Geomorphology 437 (2023) 108803

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology

The role of in-channel vegetation in driving and controlling the geomorphic changes along a gravel-bed river

L. Picco [a], G. Pellegrini [a], A. Iroumé [b], M.A. Lenzi [a], R. Rainato [a,*]

[a] Department of Land, Environment, Agriculture and Forestry, University of Padova, Padova, Italy
[b] Universidad Austral de Chile Faculty of Forest Sciences and Natural Resources, Valdivia, Chile

ARTICLE INFO

Keywords:
Riparian vegetation
Geomorphic changes
Gravel bed river
Piave River
LiDAR

ABSTRACT

Gravel-bed rivers are fluvial systems featuring highly complex morphological and evolutionary patterns because of their configuration characterized by the contemporary presence of many distinct morphological units. Complexity can also be observed in the response of gravel-bed rivers to flow conditions, which can be highly varied. This work aims to analyze the evolution of gravel and vegetated areas in a gravel-bed river during a period of persistent low flow conditions, focusing also on the responses exhibited by the different types of riparian vegetation. To this end, a 2200 m-long segment of the Piave River (NE Italy) was considered. It was surveyed twice by LiDAR (August 2003 and August 2010), permitting the analysis of the spatial-temporal evolution of gravel and vegetated areas through both cover type analysis and the DoD technique. During the study period (August 2003 – August 2010), the flow conditions were constantly ordinary, i.e., under-bankfull. The cover type analysis stressed an increase of +115 % in vegetated areas, which have diffusely colonized the river corridor. However, the low flow conditions also induced geomorphic changes with 54 % of the study area affected by variations in surface elevation. The DoD computed a diffuse deposition over the main and secondary channels, while erosion was observed in specific areas of the main fluvial island and along the right floodplain. In terms of vegetation changes, five eroded patches were identified, which contributed to 60 % of the vegetated area entirely eroded in the study reach. These patches were mainly characterized by mature vegetation taller than the mean vegetation height observed over the study reach. Therefore, the analysis of the response of the Piave River to persistent under-bankfull flows stressed a complex evolution of the gravel and vegetated areas, which can be appreciated also because of low flow conditions, emphasizing the composite dynamics typical of a gravel-bed river. These results could improve riverine management considering vegetation structure and dimension, as well as the geomorphic settings of gravel-bed rivers in view of future low flow conditions.

1. Introduction

Gravel-bed rivers are dynamic fluvial systems, flowing in one or more alluvial channels and characterized by the presence of fluvial islands, gravel, herbaceous and vegetated bars that permit the shaping of a diverse platform (Leopold and Wolman, 1957; Brierley and Fryirs, 2005; Picco et al., 2014a). The contemporary presence of several morphological units gives a high complexity in these river settings, with high dynamism in time and space (Bertoldi et al., 2009; Picco et al., 2015). Geomorphic changes are strongly correlated to the interaction between different factors such as flow conditions, sediment grain size, channel forms, and riparian vegetation (Hupp and Osterkamp, 1996; Gurnell et al., 2001; Gurnell and Petts, 2002; Mikuś et al., 2013). Analyzing different spatial scales, McBride et al. (2010) identified the bank (Pollen-Bankhead and Simon, 2010; Pizzuto et al., 2010), the floodplain (McBride, 2007), and the fluvial corridor (Surian et al., 2015) as the main areas characterized by the interaction between riparian vegetation and river morphology. In this sense, riparian and in-channel vegetation can influence bank stability (Van de Wiel and Darby, 2007; Li and Millar, 2011; Picco et al., 2016a; Vargas-Luna et al., 2019) and flow velocity (Larsen et al., 2009; Folkard, 2011; Nepf, 2012), inducing flow diversion (Rominger and Nepf, 2011; Zong and Nepf, 2011; Van Dijk et al., 2013). Tanino and Nepf (2008) demonstrated that the interaction between vegetation and water typically produces strong energy dissipation, generating vortices and turbulence. The significant role of vegetation influencing channel morphology has been increasingly

* Corresponding author.
E-mail address: riccardo.rainato@unipd.it (R. Rainato).

https://doi.org/10.1016/j.geomorph.2023.108803
Received 28 March 2023; Received in revised form 16 June 2023; Accepted 16 June 2023
Available online 19 June 2023
0169-555X/

verified in the field (Simon and Collison, 2002), numerically (Murray and Paola, 2003) as well as experimentally (Tal and Paola, 2010; Braudrick et al., 2009; Bertoldi et al., 2011). It has been demonstrated in gravel-bed rivers how vegetation can increase bank stabilization, inducing a narrowing phase (Picco et al., 2017). This action can also cause a reduction in the number of channels per cross section, favoring the transition from a braided to a wandering morphology (Comiti et al., 2011). In turn, riparian vegetation is strongly controlled by river dynamic processes, revealing a very complex process of colonization of the riverine area caused by the different tolerance of species to specific disturbances (Hupp and Osterkamp, 1996; Bendix and Hupp, 2000; Gurnell and Petts, 2002; McBride et al., 2010). The interaction between flow conditions (flood events) and riparian vegetation can also induce recruitment of large wood (LW – sensu Gurnell et al., 2000). In recent years, increasing attention has been devoted to the importance of LW (Wohl, 2017), wood budgeting (Kramer and Wohl, 2017; Tonon et al., 2017), and its dynamics (MacVicar and Piégay, 2012; Ravazzolo et al., 2015; Picco et al., 2016b; Pellegrini et al., 2022). In fact, LW can also be a source of risk, particularly once there are sensitive structures (i.e., bridges) that may be clogged, generating local scouring around bridge piers (Mazzorana et al., 2009; Lucía et al., 2015).

The high degree of human pressure (e.g., flow regulation and in-channel gravel mining) experienced by many gravel-bed rivers has resulted in significant changes in the development and stability of the riparian vegetation and fluvial islands (Comiti et al., 2011; Picco et al., 2017; Asaeda and Sanjaya, 2017; Han et al., 2020). For example, dams reduce flood peaks, increasing base flow and storing sediments (Kondolf, 1997). These conditions lead to the stabilization of gravel bars by vegetation growth (Lobera et al., 2015) that generates a further reduction in the active channel width because of the connection between the fluvial island and floodplains (Picco et al., 2014b). Such a tendency can be further favored by the alteration of flood regime observed in recent years, and is mainly related to ongoing climate change, resulting in long drought phases (Brummer et al., 2016). Human-affected rivers can also present environments with alterations in the biological habitats and the interaction of biotic-hydrologic processes (Poff et al., 2007). Such alterations have been documented for a long time (Hadley, 1961; Brice, 1964; Zimmerman et al., 1967) in terms of disturbances of river morphology and vegetation characteristics (Wharton et al., 1982; Hupp and Osterkamp, 1985; Hupp, 1988; Sitzia et al., 2016). Considering all these aspects, proper management of the riparian area is needed to improve resilience and take advantage of the intrinsic characteristics of riparian vegetation itself. To this end, in the last couple of decades, advances in survey equipment and software allowed high-resolution digital elevation models (DEMs) to be easily constructed. The use of this technology is offering an excellent opportunity to measure and monitor morphological change across a variety of spatial scales (Brasington et al., 2000; Lane and Chandler, 2003; Heritage and Hetherington, 2007; Tamminga et al., 2015; Vericat et al., 2017). In river environments, the approaches used to obtain high-resolution morphological datasets include airborne LiDAR (Charlton et al., 2003; Rumsby et al., 2008; Milan and Heritage, 2012), which enables the production of rapid and accurate topographic surveys over large areas. The calculation of the difference between subsequent DEMs (DEM of Difference, DoD) is a method commonly used to investigate and quantify channel changes (Wheaton et al., 2010, 2013). The use of DoDs permits the analysis of topographic and volumetric changes that occurred during a certain time interval at a high level of resolution (Vericat et al., 2014; Williams et al., 2020) and the identification of areas of scour and fill (Lane et al., 2003; Picco et al., 2013). DoD analysis can also facilitate the investigation of the responses of the vegetated areas to flood events, allowing vegetation characteristics to be connected to geomorphic processes (Sharpe and Kemp, 2021). This work aims to investigate the evolution of gravel and vegetated areas in a reach of the gravel-bed Piave River during a period of persistent low flow conditions (August 2003 – August 2010), focusing mainly on the different responses exhibited by the diverse types of riparian vegetation. Considering the ongoing alteration of the flood regime caused by climate change and the increasing need for cost-effective river management solutions (Rowinski et al., 2018), a better knowledge of the riparian vegetation dynamics might permit the design proper management approaches that take advantage of the positive aspects (and limiting the negative ones) of in-channel vegetation.

2. Material and methods

2.1. Study area

The Piave River originates at an elevation of 2037 m a.s.l. in the Dolomites, flowing for 222 km along northeastern Italy before reaching the Adriatic Sea (Fig. 1). The drainage basin of 3899 km^2 is composed mainly of sedimentary rocks (i.e., limestone and dolomite). The fluvial morphology of the main course of the Piave River can be divided into three parts. From the source to Longarone, the upper Piave River exhibits an incised and narrow channel. The middle course is identifiable from Longarone to Ponte di Piave and historically featured a multithread channel pattern. Finally, the lower course of the Piave River extends between Ponte di Piave and the mouth, presenting a meander and artificially straightened configuration (Surian, 1999). The Piave River basin has experienced anthropic influence for millennia and, particularly, between the eighteenth and nineteenth centuries livestock and crop farming have minimized the forested area (Agnoletti, 2000). After World War I a long period of afforestation started, which persists because of the abandonment of farming and cropping activities (Del Favero and Lasen, 1993). Large human influences can be observed in the Piave River's channel network, in which, starting from the 1930s, numerous erosion-torrential control works and dams for hydroelectric power generation were built. The current conditions of water regulation and diversion resulted in the apparent alteration of flow duration and annual runoff volume, as well as in the annual sediment yield, which decreased by about one order of magnitude compared to pre-dam conditions (Surian, 1999; Comiti et al., 2011). Dams and diversions were accompanied by about three decades (1960s - 1990s) of intense gravel mining, causing channel narrowing associated with bed incision over the twentieth century (Comiti et al., 2011). These geomorphic variations favored the expansion of riparian vegetation along the whole riverine corridor (Picco et al., 2017). Several authors have observed that the Piave River corridor is characterized by a complex vegetation pattern (Picco et al., 2016a; Sitzia et al., 2016; Sitzia et al., 2023). Stable and persistent floodplains allowed the growth of mature forest communities composed of *Quercus robur*, *Fraxinus angustifolia,* and *Fraxinus excelsior*, while on the fluvial islands *Quercus pubescens*, *Viburnum lantana*, *Alnus glutinosa,* and *Pinus sylvestris* can be found (Sitzia et al., 2016). Additionally, these authors reported the presence of alien species such as *Buddleja davidii* and *Robinia pseudoacacia*. The study reach of the Piave River is 2200 m long and is located in the middle course of the river near the city of Belluno, draining an area of ~2000 km^2 (Fig. 1). In 2003, the study reach exhibited a gradient of 0.003 m m^{-1} with an active channel width between 250 and 500 m and a total extent of 92.2 ha. The grain size distribution of riverbed sediments was: $D_{16} = 11$ mm, $D_{50} = 31$ mm, and $D_{84} = 70$ mm (Rainato et al., 2014). These conditions resulted in a transitional configuration between wandering and braided channel patterns (Picco et al., 2014a), characterized by the presence of a main channel on the right, a secondary non-flowing channel on the left, and fluvial islands (Fig. 1). Moreover, there are two groynes located along the right margin of the study reach. By definition, the wandering planform is much more stable than the braided. The study reach remains active producing lateral shifts of the main channel able to erode vegetated units and recruit LW even during floods less than bankfull (Tonon et al., 2018). The most evident proof of the passage from a braided system to a wandering setting is narrower sections that greatly increase the vertical distance between the thalweg and the top of the higher morphological units (i.e., floodplains and islands) as stated by Comiti

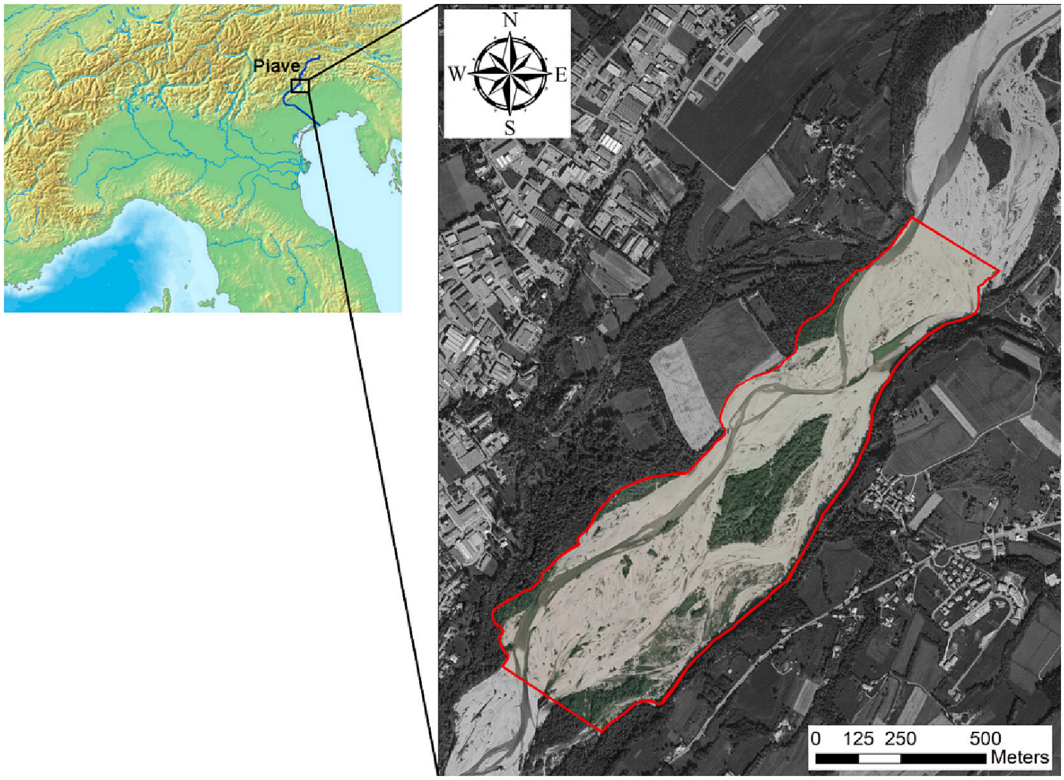

Fig. 1. Study reach (red edge) and its position along the Piave River (northeast Italy). 2003 aerial photo in the background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al. (2011).

2.2. Hydrological data

The flow conditions experienced during the study period (August 2003 – August 2010) in the study reach were described using the water discharge (Q) measured by the "Belluno Ponte Vittoria" gauging station (ARPA Veneto). This station is located ~2 km downstream of the study reach and between August 2003 and August 2010 measured the Piave River's discharge hourly. The three highest Q peaks during the study period were 619 m^3 s^{-1}, 499 m^3 s^{-1}, and 483 m^3 s^{-1} observed in December 2009, May 2010, and November 2003, respectively (Fig. 2). In the study reach, Comiti et al. (2011) estimated the bankfull discharge through a magnitude–frequency analysis applied to the flows recorded during the period 1926–2007, identifying the bankfull value as the discharge Q_2 (recurrence interval $RI = 2$ years), 700 m^3 s^{-1}. They also defined as high frequency events the floods with $Q < Q_{1.5}$ ($RI = 1.5$ years, 490 m^3 s^{-1}). Therefore, the Q recorded between August 2003 and August 2010 was constantly lower than the bankfull value, with flood peaks mainly comparable to the high frequency events observed by Comiti et al. (2011). The flood duration was also investigated because it can exert an important influence in the evolution of riparian vegetation and the geomorphic setting of gravel-bed rivers (Magilligan et al., 2014, Galia et al., 2023). We calculated the flood duration over a critical threshold of $Q_{1.5}$ for each flood event observed during the study period (Comiti et al., 2011). Only the December 2009 and May 2010 floods

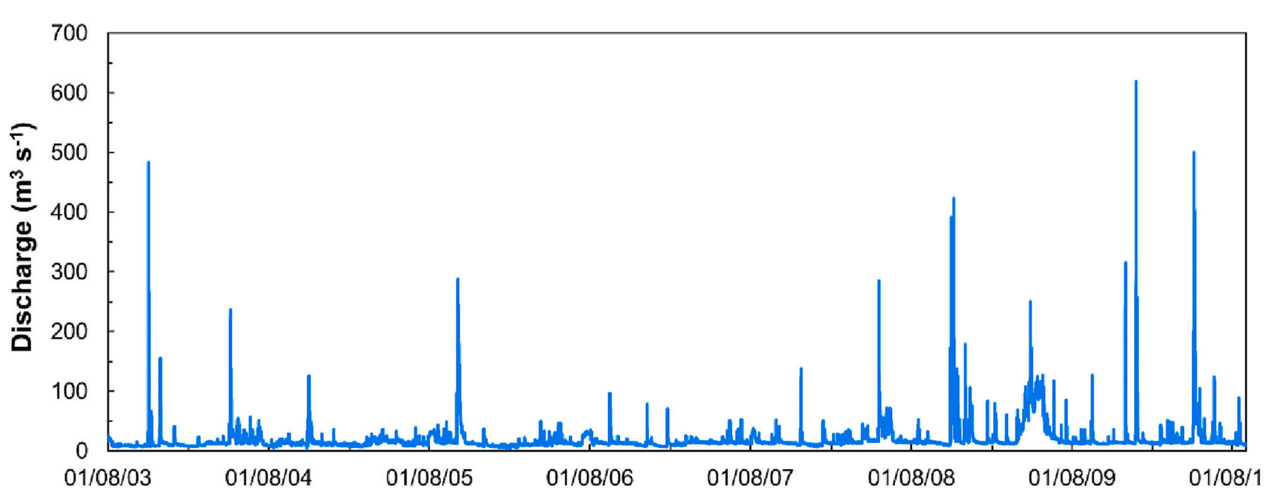

Fig. 2. Water discharge experienced by study reach and measured by the "Belluno Ponte Vittoria" gauging station between August 2003 – August 2010. The bankfull discharge is 700 m^3 s^{-1} (Comiti et al., 2011).

exhibited $Q > 490$ m^3 s^{-1}, for 5 h and 1 h, respectively. The underbankfull magnitude of the flow conditions during the study period were further stressed also by the mean discharge of 20 m^3 s^{-1}. Field surveys performed before and after the December 2009 flood permitted us to document that during this event the water level submerged the fluvial islands and high bars, almost reaching the floodplain level. Because of his, along with the features of the measured events (i.e., *Q* peak and flood duration), we assumed that the geomorphic changes that occurred between August 2003 – August 2010 were primarily attributable to the December 2009 flood.

2.3. LiDAR data

To analyze the geomorphic and vegetation evolution along the study reach, two LiDAR surveys were carried out. These were performed in August 2003 and August 2010 by Autorità di Bacino dell'Alto Adriatico e Blom GCR, respectively. Both surveys occurred during good weather conditions and with low water levels (i.e., ~25 m^3 s^{-1}), obtaining an estimated average vertical error of ±0.20 m and a filtered point density of 1–2 per m^2 (Comiti et al., 2011; Picco et al., 2017). These point densities enabled to use of a 0.50 × 0.50 m cell size resolution in the building of the Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) for both years. Once generated, DTMs and DSMs were detrended to express the elevation as deviation from the average elevation of the study reach (Bertoldi et al., 2013). By subtracting the DTM from the DSM, a canopy height model (CHM) for both 2003 and 2010 was designed. The CHMs were exploited by running the Rstudio package ForestTools (Plowright, 2018) to detect individual trees, their heights, and their crown delineation. To do so, the linear variable window function to detect individual tree locations was used. The variable window function was described using:

$$WR = b_1 + h \times b_2 \quad (1)$$

This linear equation defined the window radius (*WR*) as a function of height (h) in the CHM, using coefficients b_1 and b_2 equal to 0.60 and 0.05, respectively. In addition, a value for tree diameter was assigned to each trees' height following the empirical formula (Fig. 3) derived from the onsite 89 trees sample plots performed during 2010 (Picco et al., 2016a). The 4 × 4 m sample plots were 10 m apart to measure the height, density, and diameter at breast height (DBH) of the trees. After retrieving the diameter of the individual trees detected in the CHM, the volume was computed by applying the formula a cylinder.

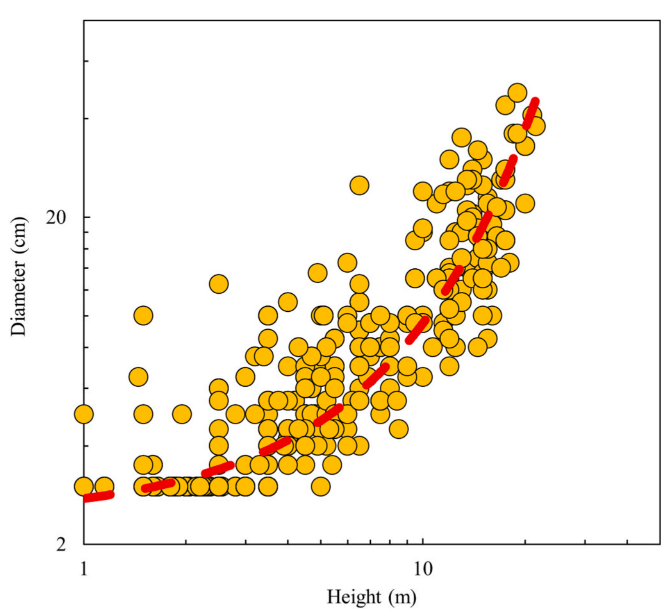

Fig. 3. Empirical exponential regression between the tree heights (x axis) and diameters (y axis). The range of diameters was between 3 and 48 cm, while the heights of the trees covered a range between 1 and 21.5 m.

The CHMs were used to map the vegetation cover types. These were classified into ground, shrub, and tree layers based on the height expressed in the CHM (Table 1). This classification was corroborated by field observations during the second LiDAR survey (i.e., 2010).

The geomorphic and vegetation changes that occurred during the study period were investigated through the DEMs of Difference (DoD) technique (Brasington et al., 2003; Lane et al., 2003). Comparison of the DTM 2003 and DTM 2010 allowed us to assess geomorphic changes and to detect the distribution of erosion/deposition, while the comparison of the corresponding CHMs allowed us to detect the increase or removal of the vegetation patches and to analyze the relationships between geomorphic and vegetation changes. The DoDs were computed in ArcMap 10.5 software using the Geomorphic Change Detection 7.4.3.0 plugin (Wheaton et al., 2010) and applying the propagating uncertainty approach. Based on the estimated vertical error (± 0.20 m) of LiDAR surveys, the error of uncertainty of each DTM and CHM was computed. Thereafter, the propagation into the final DoD was measured following Brasington et al. (2000) simple procedure and Wheaton (2008), computing the final error as the mean square root of the sum of the two DTMs (or CHMs) errors raised to the second power. The data concerning areas and volumes of sediment deposition/erosion or vegetation increase/removal were computed using probabilistic thresholding of 0.80 confidence interval.

2.4. Topographic features of the vegetated eroded areas

To determine whether the characteristics of the eroded vegetated areas were somehow controlled by the relative topographic features, the DTM 2003 was exploited using the 3D Analyst tool of the ArcGIS 10.5 software to extract three vertical profiles of riverbanks (upstream, middle, and downstream part) per eroded area. In each area, the mean riverbank vertical drop and the mean riverbank slope were obtained by averaging the values measured along the three related vertical profiles (Fig. 4).

Once the vegetation and topographic characteristics of eroded vegetated patches were determined (Table 2), a first Pearson correlation matrix and further regression models were applied via R Studio software to identify possible relationships.

3. Results

3.1. Evolution of vegetation cover types

The analysis of the 2003 and 2010 cover types showed a general increase of the vegetated areas at the expense of the exposed gravels (Fig. 5). In fact, the vegetated areas increased by 115 % from 10.9 ha to 23.5 ha (Table 3). In 2003, the vegetation was mainly clustered along the riparian zones and on the fluvial island located in the middle of the study reach. In 2010, these areas were strongly reshaped while the vegetation has expanded extensively within the river corridor, especially along the left side, through numerous vegetated patches (Fig. 5).

Focusing on the evolution of vegetation cover types, the largest increase was expressed by the ground vegetation layer, which in 2010 showed an extent about 5-fold larger than in 2003 (Table 3). The comparison between 2003 and 2010 cover types shows how the ground

Table 1
Classification of vegetation cover types based on the CHM analysis.

Vegetation cover type	Height (m)
Ground vegetation layer	< 1.5
Shrub layer	1.5–5.0
Tree layer	> 5.0

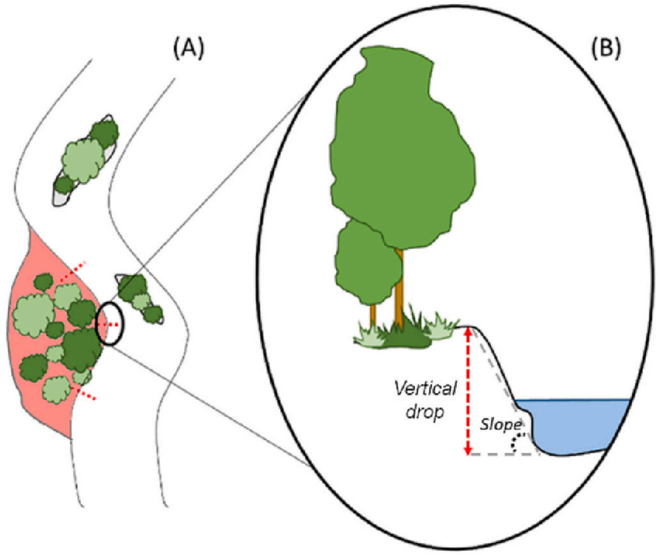

Fig. 4. Example of topographic features retrieved on the eroded vegetated area (in red). (A) Planimetric view: the red dotted lines indicate, as an example, the vertical profiles identified. (B) Transversal profile view of the riverbank, illustrating the riverbank vertical drop (red dotted arrow) and the riverbank slope. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Topographic and vegetation features analyzed in the eroded vegetated area.

Acronym	Feature	Description (unit of measurement)
RS	Riverbank Slope	Mean slope of the exposed banks (%)
RVD	Riverbank Vertical Drop	Mean vertical drop of the exposed banks (m)
ESA	Eroded Sediment Area	Area affected by sediment erosion (ha)
DSA	Deposited Sediment Area	Area affected by sediment deposition (ha)
EVA	Eroded Vegetated Area	Area affected by vegetation erosion (ha)
EVVR	Eroded Vegetated Volume Rate	Eroded vegetation volume standardized per area (m^3 ha^{-1})
VD	Vegetation Density	Number of eroded plants per area (n ha^{-1})
HV_{max}	H_{max} Vegetation	Maximum vegetation height (m)
HV_{mean}	H_{mean} Vegetation	Mean vegetation height (m)

vegetation layer expanded diffusely over the entire study reach (Fig. 5). In 2003, the largest cover type was the shrub layer, which covered 7.2 % of the 92.2 ha (Table 3). In 2010, the shrub layer remained the largest (12.3 %) but exhibited a smaller area increase than the ground vegetation layer. The expansion of the shrub layer was particularly evident in the left downstream area of the fluvial island. The smallest change was observed in the tree layer, which increased from 2.5 to 3.3 ha (Table 3). Interestingly, vegetation higher than 5 m has widely diffused within the fluvial island, while it is no longer present along the right margin of study reach (Fig. 5).

3.2. Geomorphic changes

The DoD from the 2003 and 2010 DTMs shows the occurrence of geomorphic changes along the study reach (Fig. 6). Overall, 55.0 % (50.9 ha) of the study area experienced variations in surface elevation.

Surface raising (deposition) occurred over 37.2 ha, while 13.7 ha experienced surface lowering (erosion) (Table 4). Deposition occurred mainly along the course of the 2003 main channel, particularly in correspondence with the central fluvial island. The surface raising was also detected along the left margin of the study reach but here the surface elevation variation was somewhat lower (Fig. 6). Large, eroded areas (V1, V3, V5 in Fig. 6) were instead computed by the DoD on the right margin of the study reach. Surface lowering (V2) also occurred upstream of the central fluvial island, which was also extensively eroded on its right margin (Fig. 6). Intense erosion (V4) also occurred on the left side of the main channel in the proximity of V3. Interestingly, no surface lowering was evident over the left margin of the study reach. These conditions led to an average depth of surface lowering equal to 0.94 m over the areas affected by erosion, while the zones with deposition exhibited a mean surface raising equal to 0.79 m (Table 4).

3.3. Vegetation changes

The DoD from the comparison between the 2003 and 2010 CHMs supported the general increase of vegetation over the study reach (Fig. 7). In fact, the DoD analysis shows that 46.4 % (42.8 ha) of the study reach area experienced changes in vegetation cover, with 33.9 ha experiencing an increase in vegetation cover (Table 4). The estimated area experiencing vegetation raising exceeded that experiencing vegetation lowering (8.9 ha). Spatially, the vegetation raising was distributed over the entire study area, while the vegetation erosion was limited to specific patches (Fig. 7). In particular, three large eroded areas (V1, V3, and V5) occurred on the right margin of the study reach. Also, an extended patch of surface lowering (V2) was identified in correspondence to the fluvial island with minor erosion downstream of it (V4).

These five eroded patches (V1 – V5) range between 0.1 and 1.8 ha (Table 5), accounting for an overall 60.7 % of the vegetation lowering area computed over the entire study reach. The largest patches were V1 (1.3 ha) and V2 (1.8 ha), while the smallest was V4 (0.1 ha). The analysis of the CHM 2003 realized through ForestTools (see Sections 2.3, 2.4) produced an estimate of the volume and the HV_{max} and HV_{mean} eroded in each patch (Table 5). A total volume of 224.4 m^3 of vegetation was eroded from the five patches investigated. Interestingly, despite covering an area of only 1.2 ha, the highest volume was released by V5 (126.8 m^3). Therefore, V5 expressed an eroded vegetated volume rate (*EVVR*) equal to 105.7 m^3 ha^{-1}. Also noteworthy was the *EVVR* exhibited by V1 (47.6 m^3 ha^{-1}) with 61.9 m^3 eroded over an area of 1.3 ha, while the large V2 experienced the lowest *EVVR* (10.8 m^3 ha^{-1}). HV_{max} and HV_{mean} reflected somewhat the trend of *EVVR*. In fact, the tallest trees were detected in V1 and V5, which also exhibited the higher HV_{mean}. The smallest HV_{max} and HV_{mean} were computed in V4 and V2, respectively (Table 5). However, it is worth noting that all HV_{mean} were $>$ 5.0 m, clearly exceeding the mean vegetation height for CHM 2003 (3.49 m) and falling in the tree layer (Table 1).

3.4. Influence of topographic features on the eroded vegetated patches

After the geomorphic and vegetation changes were investigated, the analyses were focused on the relationship between topographic and vegetation features of the V1 – V5 patches (Fig. 8). The correlation matrix showed a clear correlation ($r = 0.93$) between Riverbank Slope (*RS*) and the eroded vegetated area (*EVA*). No significant correlation was identified between *RS* and the remaining variables (Fig. 8). Further evidence of high correlation was observed between the Riverbank Vertical Drop (*RVD*) and both HV_{max} ($r = 0.85$) and HV_{mean} ($r = 0.92$). Both HV_{mean} (r = 0.93) and HV_{max} ($r = 0.74$) were also correlated to the volume rates of the eroded vegetation (*EVVR*). A strong positive correlation was also detected among the vegetation density (*VD*) and both HV_{max} ($r = 0.94$) and *EVVR* (r = 0.94). The latter, in turn, was correlated to the area of deposited sediment (*DSA*, $r = 0.89$). Interestingly, the eroded sediment area was correlated to the eroded vegetated area ($r = 0.91$).

The linear correlation observed between *RS* and *EVA*¸ and between *RVD* and HV_{mean} is shown in Fig. 9. The latter demonstrated how the increase in the eroded mean vegetation height (HV_{mean}) with the augment of riverbank vertical drop (*RVD*) was also accompanied by the increase of *EVVR*.

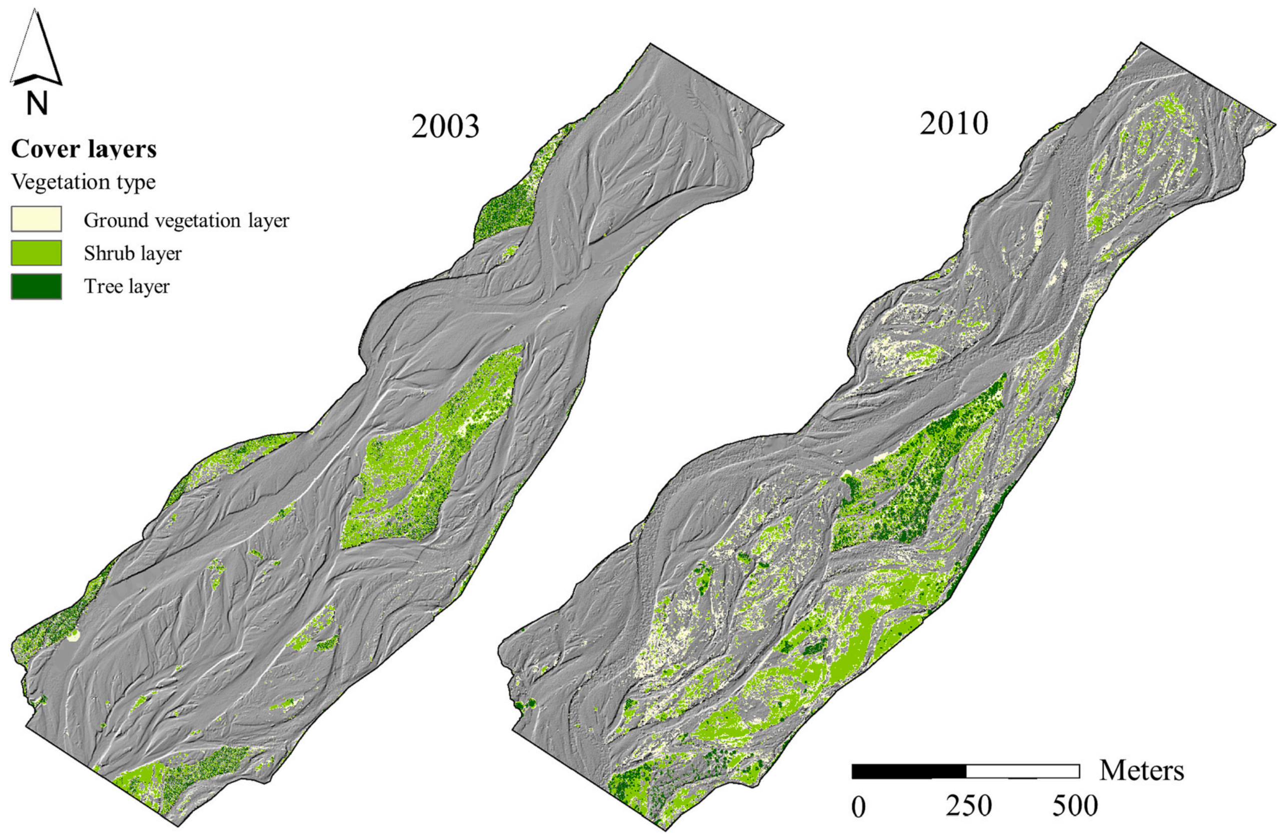

Fig. 5. Analysis of the 2003- and 2010-cover types.

Table 3
Evolution of cover types between 2003 and 2010.

	2003		2010	
	Area (ha)	%	Area (ha)	%
Ground vegetation layer	1.8	2.0	8.9	9.6
Shrub layer	6.6	7.2	11.3	12.3
Tree layer	2.5	2.7	3.3	3.6

4. Discussion

The cover type analysis revealed an evident vegetation increase over the active channel during the study period. The growth and dynamics of vegetation within gravel-bed rivers affected by intense human pressure (i.e., gravel extraction and damming) are well known in different types of rivers (Calle et al., 2017; Gurnell and Grabowski, 2015), as already shown for this study area (Comiti et al., 2011; Picco et al., 2017) and by many other scientists worldwide (Hoffmann et al., 2010; Liu et al., 2014; Fazelpoor et al., 2021). In the present study, the vegetation dynamics were favored by the persistent under-bankfull condition, allowing the vegetation to establish on the exposed gravels, which were occupied mainly by "young vegetation", i.e., by the ground vegetation and shrub layers as demonstrated by the increase in the corresponding cover types. The invasion of young vegetation in human-impacted rivers is frequently linked to the introduction of non-native species that can rapidly colonize exposed gravel and the adjacent surroundings. This colonization can significantly affect riverine biodiversity and environment (Sitzia et al., 2023). Therefore, the results seem to confirm that the distribution, persistence, and composition of vegetation can, on the one hand, be strongly controlled by the disturbance regimes (Hupp and Osterkamp, 1996; Bendix and Hupp, 2000; Gurnell and Petts, 2002) while, on the other hand, its arrangement can change the

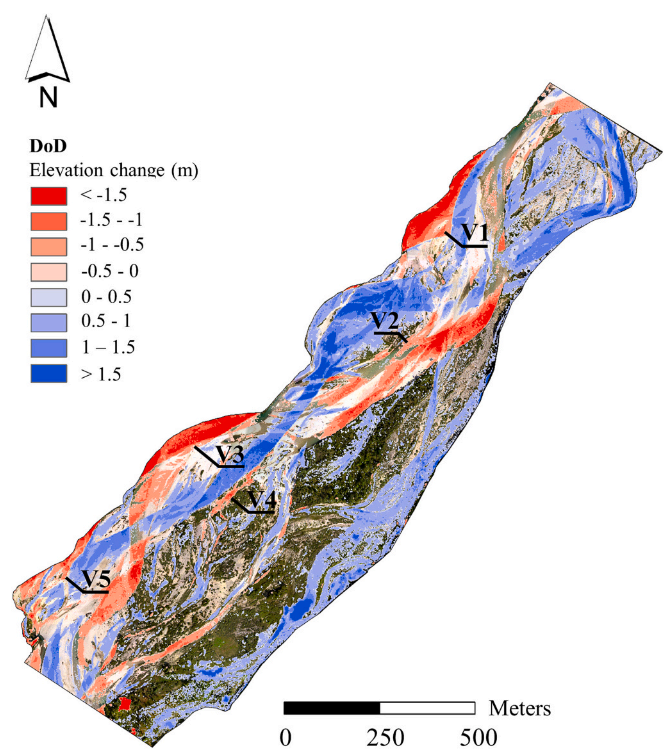

Fig. 6. DoD between DTM 2010 and DTM 2003. V1 – V5 identify the five eroded patches observed (2010 aerial photo in the background).

Table 4
Main results of DoD analyses computed with DTMs and CHMs (2010−2003).

	DTMs		CHMs	
	Raising	Lowering	Raising	Lowering
Total Area (ha)	37.2	13.7	33.9	8.9
Average Depth (m)	0.79 ± 0.28	0.94 ± 0.28	1.41 ± 0.20	2.78 ± 0.20

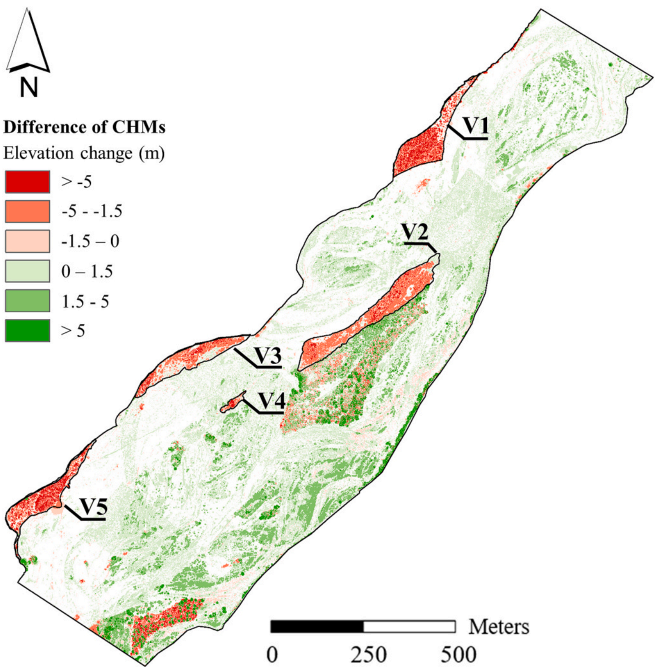

Fig. 7. DoD between CHM 2010 and CHM 2003. V1 – V5 identify the five eroded patches analyzed more in detail. The white area indicates the lack of vegetation (no data) in both 2003 and 2010 CHMs.

Table 5
Eroded vegetated area (*EVA*), volume, maximum- (HV_{max}) and mean-height (HV_{mean}) eroded in the five patches investigated. Analysis realized through the ForestTools applied to the CHM 2003.

	EVA (ha)	*Volume* (m^3)	HV_{max} (m)	HV_{mean} (m)
V1	1.3	61.9	19.5	8.1
V2	1.8	19.5	15.1	5.2
V3	0.9	13.7	14.4	5.9
V4	0.1	2.5	13.8	7.1
V5	1.2	126.8	18.7	9.5

morphodynamics of the active channel, favoring scouring in some parts and erosion in others (Henriques et al., 2022). More specifically, during the study period the absence of large floods permitted the vegetation to expand widely on the exposed gravels. The increasing presence of vegetation also favored the contemporary deposition of fine sediment (i.e., sand and silt) (Pattison et al., 2018) able to improve the characteristics of the terrain facilitating the expansion and survivance of this young vegetation (Popoff et al., 2021). This expansion of young vegetation was pronounced on the left part of the active channel and downstream of the bigger island. The presence of this well-developed, complex and stable island was able to protect the left part of the active channel, thus restricting the flowing channel to the middle and right parts. In this way, the growing vegetation was able to bridge the left part of the channel, connecting the central island to the vegetated part outside the active channel, similar to what is already observed in a downstream section of the Piave River (Picco et al., 2014b). When braided systems are under heavy human pressure (Hicks et al., 2003) and undergo this mechanism of vegetation expansion within the active channel, a change towards a wandering pattern occurs (Surian and Rinaldi, 2004), resulting in a single, narrower, and deeper channel as already shown by Manners et al. (2014). This process can lead to a main stabilization of the higher units that can be easily vegetated (Picco et al., 2017), as in the case of the present study. However, as demonstrated by the DoD analysis, the fluvial island also experienced erosion during the study period. As a result, from the upstream to the downstream end of the island, the vegetated right margin, which was originally covered by shrubs and some trees mostly located along the original boundaries (Fig. 5), has been eroded. It is interesting to note that even in the absence of significant events, other vegetated patches in the study area still experienced erosion. Therefore, it should be kept in mind that the construction of dams and other flood control measures may reduce flood peaks, which would reduce the majority of erosion processes (Kondolf, 1997; Lobera et al., 2015). However, our findings seem to show that erosion and deposition processes still remain active because of the combined action of vegetation spread and conveyance reduction that shifts the active channel from a wider braided pattern to a narrower wandering pattern, constraining the fluxes along a smaller and single strip. This condition ensures the erosion capacity of the fluxes, allowing low flows to erode the restricted cross sections, especially in those areas lacking small and dense vegetation (i.e., shrubs) that can control the erosional processes (Zong and Nepf, 2011). Looking at the structure of the vegetation cover in these areas (Fig. 7), it is interesting to note the presence of many tall trees and a generally high mean height, with larger trees located along the edges and not just far from the main source of disturbance (i.e., the active channel). This setting is far from the theoretical distribution and structure of riparian vegetation (Ellenberg and Leuschner, 2010), demonstrating once again that the triangle based on the geomorphic change, riparian vegetation, and human pressure has a wide range of characteristics that depend on the mutual interactions of these factors and their intensities. In fact, even if the study period was not affected by high flows, the tree layer exhibited an increase clearly lower than the ground vegetation and shrub layers (Fig. 5). The mature vegetation augmented inside the fluvial island but a general increase was somewhat limited by the simultaneous lateral erosion from different parts of the study reach. As already stated, the low flow conditions resulted in lateral shifts, which were primarily concentrated along the right margin of the active channel and along the right side of the fluvial island (Fig. 6). Field evidence in combination with the analysis of flood duration and flood peak discharge (see Section 2.2) suggested that such changes were primarily caused by the December 2009 event (Q peak = 619 $m^3\ s^{-1}$, $Q > Q_{1.5} = 5$ h). However, it can be assumed that some minor variations may also be induced by the November 2003 (Q peak = 483 $m^3\ s^{-1}$, $Q > Q_{1.5} = 0$ h) and May 2010 (Q peak = 499 $m^3\ s^{-1}$, $Q > Q_{1.5} = 1$ h) floods. The May 2010 event may have acted in a limited way in areas earlier destabilized by the larger December 2009 flood. Therefore, the analysis of flood duration and peak discharge demonstrated the occurrence of low flow conditions, which resulted in a persistently under-bankfull discharge ($Q_2 = 700\ m^3\ s^{-1}$) and with only 6 h exceeding the upper bound ($Q_{1.5}$) identified by Comiti et al. (2011) for the high frequent events. Despite differences in human pressure acting in the analyzed fluvial systems, the results detected in the Piave River somehow agreed with the rapid riparian vegetation turnover documented by Surian et al. (2015) in the Tagliamento River. Based on a study period of about 60 years, they observed that, in a braided reach of Tagliamento River, 50 % of riparian vegetation lasted for <5–6 years with vegetation erosion already induced by $Q < Q_{2.5}$. In the Piave River, the DoD analysis demonstrated that the erosion can be clearly identified in five patches (V1 – V5) mainly vegetated by the tree layer (5.2 m < HV_{mean} < 9.5 m). This was likely caused by the lack of a shrub buffer between higher trees and the active channel, which reduced stability or protection from erosive forces during a flood (Zong and Nepf, 2011). Such conditions caused these patches to release a total eroded

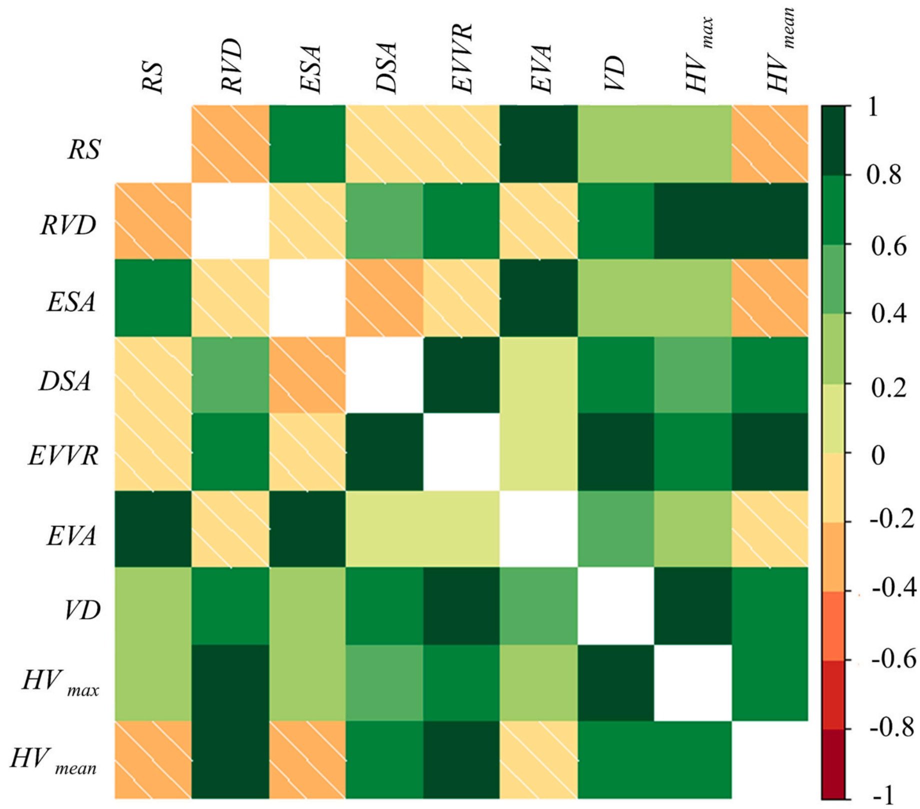

Fig. 8. Correlation matrix considering the variables described in Section 2.4. The dark green colour indicates a high positive correlation while the dark red colour suggests a strong negative correlation. As the correlation decreases, the colour becomes either light green (low positive correlation) or light red (low negative correlation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

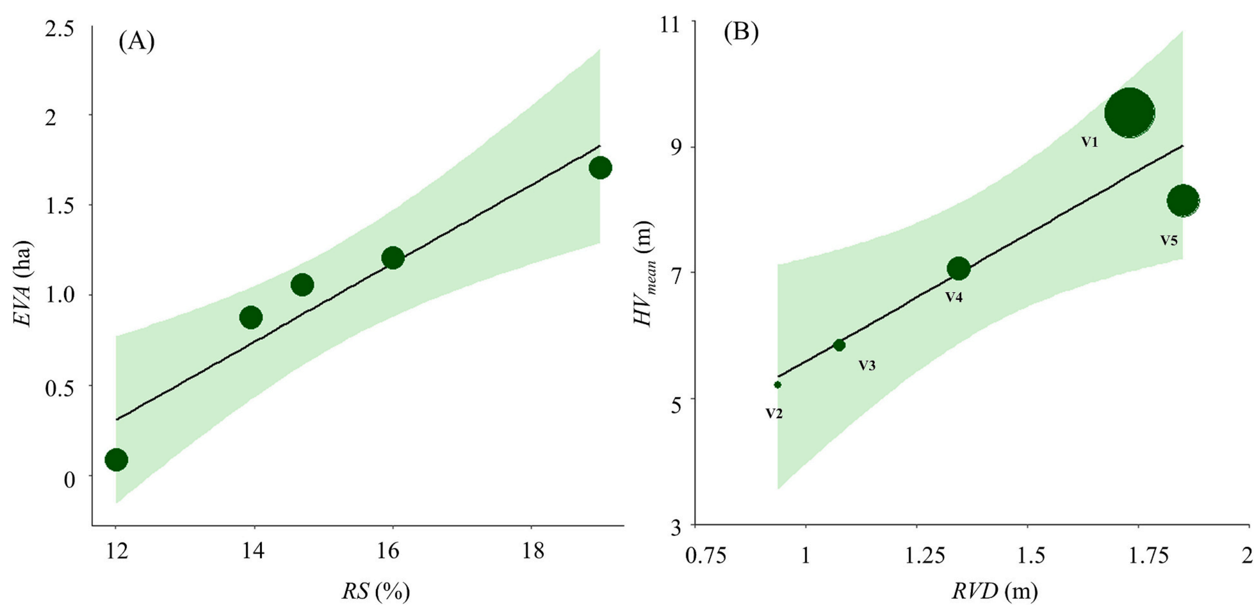

Fig. 9. (A) Relationship between eroded vegetated area (*EVA*) and riverbank slope (*RS*) in the V1 – V5 patches. (B) Relationship between the mean vegetation height (HV_{mean}) and the mean riverbank vertical drop (*RVD*) of the V1 – V5 patches. The size of the green circles increases with increasing the eroded vegetated volume rate (*EVVR*) detected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vegetation volume equal to 224.4 m^3 with an average rate of 42.3 m^3 ha^{-1}. Certainly, not all the recruited vegetation qualifies as large wood (sensu Gurnell et al., 2001), but at least the larger plants do. This is an interesting result because it shows that LW recruitment happens along these types of rivers even during low flow conditions, which means management strategies need to take this into careful consideration. In the Piave River, bank erosion and wood recruitment were documented by Picco et al. (2016b) as consequence of an over-bankfull event (*Q* peak = 1329 m^3 s^{-1}). This flood (*RI* = 6 years) recruited 690 trees, 88 % of which were from the floodplain. However, the analyses of in-channel wood by Tonon et al. (2018) showed that, in the Piave River, bank erosion can transfer LW to the active channel even as a result of low floods, which appears compatible with our findings. Our results can also improve previous research by providing a better understanding of the type of bank that is affected by erosion, as well as identifying possible hotspots that can be controlled by limiting lateral shift and/or LW recruitment. This can be interesting if there are management requests to prevent or decrease the LW load along the active channel, as to mitigate LW-related risks (Mazzorana et al., 2009; Lucía et al., 2015). Moreover, these findings seem to support the hypothesis that the erosion observed as a consequence of low flows might be induced by cantilever bank failure (Thorne and Tovey, 1981), in which the presence of mature vegetation may not favor bank stability but may instead contribute to bank failures from the excess weight exerted by taller trees on the banks. This process could be further promoted by the forest composition of local riparian vegetation, which was about 60 % covered by *Salix species* (Picco et al., 2016a), i.e., trees featuring shallow root systems. Therefore, the analyses in the Piave River seem to stress that younger vegetation (ground vegetation and shrub layers) was effective in protecting riverbanks, inducing in-channel geomorphic changes, while taller trees were not able to protect banks from erosion and may even increase instability by favoring cantilever failures and LW recruitment. Once bank stability was altered, the taller trees could be easily uprooted, leading to significant geomorphic changes. This result appears consistent with the literature that demonstrated how the low and dense riparian vegetation can produce localized erosion caused by the alterations induced in flow velocity (Folkard, 2011; Nepf, 2012) and flow direction (Rominger and Nepf, 2011; Zong and Nepf, 2011). For river managers, this protective impact offered by the low and dense vegetation might be of great relevance. On the one hand, a variety of measures along the riparian corridor can aid in reducing the hazards involved (i.e., excessive LW recruitment, lateral erosion through sensitive areas). On the other hand, appropriate silvicultural approaches can lead to holistic management, combining risk reduction efforts with a general improvement of the riparian corridor, designing the intervention to restore a vegetation distribution closer to the theoretical distribution models (Ellenberg and Leuschner, 2010). The study reach investigated in the Piave River was characterized by the large presence of mature forest with trees over 20 m tall. Under these conditions, the application of the selective cutting could be a silvicultural practice useful both in limiting the flood hazard and in maintaining the high ecological value of the riparian vegetation (Nascimbene et al., 2007; Cislaghi et al., 2021). Moreover, it is evident from our research that various geomorphic conditions also played a role in the erosional processes that affected areas with taller tree coverage. In fact, the investigation of the eroded vegetated patches highlighted the role played by the topographic features in favoring vegetation erosion. Specifically, V1 – V5 exhibited average riverbank slope (*RS*) of 15 % and riverbank vertical drop (*RVD*) of 1.4 m, stressing the steep configuration of the eroded areas. It must be stated that bank erosion is a normal occurrence of natural geomorphic processes along rivers (Florsheim et al., 2008) and that it is a crucial ecological activity (Piegay et al., 2005) that must be preserved or even required for river restoration goals. In this way, our findings can help to clarify the potential river reaches that could be impacted by such dynamics, advancing our understanding of this intricate process, and providing river managers with more tools to act along the rivers that need to mitigate bank erosion or to encourage this process. Our study appears to corroborate the idea that even common floods can have a significant negative impact on steep banks that are not protected by small, dense plants. In the Piave River, such areas may have been eroded through cantilever bank failure, in which erosion magnitude scaled almost linearly between vegetation and sedimentological terms (Fig. 8).

However, it is worth noting that the evolution of gravel and vegetated areas can be affected by a certain degree of uncertainty related to: (i) the LiDAR survey accuracy, consisting in an average vertical error of $\pm$0.20 m; (ii) the error ranges computed in the DoD analyses, that in the vertical averages varied between 7 and 35 %. Additionally, the analysis of the eroded patches was focused on the most evident areas affected by the erosion processes, excluding the zones affected by a slight degree of vertical variation. Thus, an evident eroded area located in the downstream left part of the study reach was excluded by the analysis because it was affected by tree removal from local people. Therefore, in the study reach of Piave River, the occurrence of low flow conditions, on the one hand, have somewhat favored a general expansion of vegetation, which expanded to the disadvantage of exposed gravels and, on the other hand, caused geomorphic changes that resulted in the erosion of specific vegetated patches with mature vegetation.

5. Conclusions

The reach analyzed in the Piave River exhibited a composite response to the low flow conditions recorded during the study period. The absence of high-magnitude events favored a marked expansion of the vegetated areas that occurred mainly through a large increase of the young vegetation (ground vegetation and shrub layers). This led also to a reduction of 20 % in the mean vegetation height during the period 2003–2010. However, the DoD analysis highlighted that the study reach also changed somewhat geomorphically during the study period. On the one hand, a wide area of deposition occurred along the main and secondary channels, and this, in combination with the vegetation expansion, led to the connection between the larger central island with the left bank vegetated part (floodplain and terrace). On the other hand, specific areas were eroded by the low flow conditions, which affected the right floodplain and the fluvial island. This finding, along with the field data, suggests that these variations were primarily caused by the largest flood that occurred during the study period, the December 2009 event, which appears to have triggered cantilever bank failure in locations with tall trees and steep, high banks in direct contact with the active channel. In contrast, young vegetation (ground vegetation and shrub layers) was able to protect the banks, generating localized erosional processes in the active channel. This work highlighted that in the gravel-bed rivers act a strong interplay between runoff, sediment, and vegetation. Such a dynamic is so relevant that it can also be observed in response to persistent low flow conditions. Therefore, a comprehensive management plan should be adopted for these rivers, especially considering the ongoing climate change, and even more so if these rivers are highly regulated. The method for defining the region vulnerable to bank erosion, which depends on the combination of riparian plant arrangement along the transverse profile, its structure and dimension, as well as the geomorphic settings of the bank itself, may be useful to river managers. By taking these aspects into account, managers have more tools at their disposal to better understand bank dynamics and to define interventions capable of guaranteeing stability or instability, depending on the intervention's objective.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by the University of Padova in the frame of the "CAM.SI.FLU.AL" research project, and was carried out within the PNRR research activities of the consortium iNEST (Interconnected

North-Est Innovation Ecosystem) funded by the European Union Next-GenerationEU (Piano Nazionale di Ripresa e Resilienza (PNRR) – Missione 4 Componente 2, Investimento 1.5 – D.D. 1058 23/06/2022, ECS_00000043). This manuscript reflects only the Authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. The "Autorità di Bacino dell'Alto Adriatico" is kindly thanked for providing the LiDAR dataset. Finally, we thank the Editor-in-Chief Scott A. Lecce and two anonymous reviewers, for their constructive comments, which improved the quality of the manuscript.

References

Agnoletti, M., 2000. Il Bosco in età Veneziana. In: Bondesan, A., Caniato, G., Vallerani, F., Zanetti, M. (Eds.), Il Piave. Cierre Edizioni, Verona, pp. 259–272.
Asaeda, T., Sanjaya, K., 2017. The effect of the shortage of gravel sediment in midstream river channels on riparian vegetation cover. River Res. Appl. 33 (7), 1107–1118.
Bendix, J., Hupp, C.R., 2000. Hydrological and geomorphological impacts on riparian plant communities. Geomorphology 14, 2977–2990.
Bertoldi, W., Zanoni, L., Tubino, M., 2009. Planform dynamics of braided streams. Earth Surf. Process. Landf. 34, 547–557.
Bertoldi, W., Gurnell, A.M., Drake, N.A., 2011. The topographic signature of vegetation development along a braided river: results of a combined analysis of airborne lidar, color air photographs, and ground measurements. Water Resour. Res. 47, W06525.
Bertoldi, W., Gurnell, A.M., Welber, M., 2013. Wood recruitment and retention: the fate of eroded trees on a braided river explored using a combination of field and remotely sensed data sources. Geomorphology 180, 146–155.
Brasington, J., Rumsby, B.T., McVey, R.A., 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. Earth Surf. Process. Landf. 25, 973–990.
Brasington, J., Langham, J., Rumsby, B., 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology 53, 299–316.
Braudrick, C.A., Dietrich, W.E., Leverich, G.T., Sklar, L.S., 2009. Experimental evidence for the conditions necessary to sustain meandering in coarsebedded rivers. In: Proceedings of the National Academy of Science of the United States of America, 106, pp. 16936–16941.
Brice, J.C., 1964. Channel patterns and terraces of the Loup Rivers in Nebraska. In: U.S. Geological Survey Professional Paper 422-D: 41.
Brierley, G., Fryirs, K., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Victoria, Australia (398 pp.).
Brummer, T.J., Byrom, A.E., Sullivan, J.J., Hulme, P.E., 2016. Alien and native plant richness and abundance respond to different environmental drivers across multiple gravel floodplain ecosystems. Divers. Distrib. 22 (7), 823–835.
Calle, M., Alho, P., Benito, G., 2017. Channel dynamics and geomorphic resilience in an ephemeral Mediterranean river affected by gravel mining. Geomorphology 285, 333–346.
Charlton, M.E., Large, A.R.G., Fuller, I.C., 2003. Application of airborn LIDAR in river environments: the river Coquet, Northumberland, UK. Earth Surf. Process. Landf. 28, 299–306.
Cislaghi, A., Alterio, E., Fogliata, P., Rizzi, A., Lingua, E., Vacchiano, G., Bischetti, G.B., Sitzia, T., 2021. Effects of tree spacing and thinning on root reinforcement in mountain forests of the European Southern Alps. For. Ecol. Manag. 482, 118873.
Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., Lenzi, M.A., 2011. Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200 years. Geomorphology 125 (1), 147–159.
Del Favero, R., Lasen, C., 1993. La Vegetazione Forestale del Veneto. Progetto Editore, Padova, Italy, p. 312.
Ellenberg, H., Leuschner, C., 2010. Vegetation Mitteleuropas mit den Alpen: in ̈okologischer, dynamischer und historischer Sicht. Eugen Ulmer KG, Stuttgart, Germany.
Fazelpoor, K., Martínez-Fernández, V., García de Jalón, D., 2021. Exploring the hydromorphological response to human pressure in Tagus River (1946–2014) by complementary diagnosis. Catena 198.
Florsheim, J.L., Mount, J.F., Chin, A., 2008. Bank erosion as a desiderable attribute of rivers. BioScience 58 (6), 519–529.
Folkard, A., 2011. Flow regimes in gaps within stands of flexible vegetation: laboratory flume simulations. Environ. Fluid Mech. 11, 289–306.
Galia, T., Skarpich, V., Vardakas, L., Dimitriou, E., Panagopoulos, Y., Spálovský, V., 2023. Spatiotemporal variations of large wood and river channel morphology in a rapidly degraded reach of an intermittent river. Earth Surf. Process. Landf. 48 (5), 997–1010.
Gurnell, A.M., Grabowski, R.C., 2015. Vegetation–hydrogeomorphology interactions in a low-energy, human-impacted. River Res. Appl. 32, 202–215.
Gurnell, A.M., Petts, G.E., 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. Freshw. Biol. 47, 581–600.
Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., 2000. Wood storage within the active zone of a large European gravel-bed river. Geomorphology 34 (1), 55–72.
Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surf. Process. Landf. 26, 31–62.
Hadley, R.F., 1961. Influence of riparian vegetation on channel shape, northeastern Arizona. U. S. Geol. Surv. Prof. Pap. 424-C, 30–31.
Han, M., Brierley, G., Li, B., Li, Z., Li, X., 2020. Impacts of flow regulation on geomorphic adjustment and riparian vegetation succession along an anabranching reach of the Upper Yellow River. Catena 190, 104561.
Henriques, M., McVicar, T.R., Hollan, K.L., Daly, E., 2022. Riparian vegetation and geomorphological interactions in anabranching rivers: a global review. Ecohydrology 15 (2), e2370.
Heritage, G., Hetherington, D., 2007. Towards a protocol for laser scanning in fluvial geomorphology. Earth Surf. Process. Landf. 32, 66–74.
Hicks, D.M., Duncan, M.J., Shankar, U., Wild, M., Walsh, J.R., 2003. Project Aqua: Lower Waitaki River Geomorphology and Sediment Transport. NIWA Client Report CHC01/115. National Institute of Water and Atmospheric Research, Christchurch (195 pp.).
Hoffmann, T., Thorndycraft, V.R., Brown, A.G., Coulthard, T.J., Damnati, B., Kale, V.S., Middelkoop, H., Notebaert, B., Walling, D.E., 2010. Human impact on fluvial regimes and sediment flux during the holocene: review and future research agenda. Glob. Planet. Chang. 72, 87–98.
Hupp, C.R., 1988. Plant ecological aspects of flood geomorphology and paleoflood history. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 335–356.
Hupp, C.R., Osterkamp, W.R., 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relations to landforms. Ecology 66, 670–681.
Hupp, C.R., Osterkamp, W.R., 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14, 277–295.
Kondolf, G.M., 1997. Application of the pebble count: notes on purpose, methods and variants. J. Am. Water Resour. Assoc. 33, 79–87.
Kramer, N., Wohl, E., 2017. Rules of the road: a qualitative and quantitative synthesis of large wood transport through drainage networks. Geomorphology 279, 74–97.
Lane, S.N., Chandler, J.H., 2003. The generation of high quality topographic data for hydrology and geomorphology: new data sources, new applications and new problems. Earth Surf. Process. Landf. 28 (3), 229–230.
Lane, S.N., Westaway, R.M., Hicks, D.M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surf. Process. Landf. 28, 249–271.
Larsen, L., Harvey, J., Crimaldi, J., 2009. Predicting bed shear stress and its role in sediment dynamics and restoration potential of the Everglades and other vegetated flow systems. Ecol. Eng. 35, 1773–1785.
Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering and straight. In: U.S. Geological Survey Professional Papers, 282B, pp. 39–85.
Li, S.S., Millar, R.G., 2011. A two-dimensional morphodynamic model of gravel-bed river with floodplain vegetation. Earth Surf. Process. Landf. 36 (2), 190–202.
Liu, X., Zhang, J., Zhu, X., Pan, Y., Liu, Y., Liu, Y., Zhang, D., Lin, Z., 2014. Spatiotemporal changes in vegetation coverage and its driving factors in the Three-River Headwaters Region during 2000–2011. J. Geogr. Sci. 24, 288–302.
Lobera, G.P.B., Vericat, D., Lòpez-Tarazòn, J.A., Tena, A., Aristi, I., Diez, J.R., Ibisate, A., Larrañaga, A., Elosegi, A., Batalla, R.J., 2015. Geomorphic status of regulated rivers in the Iberian Peninsula. Sci. Total Environ. 508, 101–114.
Lucía, A., Comiti, F., Borga, M., Cavalli, M., Marchi, L., 2015. Dynamics of large wood during a flash flood in two mountain catchments. Nat. Hazards Earth Syst. Sci. 15 (8), 1741–1755.
MacVicar, B., Piégay, H., 2012. Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). Earth Surf. Process. Landf. 37, 1272–1289.
Magilligan, F.J., Buraas, E.M., Renshaw, C.E., 2014. The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding. Geomorphology 228, 175–188.
Manners, R.B., Schmidt, J.C., Scott, M.L., 2014. Mechanisms of vegetation-induced channel narrowing of an unregulated canyon river: results from a natural field-scale experiment. Geomorphology 211, 100–115.
Mazzorana, B., Zischg, A., Largiader, A., Hübl, J., 2009. Hazard index maps for woody material recruitment and transport in alpine catchments. Nat. Hazards Earth Syst. Sci. 9 (1), 197–209.
McBride, M., 2007. Riparian Reforestation and Channel Change: Key Driving Mechanisms in Small Streams. Ph.D. dissertation,. University of Vermont, Burlington (185 pp.).
McBride, M., Hession, C.W., Rizzo, D.M., 2010. Riparian reforestation and channel change: how long does it take? Geomorphology 116, 330–340.
Mikuś, P., Wyżga, B., Kaczka, R.J., Walusiak, E., Zawiejska, J., 2013. Islands in a European mountain river: linkages with large wood deposition, flood flows and plant diversity. Geomorphology 202, 115–127.
Milan, D.J., Heritage, G.L., 2012. LiDAR and ADCP Use in Gravel-Bed Rivers: advances since GBR6. In: Church, M., Biron, P.M., Roy, A.G. (Eds.), Gravel-Bed Rivers: Processes, Tools, Environments.
Murray, A.B., Paola, C., 2003. Modelling the effect of vegetation on channel pattern in bedload rivers. Earth Surf. Process. Landf. 28, 131–143.
Nascimbene, J., Marini, L., Nimis, P.L., 2007. Influence of forest management on epiphytic lichens in a temperate beech forest of northern Italy. For. Ecol. Manag. 247, 43–47.
Nepf, H.M., 2012. Hydrodynamics of vegetated channels. J. Hydraul. Res. 50 (3), 262–279.
Pattison, Z., Whytock, R., Willby, N., 2018. Invasion legacy effects versus sediment deposition as drivers of riparian vegetation. Biol. Invasions 20, 1189–1198.
Pellegrini, G., Martini, L., Rainato, R., Picco, L., 2022. Large wood mobilization and morphological changes in an alpine river following the release of an ordinary experimental flood from an upstream dam. Catena 216, 106398.

Picco, L., Mao, L., Cavalli, M., Buzzi, E., Rainato, R., Lenzi, M.A., 2013. Evaluating short-term morphological changes in a gravel-bed braided river using terrestrial laser scanner. Geomorphology 201, 323–334.
Picco, L., Ravazzolo, D., Rainato, R., Lenzi, M.A., 2014a. Characteristics of fluvial islands along three gravel bed-rivers of North-Eastern Italy. Cuadernos de Investigacion Geografica 40, 53–66.
Picco, L., Mao, L., Rainato, R., Lenzi, M.A., 2014b. Medium-term fluvial island evolution in a disturbed gravel-bed river (Piave River, Northeastern Italian Alps). Geogr. Ann. 96 (1), 83–97.
Picco, L., Tonon, A., Ravazzolo, D., Rainato, R., Lenzi, M.A., 2015. Monitoring river islands dynamics using aerial photographs and LiDAR data: the Tagliamento river study case. Appl. Geomatics 7, 163–170.
Picco, L., Sitzia, T., Mao, L., Comiti, F., Lenzi, M.A., 2016a. Linking riparian woody communities and fluviomorphological characteristics in a regulated gravel-bed river (Piave River, Northern Italy). Ecohydrology 9, 101–112.
Picco, L., Tonon, A., Rainato, R., Lenzi, M.A., 2016b. Bank erosion and large wood recruitment along a gravel bed river. J. Agric. Eng. 47 (2), 72–81.
Picco, L., Comiti, F., Mao, L., Tonon, A., Lenzi, M.A., 2017. Medium and short term riparian vegetation, island and channel evolution in response to human pressure in a regulated gravel bed river (Piave River, Italy). Catena 149, 760–769.
Piegay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Res. Appl. 21, 773–789.
Pizzuto, J., O'Neal, M., Stotts, S., 2010. On the retreat of forested, cohesive riverbanks. Geomorphology 116, 341–352.
Plowright, A., 2018. Package "ForesTools". https://cran.r-project.org/package=ForesTools.
Poff, N.L., Olden, J.D., Merritt, D.M., Pepin, D.M., 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proc. Natl. Acad. Sci. U.S.A. 104, 5732–5737.
Pollen-Bankhead, N., Simon, A., 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: is mechanical root reinforcement the whole story? Geomorphology 116, 353–362.
Popoff, N., Jaunatre, R., Le Bouteiller, C., Trinquier, M., Paillet, Y., Evette, A., 2021. Ecological succession and fine sediment accretion influence local patch dynamics of a pioneer riparian species (Typha minima Hoppe). Freshw. Biol. 66, 2351–2363.
Rainato, R., Picco, L., Mao, L., Moretto, J., Lenzi, M.A., 2014. The extent of partial transport in a disturbed gravel-bed braided river. In: Ferro, V., Niedda, M. (Eds.), Dissesto Idrogeologico e Processi Erosivi in Ambiente Collinare e Montano. EdiBios, Quaderni Idronomia Montana 32/1, pp. 265–276.
Ravazzolo, D., Mao, L., Picco, L., Lenzi, M.A., 2015. Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices. Geomorphology 228, 226–233.
Rominger, J., Nepf, H.M., 2011. Flow adjustments and interior flow associated with a rectangular porous obstruction. J. Fluid Mech. 680, 636–659.
Rowinski, P.M., Vastila, K., Aberle, J., Jarvela, J., Kalinowska, M.B., 2018. How vegetation can aid in coping with river management challenges: a brief review. Ecohydrol. Hydrobiol. 18, 345–354.
Rumsby, B.T., Brasington, J., Langham, J.A., McLelland, S.J., Middleton, R., Rollison, G., 2008. Monitoring and modelling particle and reach-scale morphological change in gravel-bed rivers: applications and challenges. Geomorphology 93 (1–2), 40–54.
Sharpe, R., Kemp, J., 2021. Vegetation disturbances and flood energy during an extreme flood on a sub-tropical river. Earth Surf. Process. Landf. 46 (14), 2841–2855.
Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surf. Process. Landf. 27 (5), 527–546.
Sitzia, T., Picco, L., Ravazzolo, D., Comiti, F., Mao, L., Lenzi, M.A., 2016. Relationships between woody vegetation and geomorphological patterns in three gravel-bed rivers with different intensities of anthropogenic disturbance. Adv. Water Resour. 93, 193–204.
Sitzia, T., Iacopino, S., Alterio, E., Comiti, F., Surian, N., Mao, L., Lenzi, M.A., Campagnaro, T., Picco, L., 2023. Revisiting vegetation gradient analysis and the intermediate disturbance hypothesis for the interpretation of riverine geomorphic patterns. Land 12, 378.
Surian, N., 1999. Channel changes due to river regulation: the case of the Piave River, Italy. Earth Surf. Process. Landf. 24, 1135–1151.
Surian, N., Rinaldi, M., 2004. Channel adjustments in response to human alteration of sediment fluxes: examples from Italian rivers. In: Golosov, V., Belyaev, V., Walling, D.E. (Eds.), Sediment Transfer Through the Fluvial System, Publication 288. IAHS, pp. 276–282.
Surian, N., Barban, M., Ziliani, L., Monegato, G., Bertoldi, W., Comiti, F., 2015. Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. Earth Surf. Process. Landf. 40 (4), 542–558.
Tal, M., Paola, C., 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. Earth Surf. Process. Landf. 35, 1014–1028.
Tamminga, A., Hugenholtz, C., Eaton, B., Lapointe, M., 2015. Hyperspatial remote sensing of channel reach morphology and hydraulic fish habitat using an unmanned aerial vehicle (UAV): a first assessment in the context of river research and management. River Res. Appl. 31, 379–391.
Tanino, Y., Nepf, H.M., 2008. Lateral dispersion in random cylinders arrays at high Reynolds number. J. Fluid Mech. 600, 339–371.
Thorne, C.R., Tovey, N.K., 1981. Stability of composite river banks. Earth Surf. Process. Landf. 6, 469–484.
Tonon, A., Iroumé, A., Picco, L., Oss-Cazzador, D., Lenzi, M.A., 2017. Temporal variations of large wood abundance and mobility in the Blanco River affected by the Chaitén volcanic eruption, southern Chile. Catena 156, 149–160.
Tonon, A., Rainato, R., Picco, L., 2018. Test of methodology for developing a large wood budget: a 1-year example from a regulated gravel bed river following ordinary floods. Catena 165, 115–124.
Van de Wiel, M.J., Darby, S.E., 2007. A new model to analyse the impact of woody riparian vegetation on the geotechnical stability of riverbanks. Earth Surf. Process. Landf. 32, 2185–2198.
Van Dijk, W.M., Teske, R., Van de Lageweg, W.I., Kleinhans, M.G., 2013. Effects of vegetation distribution on experimental river channel dynamics. Water Resour. Res. 49 (11), 7558–7574.
Vargas-Luna, A., Duró, G., Crosato, A., Uittewaal, W., 2019. Morphological adaptation of river channels to vegetation establishment: a laboratory study. J. Geophys. Res. Earth Surf. 124 (7), 1981–1995.
Vericat, D., Smith, M.W., Brasington, J., 2014. Patterns of topographic change in sub-humid badlands determined by high resolution multi-temporal topographic surveys. Catena 120, 164–176.
Vericat, D., Wheaton, J.M., Brasington, J., 2017. Revisiting the morphological approach. In book: Gravel-Bed Rivers: Processes and Disasters (pp. 121-158) (Chapter: 5) Publisher: Wiley Editors: Daizo Tsutsumi, Jonathan B. Laronne.
Wharton, C.H., Kitchens, W.M., Pendleton, E.C., Sipe, TW., 1982. The ecology of bottomland hardwood swamps of the southeast- a community profile. U.S. Fish and Wildlife Service Technical Report, FWS/OBS/ 81–37, 1–33.
Wheaton, J.M., 2008. Uncertainty in Morphological Sediment Budgeting of Rivers (Ph.D. Thesis). University of Southampton, Southampton, UK (412 pp.).
Wheaton, J.M., Brasington, J., Darby, S.E., Merz, J., Pasternak, G.B., Sear, D.A., Vericat, D., 2010. Linking geomorphic changes to salmonid habitat at a scale relevant to fish. River Res. Appl. 26, 469–486.
Wheaton, J.M., Brasington, J., Darby, S.E., Kasprak, A., Sear, D.A., Vericat, D., 2013. Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. J. Geophys. Res. 118 (2), 759–779.
Williams, R.D., Bangen, S., Gillies, E., Kramer, N., Moir, H., Wheaton, J., 2020. Let the river erode! Enabling lateral migration increases geomorphic unit diversity. Sci. Total Environ. 715, 136817.
Wohl, E., 2017. Bridging the gaps: an overview of wood across time and space in diverse rivers. Geomorphology 279, 3–26.
Zimmerman, R.C., Goodlet, J.C., Comer, G.H., 1967. The influence of vegetation on channel form of small streams. In: In Proceedings of the Symposium on River Morphology, International Association of Hydrological Sciences Publication 75: 255–275. IAHS Press, Wallingford, UK.
Zong, L., Nepf, H., 2011. Spatial distribution of deposition within a patch of vegetation. Water Resour. Res. 47, W03516.