the estimation of volumetric and geomorphic variations, not using a simple difference between DEM, but rather by a accurate multi-parametric analysis, that permits to eliminate the higher uncertainties. Moreover a proper assessment of these variations represents a valuable data that can be used in the flood management programs. In conclusion, the analyzes performed have confirmed the high dynamism of the Tagliamento river, typical feature of gravel bed rivers, especially if characterized by braided morphology, as in this case.

References

Brasington J., Langham J., Rumsby B.T., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology 53, 299–316. DOI: 10.1016/S0169-555X(02)00320-3.

Brasington J., Rumsby B.T., McVey R.A., 2000. Monitoring and modeling morphological change in a braided gravel-bed river using high resolution GPS-based survey. Earth Surf. Processes and Land. 25, 973–990. DOI: 10.1002/1096-9837(200008)25:9<973.

Buffington J.M., 2012. Changes in channel morphology over human time scales. Gravel-bed Rivers: processes, tools, environments. Edited by Michael Church, Pascale Biron, Andrè G. Roy. Wiley-Blackwell, 435-463. DOI: DOI: 10.1002/9781119952497.ch32.

Church M., Ashmore P., 1998. Sediment transport and river morphology: a paradigm for study. In Gravel-Bed Rivers in the Environment, Klingeman PC (ed). Water Resources Center: Highlands Ranch, CO.

Gray D., Harding J.S., 2007. Braided river ecology, a literature review of physical habitats and aquatic invertebrate communities, Science for conservation 279, Science & Technical Publishing, Department of Conservation, Wellington, New Zealand.

Heritage G.L., Hetherington D., 2007. Towards a protocol for laser scanning in fluvial geomorphology. Earth Surf. Processes Land. 32, 66–74.

Lisle T.E., Nelson J.M., Pitlick J., Madej M.A., Barkett B.L., 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. Water Resources Research, Vol. 36, No. 12, 3743-3755. DOI:10.1029/2000 WR900238.

Milan D.J., Heritage G.L., Hetherington D., 2007. Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. Earth Surf. Processes Land. 32, 1657–1674. DOI: DOI: 10.1002/esp.1592.

Picco L., 2010. Long period morphological dynamics in regulated braided gravel-bed rivers: comparison between Piave River (Italy) and Waitaki River (New Zealand), PhD thesis, University of Padova, 190 p.

Picco L., Mao L., Rigon E., Moretto J., Ravazzolo D., Delai F., Lenzi M.A., 2012. Riparian forest structure, vegetation cover and flood events in the Piave River, WIT Transactions on Engineering Sciences, Vol.73, 137-147, ISSN: 1743-3553, DOI: 10.2495/DEB120121.

Picco L., Tonon A., Ravazzolo D., Rainato R., Rigon E., Moretto J., Delai F., Lenzi M.A., 2013. Monitoring river islands dynamics using aerial photographs and LiDAR data: the Tagliamento river study case. Atti del Convegno "The Role of Geomatics in Hydrogeological Risk". Padua, Italy, 27-28 February 2013.

Picco L., Mao L., Cavalli M., Buzzi E., Rainato R., Lenzi M.A., (submitted). Evaluating short-term morphological changes in a gravel-bed braided river using Terrestrial Laser Scanner. Geomorphology.

Rumsby B.T., Brasington J., Langham J.A., McLelland S.J., Middleton R., Rollinson G., 2008. Monitoring and modeling particle and reach-scale morphological change in gravel-bed rivers: Applications and challenges, Geomorphology 93(1-2), 40-54. DOI: 10.1016/j.geomorph.2006.12.017.

Tockner K., Ward J.V., Arscott D.B., 2003. The Tagliamento River: a model ecosystem of European importance. Aquatic Sciences 65, 239-53. DOI 10.1007/s00027-003-0699-9.

Wheaton J.M., Brasington J., Darby S.E., Sear D.A., 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf. Processes Land. 35, 136–156. DOI: 10.1002/esp.1886.