Thirty years of vegetation cover dynamics and planform changes in the Brenta River (Italy): implications for channel recovery

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Abstract The timing and extent of the morphological changes that occurred in the last 30 years in a gravel-bed river (the Brenta River, eastern Italian Alps) have been analysed using eight sets of aerial photos, repeated topographic measurements and morphological–vegetational surveys. Human activities have produced modifications in the natural sediment regime and the cessation of gravel extraction in the late 1990s seems to have caused vegetation erosion and channel widening. Alteration of sediment regime has played a major role in the medium and short-term channel evolution. However, only relevant flood events (RI > 10 years) appear to determine substantial islands erosion. The analysis at smaller scale (sub-reach level) proved to be more effective in describing morphological responses and its relationships with the sediment dynamics within the study reach (20 km). The understanding of sediment transfer at the sub-reach level will provide helpful guidelines for the discussion of channel recovery potential.

Key words channel changes; fluvial erosion; vegetation cover dynamic; river restoration

INTRODUCTION

The anthropogenic activities over the past 200 years, such as urbanization, dam building, water diversions, have altered the natural dynamic stability of most European rivers (Gurnell *et al*., 2009; Surian *et al*., 2009; Comiti *et al*., 2011). Considering Italian rivers, a common trend of considerable channel responses has been recognized in recent decades, consisting of a major phase of narrowing and incision followed by more recent widening processes (Surian & Rinaldi, 2003, 2004). The morphology of fluvial systems has changed considerably. In fact, multi-channel patterns were more common previously. Contemporary braided rivers are far less dynamic than in the past. A river reach disturbed by a series of human interventions usually reacts, adjusting its morphological pattern to changing water and sediment input conditions (Lenzi *et al*., 2006; Mao & Lenzi, 2007), modifying the features and covering of riparian vegetation (Surian & Rinaldi, 2003; Comiti *et al*., 2011; Picco *et al*., 2012a) and determines the amount of in-channel wood (Comiti *et al*., 2006; Rigon *et al*., 2012). Understanding fluvial processes and channel evolution is a crucial issue for a sustainable management and restoration of largely impacted streams. An effective river restoration, as defined in the EU Water Framework Directive, is now required for most Alpine rivers that are characterized by channel instability, flood problems and biodiversity decline.

This paper deals with the morphological evolution and the associated vegetation dynamics of the lower course of the Brenta River over the last 30 years. The evolution of this stretch of the Brenta River is interesting to study because this reach was affected by human pressure coming from a dense hydropower scheme and past gravel mining activity. The present work presents an analysis of lateral adjustments and vegetation cover dynamics during the last 30 years. The varying channel response exhibited at sub-reach scale is analysed so as to improve the knowledge of connection between driving factors and responses through precise reconstruction of channel evolution. The analysis of the erosion and deposition patterns caused by large floods will be supported by a study (Moretto *et al*., 2012) which has detected the short term morphological adjustments at sub-reach (in Brenta River) by comparison of two high definition digital terrain models, obtained by fusion of LIDAR surveys and bathymetry from aerial photos.

The objectives of this paper are: (i) to quantify the variation of vegetation cover, with particular emphasis on islands dynamics; (ii) to quantify the morphological changes in bed planform; (iii) the identification of the driving factors of channel evolution and vegetation cover changes thus envisaging the most likely future trends; (iv) to explore possibilities and limitations of physical processes of restoration in order to reduce the alteration of sediment fluxes. Specifically it will seek to determine whether gravel mining is the main factor driving recent channel and vegetation cover changes, and if the recent channel changes at sub-reach scale may be considered short-term fluctuations related to specific flood events, rather than real medium-term adjustments.

GENERAL SETTINGS OF THE STUDY AREA

Brenta basin

The Brenta is one of the most important rivers of the Venetian plain (Fig. 1), and the drainage area extends for 1567 km^2. The river length is 174 km, and the first 70 km (unicursal and straight channel) are within a mountain basin. Downstream, the river evolves in a braided-wandering pattern in the piedmont area (Surian & Cisotto, 2007), before becoming meandering and then heavily rectified in its lower course. The geological setting is rather complex and includes limestone, dolomite, gneiss, phyllite, granite, and volcanic rocks.

In past centuries, the Brenta River has suffered the consequences of multi-spatial and temporal human pressure, that consist mostly of direct interventions, such as channelization, gravel mining and dam, levees and groins construction, but also of indirect effects on river dynamics, such as reforestation (Surian *et al*., 2009). Gravel mining has been recognized as the human intervention with the greatest impact, particularly in the plain stretch (extraction peak in the 1950s–1980s) exceeding replenishment rates and producing a significant alteration in sediment fluxes. The second most important human disturbance has been the construction of several dams and barrages which have reduced both flow and sediment discharges. The largest dam, built in 1954 in the Cismon torrent, is the Corlo dam (42 million m^3 reservoir). The natural reforestation in mountainous areas has contributed to the reduction of available sediment. Testimonies of these impacts are the narrowing of the average river bed width from around 440 m at the beginning of the 1800s, to around 220 m in 2003 and the remarkable channel incision up to 7 m (Surian & Cisotto, 2007).

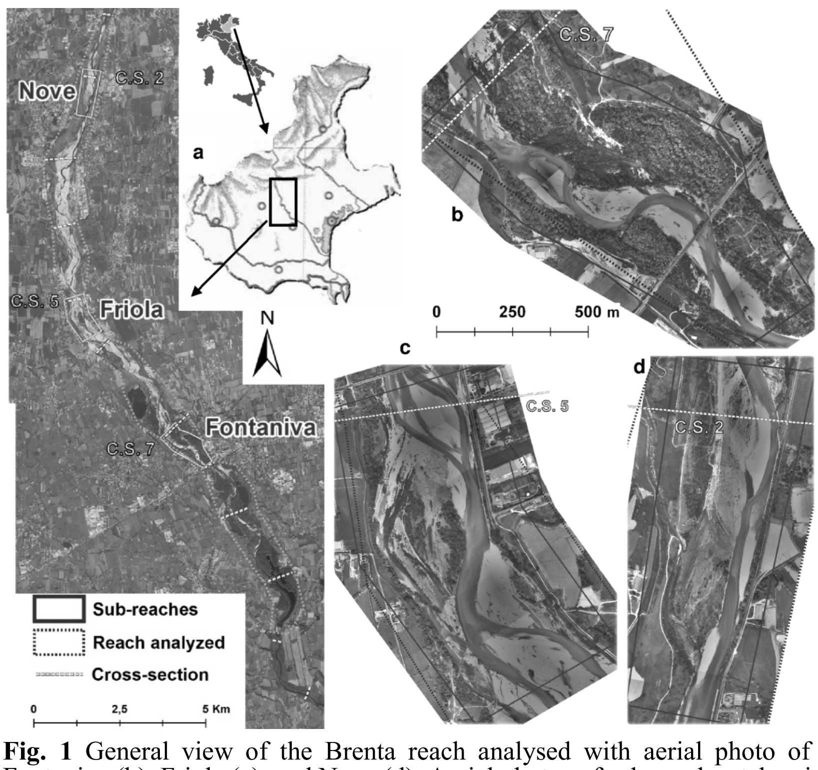

Fig. 1 General view of the Brenta reach analysed with aerial photo of 2006 (a) and sub-reaches: Fontaniva (b), Friola (c), and Nove (d). Aerial photos of sub-reaches taken in 2011.

Study reach and sub-reaches

The Brenta River's reach analysed is approximately 20 km long and is located between the cities of Bassano del Grappa and Piazzola sul Brenta (Fig. 1(a)). The upper portion of the reach, located immediately downstream of the mountain area, features a fairly straight channel and a narrow alluvial plain. In the middle portion the river widens, the slope is lower and the river features a braided pattern with vegetated islands. In the lower portion, the river exhibits a meandering aspect with moderate sinuosity (≈1.12) and there is the presence of extensive riparian vegetation. In this river reach, three sub-reaches have been highlighted for detailed study: Nove (Fig. 1(d)), Friola (Fig. 1(c)), and Fontaniva (Fig. 1(b)). The Nove sub-reach features a single channel and the average width of the bankfull is 390 m. The Friola sub-reach is wider (around 500 m) has a braided pattern with densely vegetated island. In the lower sub-reach (Fontaniva), the Brenta River features an island-braided pattern, active width increases up to 800 m. Table 1 summarizes data for the sub-reaches. Within the study reach (and sub-reaches) there is a wide range of human infrastructure such as embankments, bridges, water intakes, and transversal structures that affect the fluvial morphology and dynamics.

Table 1 Characteristics of the analysed sub-reaches. Bankfull and floodplain width are derived from the 2011 aerial photos. Grain size of surface sediments derive from a 2010 field survey.

SUB-REACH	A (km^2)	Wb (m)	Wf (m)	Elv (m a.s.l)	S (%)	D_{50} (mm)	D_{84} (mm)
Nove	1.22	182	390	81.4	0.39	37	87
Friola	0.62	272	484	53.1	0.26	35	79
Fontaniva	0.56	316	678	37.1	0.31	31	64

A: surface area; W*b*: mean bankfull width; W*f*: mean plan bed width; Elv: mean elevation; S: mean slope; D_{xx}: grain size of the xxth percentile of surface sediments.

MATERIALS AND METHODS

The top 10 historical sections (12 in total, for details see Surian & Cisotto, 2007) were re-surveyed with a DGPS with a maximum vertical error of ±0.02 m. Cross-sections 2, 5, and 7 are located in the Nove, Friola, and Fontana sub-reaches, respectively (Fig. 1). The longitudinal profile along the river reach was derived from an averaged cross-section elevation, calculated using all points within the active channel.

The hydrological analysis has been carried out with the historical series of hydrometric levels registered at the gauging station of Barzizza (Bassano del Grappa), managed by ARPAV (Environmental Protection Agency of Veneto Region). The station is located 5 km upstream from the analysed reach. Mean daily discharges are available from 1924 to 2011. In order to evaluate their frequency of occurrence, the return interval of each flood was estimated from values of annual maximum discharge over 87 years. The bankfull discharge (recurrence interval of 1.5 years) has been calculated around 350 $m^3 s^{-1}$, which is exceeded 2.4 days per year. The greatest flood event was registered in November 1966 with 1330 $m^3 s^{-1}$ (RI = 200 years). Figure 2 reports the average daily discharge and annual peak discharges.

Riparian vegetation and bed river morphology evolution over the last 30 years have been analysed, taking advantage of eight series of aerial photos, always taken during low-water level conditions. The photos were scanned at a resolution of 1 m for the older flights (1981, 1990), and then at higher resolution up to 0.15 m for the 2010 and 2011 photo. Aerial photographs were rectified and co-registered to a common mapping base at 1:5000 using GIS software (ESRI® ArcGIS 10). Approximately 40 ground control points were used to rectify each single frame, and third-order polynomial transformations were then applied, obtaining root mean square errors (RMSE) ranging from 1 to 2 m. These photos have been analysed using the same method described in Comiti *et al*. (2011) in order to identify the active channel and island extent. The

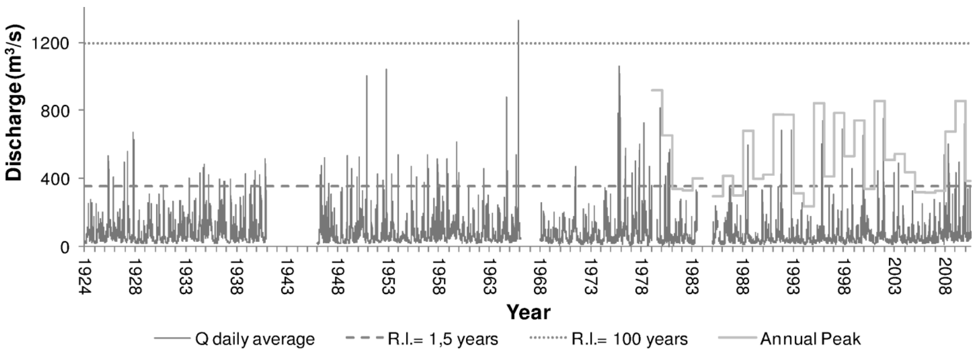

Fig. 2 Daily average discharge record at the hydrometric station of Barzizza (Bassano del Grappa).

active channel is defined as the area without arboreal vegetation, thus including naked bars and active and inactive channels, while the fluvial islands include pioneer, young and stable islands according to the classification of Gurnell & Petts (2002). Active channel and island width were taken in 85 positions, 250 m apart in transects perpendicular to the river axis which were created in GIS environment.

RESULTS

Changes of island area and active channel along the whole study reach

The extension of islands and active channel within entire reach scale was calculated, by photo-interpretation from the historical series of aerial photos from 1981 to 2011. Some images of island and channel evolution is reported in Fig. 3. The analysis of the active channel has confirmed remarkable fluctuations during the last 30 years (Fig. 4).

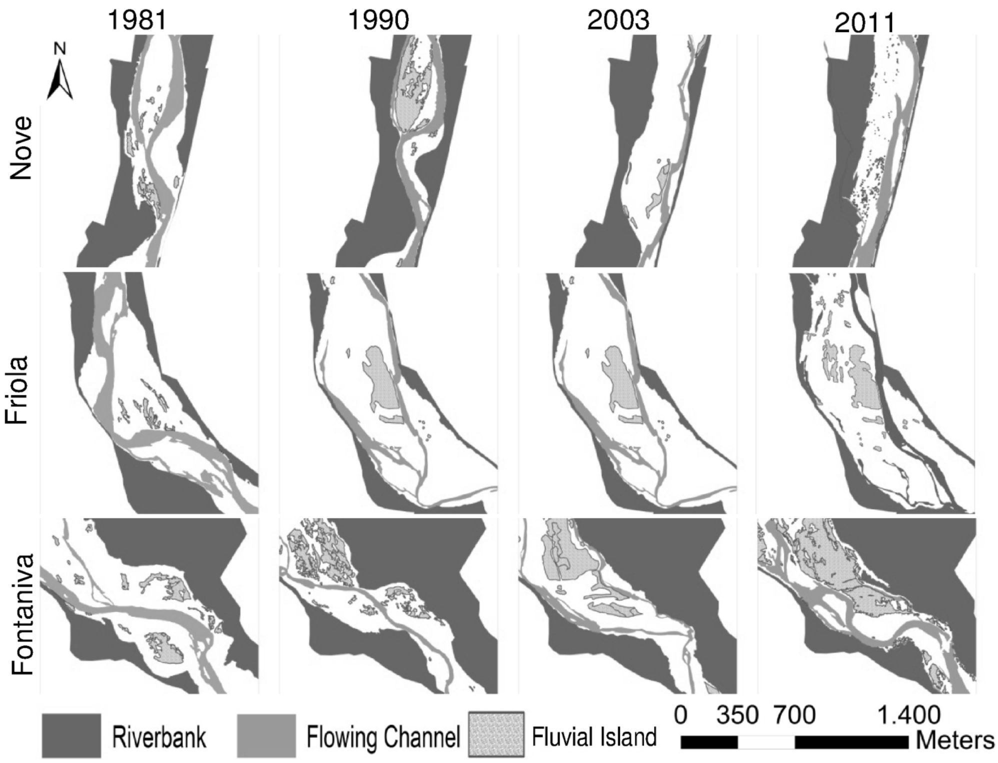

Fig. 3 Morphological and island evolution of sub-reaches derived from photo interpretation.

Four significant periods characterized by different dynamics of active channel and islands changes could be identified: 1981–1990, 1990–2003, 2003–2008, and 2008–2011. It is interesting to observe that the variation of islands area reflects the trend of the active channel area. The first phase from 1981 to 1990 is characterized by an increase of 77 ha of islands, and a decrease of the active channel (–148 ha). The second phase from 1990 to 2003, is characterized by 14 over-bankfull floods, of which one in 2002 had a higher than 10-year return interval and features a marked decrease of island area (–52 ha) and an increase of active channel of 58 ha. Afterwards, due to the lack of high-magnitude floods from 2003 to 2008, islands area increased (52 ha). The most recent phase from 2008 to 2011 is characterized by a reduction of 26 ha of islands area and an increase of 51 ha of the active channel. Interestingly, the maximum islands extension occurred in 1990 (that corresponded to 25% of the fluvial corridor) coincides with the minimum extension of the active channel. Conversely, the minimum island extension coincides with the maximum extent of the active area (1981).

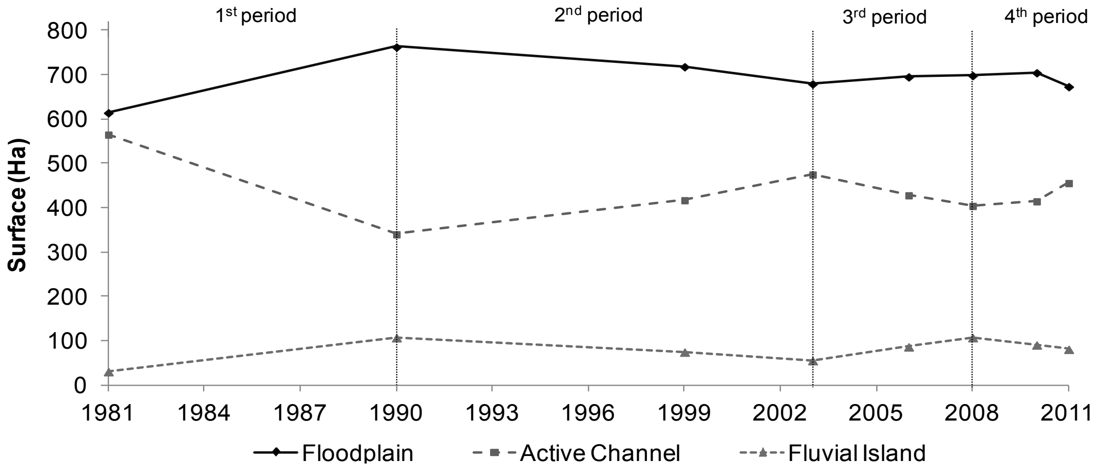

Fig. 4 Temporal variation of the surface of the active channel (excluding islands area), floodplain and islands in the analysed reach of Brenta River.

During the first decade of the analysed period (1981–1990) the average active channel width (Table 2) decreases from 266 m to 181 m (–32%; 9.44 m year^{-1}). The active channel narrowing seems to have occurred along the whole river reach, except for a rather marked enlargement occurring near the Fontaniva sub-reach. In the period 1990–2003 there was an inverse tendency, expressed by an increase of the average width, up to 17 m (from 1990 to 1999) and then of a further 28 m from 1999 to 2003 (7 m year^{-1}). In the most recent years (2003–2008) the active channel width reduced again from 226 m to 200 m (5.2 m year^{-1}). Finally, during the last identified period (2008–2011), there was an initial slight narrowing followed by a very recent enlargement narrowing phase between 2010 and 2011 with a rate equal to 18.7 m year^{-1} which is the greatest variation registered in the last 30 years.

Table 2 Temporal variation of the average active channel width in the whole reach and sub-reaches. Data derived from the intersection of 85 transects (in GIS) with interpretation of the aerial photos.

Average width (m)	1981	1990	1999	2003	2006	2008	2010	2011
Whole reach	266	181	197	226	225	200	196	215
Nove	208	127	226	205	188	171	192	203
Friola	306	180	282	361	337	333	328	352
Fontaniva	333	187	188	194	139	137	164	196

Changes of active channel and island areas at the sub-reaches scale

Figure 5(a) shows the surface (ha) variation of the active channel along the three study reaches during the analysed period. In the first decade (1980–1990) we can observe a general decrease of about 40% of the active channel surface in all sub-reaches, whereas during the second identified period (1990–2003) a different behaviour is recognizable among the sub-reaches: in Friola the active channel area doubles, in Fontaniva is characterized by a slight narrowing, and in Nove experiences an increasing trend until 1999 (63%) followed by a slight areal reduction until 2003. The third phase (2003–2008) exhibits a fairly uniform tendency among the three sub-reaches, which reduced their active channel area with a rate ranging from 7% (Friola) and 28% (Fontaniva). Over the last years (2008–2011) all sub-reaches experienced an increase of active channel surface.

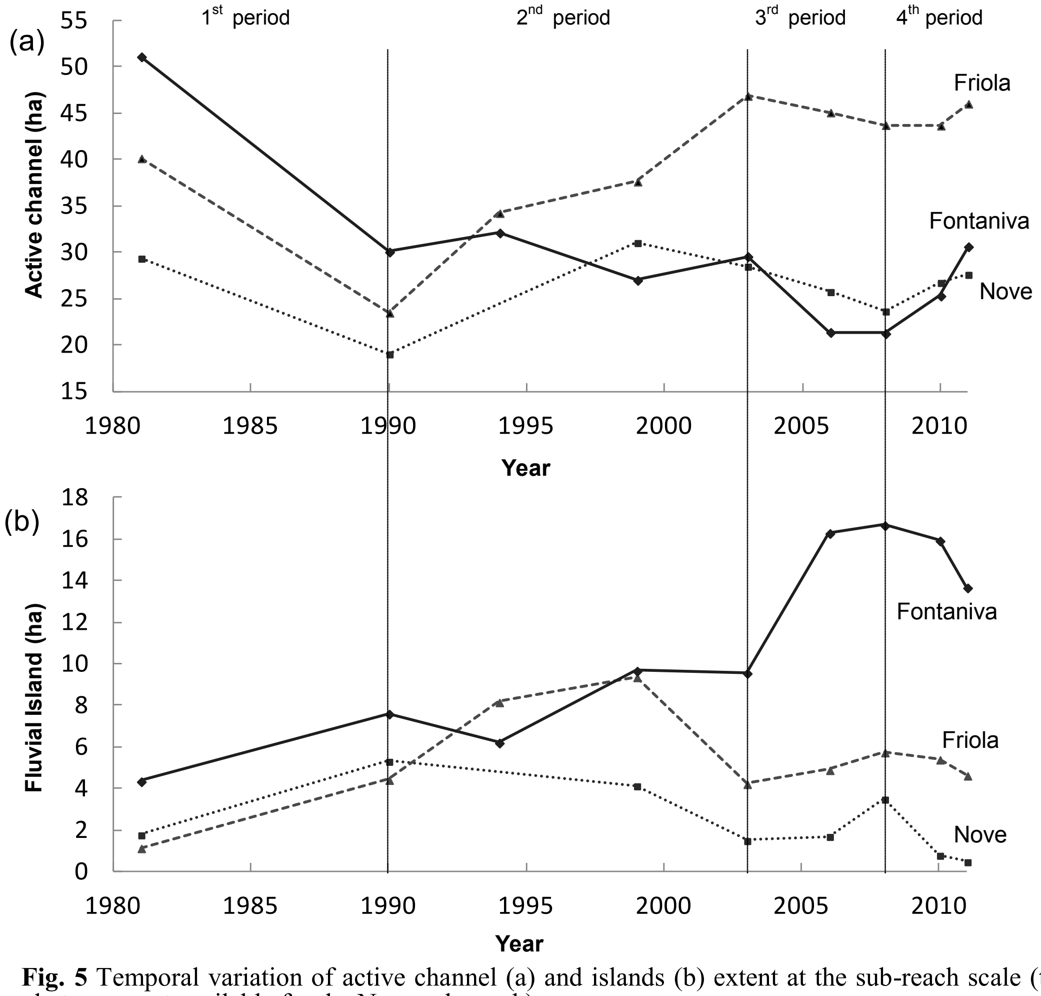

Fig. 5 Temporal variation of active channel (a) and islands (b) extent at the sub-reach scale (the 1994 photo was not available for the Nove sub-reach).

Regarding the temporal trend of islands evolution, different sub-reaches experienced divergent behaviour from the overall tendency (Fig. 5(b)). In the first phase (1981–1990), mainly due to the lack of high-magnitude flood events, there was a common increase of island extent at virtually the same rate (0.37 ha year^{-1}). During the following period Fontaniva exhibited an initial decrease followed by a rising tendency between 1994 and 2003, Nove is characterized by island reduction, while Friola experienced an increasing trend which changed into an intense reduction from 1999 to 2003. The third phase (2003–2008) is marked by a general increase of islands surface particularly strong in Fontaniva (2.2 ha year^{-1} in the period 2003–2006). In the last period (2010–2011), the reduction of the surface occupied by fluvial islands becomes more evident in the three sub-reaches, especially at Fontaniva (–2.26 ha year^{-1}). Currently, at Nove the islands have almost been eliminated (only 0.8 ha).

DISCUSSION

The study reach of the Brenta River was characterized by an initial period of strong narrowing of the active channel (from 1980 to 1990) followed by a general recovery phase (Fig. 4). A similar situation was found in the Piave River (Comiti *et al*., 2011). These planimetric changes are often also accompanied by changes in active channel bed level. In the past (until the 1980s) there was a general bed incision of the River Brenta (Surian & Cisotto, 2007). Over the past 30 years (1997–2010) in different sections (Fig. 1) of the upstream Brenta River where the incision has maintained, we observe a widening of the active channel, while in the downstream sections in which there are widening processes, there were no major changes (for details see Moretto *et al*., 2012).

If we analyse the influence of the effects of floods from 1981 to today we see a directly proportional relationship between lateral annual adjustment (m year^{-1}) and the mean annual peak discharge registered at the Barzizza gauging station (Fig. 6). Thus a higher magnitude of flooding corresponds to a higher active channel widening. Naturally, the reduction of the active channel width is due to the expansion of riparian vegetation establishing in floodplains and islands during periods lacking major disturbance processes. Figure 6 shows that points are fairly distributed in a linear relationship, except for the values referring to the period 2006–2008, for which the relatively low mean annual peak discharges (317 m^3 s^{-1}) did not produce the expected reduction of the active channel width. This is likely due to the fact that only two years with lack of major flood events are not enough to create new stable sites for the development of woody vegetation. Even though the historical data series are limited and do not permit advanced statistical analysis, an interesting positive correlation was found between the adjustment rate of the active channel width at the reach scale (m year^{-1}) and the mean annual peak discharge (m^3 s^{-1}) over each considered period (R = 0.70; p = 0.08). A similar relationship is recognizable for the Friola sub-reach, while the correlation is lower for Fontaniva (R = 0.57; p = 0.18) and weaker for Nove (R = 0.28; p = 0.95). At reach scale, only floods with discharges higher than 600 m^3 s^{-1} are able to cause significant morphological changes. Also at sub-reach scale, except for Nove, positive variations in width are registered only with flood events above the bankfull discharge. Similar results were highlighted by Comiti *et al*. (2011) which estimate in 10 years the return interval of the peak discharge able to modify the fluvial planimetric shape, especially floodplains and islands. This fact is also confirmed by island reduction processes which take place due to flood events of considerable magnitudes (Surian *et al*., 2009; Comiti *et al*., 2011; Picco *et al*., 2012b). In relation to the Tagliamento River, the observations of Bertoldi *et al*. (2009) reinforce a strong association between island dynamics and major floods (RI > 10–15 years).

Despite the fact that natural channel adjustments at the reach scale are mainly due to the occurrence of floods events, a fundamental role is played by the individual characteristics at the sub-reach level, which can strongly influence the responses in the different parts of the river. The Differences of DTMs (DoD) of the three sub-reaches, created by overlapping the 2010 and 2011 DTM's (see Moretto *et al*., 2012), have underlined a predominance of erosion processes due to the November/December 2010 flood events. Interestingly, this erosion tendency tends to reduce along downstream sub-reaches. The difference between erosion and deposition amounts is higher (up to three times) and more concentrated in the uppermost sub-reach Nove and decreases in the downstream sub-reaches. Generally, differences in adjustment responses to the 2010–2011 flood events among the three sub-reaches could be linked to different physical aspects of river patterns (bed slope and grain sizes), but also to the alteration of sediment flux and sediment availability from the upstream river basin.

The recent evolution (past 30 years) of the Brenta River plain shows a deficit of sediment from the mountain catchment. The abandonment of mining is reflected in the riverbed by the

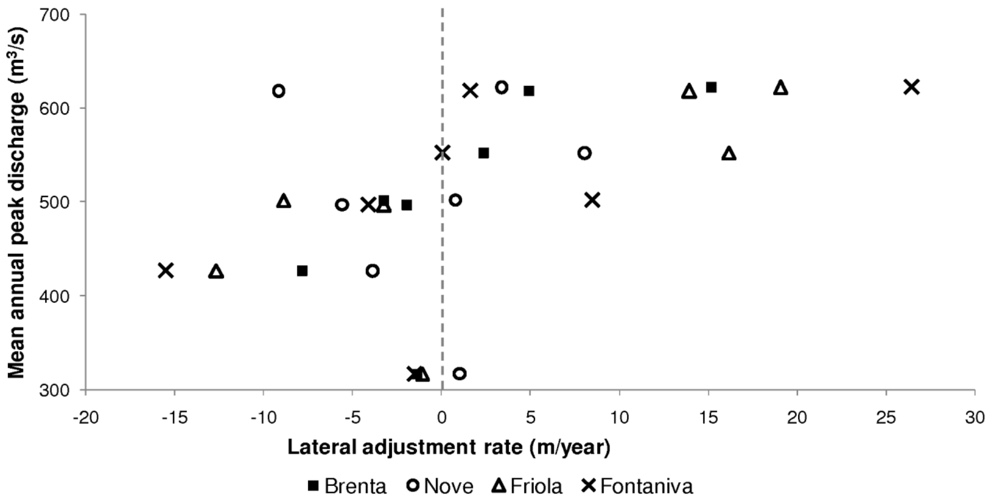

Fig. 6 Rate of active channel width variation (m/year) in relation of the average of annual peak discharge (m^3/s) over photo periods.

partial recovery of morphology (active channel aggradations) in the final stretch of river studied. To avoid the adverse effects associated with the morphological deterioration that we saw in the past, which still occur, we should try to stop the channel incision, and promote the bankfull expansion. These objectives can be achieved through proper management of sediment with measures to: (i) prevent the extraction of gravel in channel, and if possible, locate these activities upstream of the dams, favouring the transfer of deposited sediment downstream (Palmieri *et al*., 2001); (ii) construct new torrent control works, or modify existing ones with hydrodynamic filtering mechanisms (D'Agostino *et al*., 2004); (iii) promote the formation of an erodible river corridor (Piegay *et al*., 2005), avoiding occupied areas within the levees with historical structures or activities; iv) go back to manage the forest in mountainous areas, so as to promote recruitment processes of sediment from the slope. The moderate recovery we are seeing in the River Brenta will continue and increase only if the actions described above are applied. If instead we only take action on the reach scale, the present phase will remain, or if no interventions are carried out a new phase of incision and narrowing will occur (Surian *et al*., 2009).

FINAL REMARKS

The morphological evolution and associated vegetation dynamics of the lower course of the Brenta River over the last 30 years show that after the abandonment of mining in the river bed (90s), the river has partially recovered morphology. However, this trend is not yet stable and not distributed along the whole reach studied. In the upstream area there is still an incision processes and widening of the active channel as a result of bank erosion. The high-resolution analysis at the sub-reach level highlights that the extraordinary flood events (RI > 10 years) cause substantial morphological modifications and the erosion tends to reduce along downstream reaches. The restoration strategies for a more substantial channel recovery must be applied at the basin scale in order to restore the connectivity with upstream sediment sources. These interventions must be accompanied by continuous monitoring in order to verify the effectiveness, and to evaluate the future evolution of the river system.

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