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Channel adjustments and island dynamics in the Brenta River (Italy) over the last 30 years

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ABSTRACT

Many gravel bed rivers in the European Alpine area suffered different ranges and types of human pressure that modified their morphology and altered their processes. This work presents the case of the middle portion of the Brenta River, historically impacted by human activities such as floodplain occupations, bank protection, gravel mining, hydropower schemes and water diversion. Dam operation and gravel mining have produced considerable modifications in the natural sediment regime generating important morphological channel responses (narrowing and incision). Large areas of the former active channel have been colonized by riparian vegetation, both as islands and as marginal woodlands. Overall, the river changed its morphological pattern from braided to wandering. The present study analyzes the timing and extent of the planform morphological changes that occurred over the last 30 years along the middle portion of the river (20 km long) through the examination of aerial photos, repeated topographic measurements, and hydrodogical data. A series of recent aerial photos (1981, 1990, 1994, 1999, 2003, 2006, 2008, 2010 and 2011) have been used to assess the medium and short-term morphological changes of the floodplains and the active channel area. As to the medium-term modification, the recent changes in in-channel gravel mining have determined a new trend of active channel widening through erosion of vegetated areas. The analysis has also allowed to assess the morphological effect of single flood events. Only floods with RI higher than 8-10 years appear to be able to determine substantial erosion of floodplain and island margins.

Keywords: planform changes, islands dynamics, human impact, floods, Brenta River.

1. Introduction

Over the last 200 years the most Italian and European rivers have suffered considerable human pressures both at the basin and channel scales (Liébault and Piégay, 2002; Gurnell *et al.*, 2009; Surian *et al.*, 2009a; Comiti *et al.*, 2011). Phases of deforestation and reforestation, channelization, sediment mining, urbanization, dam building, torrent-control works, water diversion for agriculture and hydro-electric power generation, and many other interventions have modified natural water and sediment fluxes and boundary conditions. Sediment retention below dams and other minor structures can reach 50% of the total sediment load (Surian, 1999; Liébault and Piégay, 2001; Globevnik and Mikoš, 2009). Deficit of sediment supply in many Italian rivers was aggravated by in-channel mining especially between 1960 and 1980 (Comiti *et al.*, 2011). As a result, many Italian Alpine rivers, suffered a first, major phase of narrowing and incision followed by a more recent recovering widening trend (Surian and Rinaldi, 2003). For instance, in the Piave River natural and artificial reforestation (mainly after the 1950s) and erosion- and torrent-control works (after the 1970s), led to a strong river narrowing during the last century and a change from braided to wandering/single-thread morphology, leaving large areas available to the establishment of riparian forests (Surian *et al.*, 2009b; Comiti *et al.*, 2011). Bed incision reached 1 m and bed width decreased of about the 50% (Comiti *et al.*, 2011).

The type and dynamics of islands in a riverine system can help to depict processes of river changes and temporal evolution. Gurnell and Petts (2002) determined that most European rivers were once islands-dominated (pre-1900), but have become devoid of islands due to human interference. Away from areas of agricultural or urban development in Europe, islands remain a common feature of riverine landscapes, such as in the Tagliamento River in northeastern Italy (Ward *et al.*, 1999). The presence of a certain species of plant on the islands can help to determine the flow conditions in the area. Some plant species require specific growth conditions, such as inundation duration, gradient, and particle size (Picco *et al.*, 2012, Bertoldi *et al.*, 2011. The flows of larger rivers are regulated to some degree. This can have implications for fluvial islands development and stability. Dams reduce flood peaks, increase base flow, and store sediments (Kondolf, 1997; Braatne *et al.*, 2003), being the sediment transported downstream of a dam only a fraction of the normal sediment load (Surian, 1999). This also generally reduces the biologic habitat, diversity, and interactions between biotic and hydrologic processes (Poff *et al.*, 2007). While dams can reduce erosion and destruction of fluvial islands, they also promote bank attachment by decreasing the sediment supply and reducing the downstream transport capacity which leads to deposition of tributary input sediment.

This paper deals with the morphological evolution and the associated island dynamics of the middle course of the Brenta River (from Bassano Del Grappa to Piazzola sul Brenta) over the last 30 years. Previous studies in this river basin have analyzed: (i) morphological changes of the river channel (Surian and Cisotto, 2007; Surian *et al.*, 2009b; Moretto *et al.*, 2011); (ii) land use changes within the fluvial corridor and the abundance of in-channel wood (Comiti *et al.*, 2006, 2008; Rigon *et al.*, 2008, 2012; Vitti *et al.*, 2011); and (iii) sediment transport and sediment budget in the headwaters (Lenzi *et al.*, 2006, Mao and Lenzi, 2007). The evolution of the reach between Bassano Del Grappa and Piazzola sul Brenta is interesting to be explored because it was heavily affected by human pressure due to a dense hydropower scheme in the basin and severe past gravel mining activity.

This paper adds novel findings to previous papers dealing with similar regulated Italian rivers (e.g. Surian *et al.*, 2009b; Comiti *et al.*, 2011) on three aspects. Firstly, the paper presents a combined analysis of lateral and vertical channel adjustments with islands dynamics during the last 30 years; secondly, the varying channel response exhibited along the study reach is analyzed and connected to natural as well as human-induced factors at this scale. Finally, the paper takes advantage of evidences of channel changes during the 2010-2011 period, characterized by two considerable flood events with recurrence interval (RI) of 8 and 10 years.

The objectives of this paper are: (i) to quantify the geomorphic changes, both in bed planform and in bed elevation; (ii) to analyze the islands dynamics; (iii) to identify the driving factors of channel evolution and island dynamics changes thus envisaging the most likely future trends; (iv) to explore chances and limitations of river restoration in the studied reach.

2. General settings of the study area

2.1. Climatic, geological and morphological setting of the Brenta River basin

The Brenta River is one of the most important rivers of the Southern Alps (Italy) flowing into the upper Adriatic sea (Figure 1). The mountain drainage basin covers a surface of 1567 km^2. The river length is 174 km and can be divided into two main reaches: an upper 70 km long stretch flowing within the mountain basin, and a 104 km long stretch flowing within the Venetian floodplain area (Surian and Cisotto, 2007). The upper basin features a typical continental-Alpine climate with annual rainfall of about 1500 mm (Giuliacci *et al.*, 2001). The geological setting is rather complex and includes limestone, dolomite, gneiss, phyllite, granite and volcanic rocks. Regarding its morphology, the river exits from the Caldonazzo lake as a straight channel, and then evolves in a braided-wandering pattern in the piedmont area (Surian and Cisotto, 2007), before becoming meandering and then heavily rectified in its lower course.

2.2. Human impacts within the Brenta River basin

During the past centuries, the Brenta River has been affected by multi-spatial and temporal human interventions (Surian and Cisotto, 2007) which have heavily modified its natural characteristics. The magnitude and consequences of such disturbances have increased during the last 100 years. The human impacts 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.*, 2009b). In particular, gravel mining has been recognized as the human intervention with the greatest impact on channel morphology. This activity, which has mostly occurred in the lower reaches especially between 1950 and 1980, removed a large volume of sediments, exceeding replenishment rates and producing a significant alteration in sediment fluxes (Surian and Cisotto, 2007). Indeed, official estimates set volumes of extracted sediment to around 6-8 million m^3 from 1953 to 1977. However, these values are most likely to be far underestimated (Castiglioni and Pellegrini, 2001). The second most important human disturbance has been the construction of several dams which have reduced both flow and sediment discharges. The largest dam, built in 1954 for hydroelectric power generation and irrigation purposes, is the Corlo dam, in the Cismon torrent, with its 42 million m^3 reservoir (the main tributary of Brenta River). It is also worth mentioning the impacts of torrent-control works in the low-order mountain streams and the last trend of basin natural reforestation, which have reduced the sediment yield at the basin scale contributing to channel incision. These impacts resulted in 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 of up to 7 m (Surian and Cisotto, 2007).

2.3. Study reach

The Brenta River's reach considered in the present study is approximately 20 km long and is located in the piedmont area of the basin (area of about 1567 km^2) between the cities of Bassano Del Grappa and Piazzola sul Brenta (Figure 1a). The upper part of the reach, located immediately downstream of the mountain area, features a fairly straight channel and a narrow alluvial plain. In its middle portion the river widens, the slope is lower (about 0.3 %) and the river features a braided pattern with islands. In its lower part, the river exhibits a wandering pattern with higher sinuosity (≈ 1.12) and the presence of extensive riparian vegetation on floodplains. Within the study reach there is a wide range of human infrastructures such as embankments, bridges, and transversal works such as the Carturo transverse (located at the very end of the study reach). Also, the floodplains are characterized by the presence of urbanized areas, and much of the discharge is diverted for irrigation and hydroelectric purposes.

3. Materials and methods

3.1. Cross-sections and longitudinal profile

Twelve historical cross-sections described in detail by Surian and Cisotto (2007) lie within the study reach (Figure 1a). They were first surveyed in 1932, and then in 1997 with a total-station device. In 2010, the first 10 cross-sections were re-surveyed with a DGPS with a maximum vertical error of ± 0.03 m. Two Light Detection and Ranging (LiDAR) surveys taken in 2010 and 2011 are available for the study area. Further re-surveys of the study cross-sections were derived from these data, taking advantage of the ground points of the filtered LiDAR data and the underwater points obtained by an image analysis of coloured aerial photos taken during the same flight (Moretto *et al.*, 2012). The vertical error of these cross-sections was estimated to be around ± 0.15 m. The longitudinal profile along the river reach was derived from an averaged cross-section elevation, calculated using all points within the active channel (i.e. excluding banks and floodplains).

3.2. Flow regime

The Flow regime was measured at the basin outlet, Barzizza gauging station, by the former Italian National Hydrographical and Hydrological Agency from 1924 to 1996, and by ARPAV (Environment Protection Agency of Veneto Region), from 1997 to 2010. The station is located 5 km upstream of the analyzed reach (see Figure 1). Mean daily discharges (Q) were available for two periods: 1924-1996 and 2005-2011. From 1997 to 2004, Qd was obtained throught the application of the stage-discharge rating curve validated by ARPAV for the period 2005-2011. All values of the two series of data were checked and original missing data were calculated by cross-correlation and interpolation techniques (Kaless *et al*., 2011; Lenzi *et al*., 2010).

Nevertheless, values of water levels recorded at the Barzizza station, were not available for most part of the years 1942, 1943, 1944, 1945, 1946, 1967, 1968 and 1984 and was thus not possible to estimate mean daily water discharges by interpolation techniques (Figure 2).

A comparison between maximum instantaneous peak water discharge, maximum hourly daily water discharge and maximum main daily discharge, was carried out for 24 floods events measured in the field by the ARPAV, and occurred in the period 2004-2009. Flood events were chosen with the criteria of guaranteeing both the non-dependency between two consecutive floods (on the value of the peak discharge for each event) and to cover a large range of water discharge peak values. A very good correlation was obtained (Kaless *et al*., 2011) between the values of maximum hourly daily and maximum main daily water discharge ($r^2 = 0.96$). Extending this analysis to the entire available data set, a total of seventy nine (79) flood events were chosen, checked and considered for testing different probability distribution functions and for the flood frequency-return time estimations (see point 4.2 Flow regime analysis).

3.3. Identification of geomorphological and island features from aerial photos

The evolution of islands and bed river morphologies over the last 30 years was analyzed taking advantage of nine series of aerial photos, acquired always during low-water level conditions (see details of the photos in Table 1). Aerial photographs were rectified and co-registered to a common datum base at 1:5000 using a 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 0.3 to 1 m. The higher RMSE are for 1981, 1990 and 1999 (1 m of pixel size).

These photos were analyzed using the same method described in Comiti *et al*. (2011), in order to identify the active channel and islands extents along the whole 20 km-long study reach. The active channel is defined as the area without shrub vegetation, thus including unvegetated bars and active and inactive channels, while the fluvial islands class include pioneer, young and stable islands according to Gurnell and Petts (2002) classification. In order to analyze morphological changes along the study reach, active channel and islands widths were taken in 85 position, 250 m apart in transects perpendicular to the river axis which were created in GIS environment.

3.4. Photo-interpretation errors

The errors related to the photo-interpretation assessment were performed using the Mount *et al*. (2003) method. This procedure consists of the estimation of two independent errors, the first represents the operator error associated with the bankline digitalization, while the second defines the uncertainty deriving from the air images. Considering the first type, we multiplied the pixel resolution (R) by the mean of the maximum number of pixels (p) of repeated right and left delineations of the bankline. Given that the error range was below 2 m (among all photo sets), we decided to group together the offset data for each set, reaching one average pixel error value (p). The distortion degree within each air image was assessed by comparing positions (i.e. building corners) easily identifiable on all photo sets with the same ones found on the 2006 ortho-photographs. Finally the quantification of the distance difference was carried out. Thus, the photo distortion error considering each image set (θ), represents the mean distance difference between points. Concluding the process of error identification, the total error in width (E_w) was assessed by Mount *et al*. (2003) equation:

$$E_w = 2^{1/2}pR + 2\theta \qquad (1)$$

Accounting for the polygonal areal error (erosion, channel, islands), we needed to set two assumptions: (1) the constancy (no error) of eroded bank segments, channel length or islands and (2) the rectangular form of the polygons describing these areas. In this sense, the assessment error related to the area was equal to the product between the polygon length and the width error (Mount *et al.,* 2003).

4. Results

4.1 Flow regime analysis

The RI of each flood was estimated from the maximum annual values of the mean daily water discharge (Qd) over 79 considered hydrological years. Various functions of the hydrological probability distribution were tested and the Gumbel distribution (OLS) was chosen, due to the best performance of the Kolmogoroff test. The bankfull discharge (RI ~ 1.5 years) was calculated around 350 $m^3 s^{-1}$ ($Q_{1.5}$), which is esceeded 2.4 days per year, and the discharge with RI of 10 years was estimated to about 750 $m^3 s^{-1}$ (Q_{10}). The largest flood event was registered on the 4th of November 1966, with 1330 $m^3 s^{-1}$ as mean daily discharge (RI ~ 200 years).

The flow regime of the Brenta River is characterized by rainfall and snowmelt contributions in spring and by autumn rainfall (Lenzi *et al.*, 2010; Kaless *et al.*, 2011). Also, flood events tend to occur in May, October and November, when more than 50% of all flood events recorded from 1924 to 2011 occurred (Lenzi *et al.*, 2010; Kaless *et al.*, 2011).

Over the last thirty years, four flood events with RI equal or greater than 10 years were registered (1980, 1996, 2002 and 2010). Two severe flood events occurred in November and December 2010. The first flood, caused by prolonged and extended rainfall , lasted from 31st October to 2nd November 2010, with peak discharge of about 720 $m^3 s^{-1}$ (RI ~ 8 years). The second flood, originated by intense precipitations occurred between 21st and 26th December 2010 and peaked at 759 $m^3 s^{-1}$.

4.2. Bed-level changes along the study reach

The vertical adjustment of the river bed was analyzed using the 10 historical cross-sections measured from 1932 to 2010, along with results coming from LiDAR analysis carried out by Moretto *et al.* (2012). If compared with the profile of 1932 (Figure 3) it appears that, as already highlighted by Surian and Cisotto (2007), the river experienced incision up to 5-8 meters except for section 1, where vertical adjustments were lower than -0.35 m. Instead, over the last 13 years (1997-2010), the river bed experienced a general incision of around 0.2 m. However, significant differences in vertical adjustments appear along the reach. In fact, in the upstream portion of the study reach, from section 1 to 5, average vertical adjustments of the active-channel during the last thirteen years range from -0.35 m (section 1) to -0.92 m (section 2), with an average of -0.7 m (average level of the active channel). If the talweg line is considered (table 2), the largest incision of the river is equal to 1.78 m in correspondence of section 1. The middle portion of the study reach seems to be in an equilibrium condition since a vertical variation of only -0.01 m and 0.11 m occurred on section 6 and 7, respectively. Conversely, the lower portion of the study reach has been aggrading from 1997 to 2010, since the mean level of the last three historical sections (8, 9, and 10) has raised between 0.42 m and 0.48 m. The largest aggradation of the river along the talweg (table 2) in the period 1997-2010 was reached by section 7 with 0.69 m. The channel slope of the whole study reach remained virtually constant from 1997 to 2010, passing from 0.0036 m m^{-1} to 0.00356 m m^{-1} with a relative variation of only 1%.

The analysis of the cross-sections derived from the 2011 LiDAR survey (Moretto *et al.*, 2012) confirmed the vertical adjustment trends from 1997 to 2010 (Figure 3). The mean elevation of sections 2 and 5 experienced a further reduction (5 and 8 cm, respectively), and section 7 increased its elevation of 14 cm, if compared to 2010. However, it should be noted that the 2011 cross-sections could be affected by a greater error in respect to those of 2010 since they are derived from the LiDAR survey. In Figure 4, sections 2, 5, and 7 (as representative of the upper, middle and down-stream part of the study reach) are shown, and the horizontal line represents the bankfull level as surveyed in the field in 2010. Incision and narrowing tendencies are evident in the three cross-sections. In section 5 (Figure 4b), the main channel shifted progressively leftwards and reached the main embankment. A different behavior in the lower portion of the reach is evidenced by the fact that section 7 (Figure 4c) remained fairly unchanged over the last 13 years.

4.3. Changes of active channel area and width along the study reach

The analysis of the extent of active channel conducted by using aerial photos has confirmed remarkable fluctuations during the last 30 years (Figure 5). Five significant periods characterized by different dynamics of active channel changes could be identified: 1981-1990, 1990-2003, 2003-2008, 2008-2010 and 2010-2011. The first and third periods are characterized by a decrease of active channel surface (-148 ha and -70 ha, respectively), whereas the second, the fourth, and the fifth periods are characterized by an increase of the active channel surface (135 ha, 10 ha and 41 ha, respectively). Figure 6 depicts the longitudinal variation of active channel width within the 5 identified periods of different morphological behavior. The average values of channel width for the entire analyzed reach in 1981, 1990, 1999, 2003, 2006, 2008, 2010 and 2011 have respectively the following values: 266, 181, 197, 226, 225, 200, 196 and 215 m. During the first nine years of the analyzed period (1981-1990), the average active channel width decreased from 266 m to 181 m (9.44 m year^{-1}). The active channel narrowing seems to have occurred along the whole river reach, except for a rather marked enlargement occurred near the 7th section (Figure 6). In the period 1990-2003 there was an inverse tendency, characterized by an increase of the average width, up to 16 m (from 1990 to 1999, at the rate of 1.78 m year^{-1}) and then of a further 29 m from 1999 to 2003 (7.25 m year^{-1}). The average widening trend was not uniformly distributed along the reach, but appears to be more concentrated between the fourth and thirteenth km. In the most recent years (2003-2008) the active channel width reduced again from 226 m to 200 m (5.2 m year^{-1}). This average trend is mainly due to intense localized narrowing processes occurred around the thirteenth km, while in the rest of the channel the width remained fairly constant. During the period 2008-2010, there was a slight narrowing concentrated at about the thirteenth and eighteenth km along the studied reach from 200 m to 196 m (2 m year^{-1}), followed by a very recent enlargement phase between 2010 and 2011 from 196 m to 215 m, respectively, with a rate equal to 19 m year^{-1} which is the largest variation registered in the last thirty years. Overall, the active channel width reduced by 51 m from 1981 to 2011, even if different temporal trends are observed during the studied period and along the reach. It is worth noticing the effect of November and December 2010 floods (RI = 8 and 10 years, Lenzi *et al.,* 2010), which caused channel widening fairly distributed along the whole reach (Figure 6).

4.4 Changes of islands area and width along the study reach

The extension of islands within the entire reach (Figure 5 and 7) was calculated, as for the active channel area, by photo-interpretation from the historical series of aerial photos from 1981 to 2011. Changes in island area reflect the trend of the active channel area (Figure 5) but it is not uniform along the whole reach (Figure 7). The first phase from 1981 to 1990 is characterized by an increase of 77 ha of islands and a decrease of the active channel. This appears to be more concentrated around sections 2 and 5 and below section 7. The second phase from 1990 to 2003 is characterized by 14 over-bankfull floods (with one > 10 years RI in 2002), and features a marked decrease of islands area (-52 ha). Afterwards, due to the lack of high-magnitude floods from 2003 to 2008, the areal extent of islands increased (52 ha), being this expansion relativelly uniform in whole reach. The phase from 2008 to 2010 is characterized by a reduction of

17 ha of islands area, bringing the overall distribution of them in a similar situation as in 2003. The only exception is for a new relevant island area between the 17th and 18th km from section 1 (Figure 7 - 2008 *vs.* 2010), Subsequently, another decrease phase of about 10 ha from 2010 to 2011, more marked from the beginning of the study reach to the 7th cross-section.

Major island extension values (108 ha in 1990 and in 2008) are associated with the major narrowing of the active channel (341 ha in 1990 and 405 ha in 2008). On the opposite, the minimum islands extension coincides with the maximum extent of the active area (1981), equal to 51% of the entire area of the river corridor.

5. Discussion

5.1. Vertical and lateral adjustments along the middle portion of Brenta River over the last 30 years.

The relationship between the vertical adjustment of the average elevation of cross-sections and the associated changes of active channel width was evaluated using ten historical cross-sections and considering two different periods: 1932-1997, and 1997-2010. Aerial photos of 1999 and 2010 were also used in order to improve the interpretation of the active channel width of cross-sections (Table 2). In Figure 8, lateral and vertical adjustments of the active channel extent of 10 cross-sections are depicted. In the period 1932-1997, which corresponds to the incision/narrowing phase (except for section 1), vertical and lateral adjustments are not significantly correlated (R Spearman; $p >> 0.05$). Channel incision and narrowing processes occurred at the same time in other

Italian rivers as, for example, the Piave, the Po and the Tevere (Surian and Rinaldi, 2003). The weak correlation between vertical and planimetric adjustments over the last 30 years in the Brenta River could be related to the different temporal and spatial extent of the sediment dynamic processes. Similar processes occurred in the Piave River, which for instance experienced channel widening and incision at the same time from 1991 to 2006 (Comiti *et al.,* 2011). The decoupled tendencies of vertical and lateral adjustment may be due to the fact that morphological variations can be very different at the sub-reach scale because of local constraints. Changes in active channel width were very different in the period 1997-2010, being the narrowing phase finished (Figure 8), and being some sections even widening (sections 2 to 5). Within the general widening trend over the recent 5 years, the upper reach part (except for section 1) experienced channel incision . This seems to be related to the paucity of sediment supply coming from upstream reaches due to the low connectivity with the mountain reach (Surian *et al*., 2009a). In some portions of the upper reach (e.g. section 2), the severe incision (up to 5 m) has probably lead to reach a very coarse sub-layer, and the bed appears remarkably armoured (and possibly non completely alluvial), leading to a prevalent tendency to erode the banks rather than to further incise the channel. In the downstream reaches, where aggradation or equilibrium tendency are dominant, active channel is not widening, most likely due to two reasons: i) the longitudinal control works (built since the 1960s) greatly reduce the possibility of lateral migration of the river; ii) a mature riparian vegetation next to the active channel that stabilize the soil and reduce bank erosion.

5.2. Are flood events the main driving factor of channel changes and islands dynamics in the Brenta River?

Looking at the multi-temporal analysis of the active channel width conducted using aerial photos taken from 1981 to 2011, a certain correspondence between widening trends of the active channel and the occurrence of flood events appears to exist (Figure 9). If the lateral annual adjustment (m $year^{-1}$) is related with the average of annual daily peak discharge over the photo period registered at the Barzizza gauging station for the analyzed photo period, a directly proportional relationship seem emerges (Figure 10), showing that at higher magnitude of flooding corresponds a stronger active channel widening. Minimum channel widening value of 1.5 m is obtained only with Qd_{mean} over 450 m^3 s^{-1}. Active channel narrowing is clearly due to the expansion of riparian vegetation in floodplains and islands during periods lacking major disturbing processes (r^2=0.87; Figure 10). Higher correlation is obtained (r^2 = 0.91) if the lateral adjustment rate is related to the number of the days per year where Q is greater than 450 m^3 s^{-1}, over the step time (Figure 11). For the period 1999-2003 (1407 days), 13 days with Qd over 450 m^3 s^{-1} were registered (3.4 days per year) and a widening of 7.4 meters per year was observed. A greater lateral adjustment rate of about 31.2 m $year^{-1}$ was calculated for the step time 2010-2011 (225 days), with 6 days of Qd over the the threshold value of 450 m^3 s^{-1} (Figure 11). Two major floods (RI> 10 years) occurred on each of these periods.

Overall, it appears that floods events with mean daily discharges (Q) around 750 m^3 s^{-1} (RI ~ 10 years) were able to cause evident widening of the bankfull section (>10-20 m). A similar flood magnitude has been reported by Comiti *et al.* (2011), that quantified in 10 years the RI flood needed to modify considerably the fluvial planimetric shape, especially floodplains and islands, in the Piave River. Further studies confirmed that island reduction processes take place due to flood events of considerable (>10 years) magnitude (Bertoldi *et al.,* 2009; Surian *et al.,* 2009b; Comiti *et al*., 2011; Vitti *et al*., 2011; Picco *et al*., 2012.

Despite the fact that natural channel adjustments at the reach scale are mainly due to the occurrence of floods events, a fundamental role is also played by the individual characteristics of each small reach (Figure 6), which can strongly influence the change responses in the different portions of the river. Overall, differences in adjustment responses to the 2010-2011 flood events along the reach could be linked to different physical settings (especially bed slope), but also to the disturbance in sediment flux and sediment availability from upstream reaches. The higher erosional trend (Figure 4) in the upper part of the study reach is likely due to the higher physical constrains which do not allow the channel to migrate. In fact, human structures aimed at protecting the nearby areas against floods (e.g., embankments, groins, and rip raps), are most likely to have reduced the active channel width, causing severe incision as partially confirmed by the recent multi-temporal analysis. The concentrated bank erosion could be enhanced by both the alteration of sediment flux due to the low connectivity with the upstream drainage basin already identified by Surian *et al.,* (2009b), and by the scarcity of vegetation growing on the banks. Sediment supply to the upstream reach is very low due to the presence of dams and torrent control works in the mountain basin. As a result, the connectivity with the upstream basin is virtually negligible for bedload and coarse sediment input to this sub-reach (cross-section 2). Moreover, a knickpoint in the longitudinal profile appears around cross section 3, located 4.4 km downstream section 1, indicating that this portion of the river is likely in a current transient condition to equilibrium. Channel incision in the upper part of the study reach is than likelly continue until a urther adjustment of slope, or unitl a further development of armour layer.

The application of a 2D hydrodynamic and morphodinamic model for gravel bed rivers recently developed by Kaless (2012), to the Brenta River's Nove sub-reach (around section 2), indicates that the most probable short-term evolution of the reach will depend on the floods magnitude. Ordinary events (discharges below 450 m^3 s^{-1}) will produce negligible changes within the channel bed. On the other hand, more infrequent floods (RI > 10 years), are expected to produce remarkable banks erosion. Widening is the main processes able to stabilize the channel owing to the reduction in shear stress and the delivery of sediment into the channel.

In the middle portion of the study reach (around cross-section 5), the channel has recently been realivelly stable, likely because in-channel mining hasn't longer been carried out since 1992-1994, and significant bank erosion has recently occurred in the upstream sub-reach, supplying eroded sediments and coarse material. In fact, the sub-reach around cross-section 6 appears to have been stable over the past few years (Figure 3 and 8), suggesting that major sediment supply is not to be expected in the further downstream reach. Indeed, gravel mining activities were not intensive in this part in the past, and enough volumes of coarse and fine sediments are available from bank erosion of the upper part of the study area.

Generally, it appears that portions of the study reach with lower human disturbances and structural constraints are currently widening, whereas reaches heavily constrained are still suffering considerable erosion processes (Figure 4 and 6). The dominance of erosional processes in the upstream and a general stability depositional phase on the downstream portion of the study reach is also reflected by the different islands dynamics. In the far downstream reach, (around section 7), the sediment deposition and the higher morphological stability creates suitable conditions for the stabilization of vegetation, while other active channel areas are more disturbed by floods and the islands are more affected by erosion processes. Beyond these aspects, it's worth considering the relevant influence of direct human actions (e.g. vegetation removal, local clearcuttings, bank protections, agricultural settlements, recreational areas) which are still present along the river corridor and can modify locally both the morphological and vegetation dynamics (Picco *et al*., 2012). The analyzed fluvial system is the result of centuries of alterations, as highlighted for other rivers of the Veneto Region (Comiti *et al*., 2011). In the period 1990-2011, the fluvial dynamics of the Brenta River appears to be less affected by human alterations, due particularly to the decrease or almost the abandonment of mining activities within the channel.

5.3. Driving factors of channel evolution over the last 30 years and implications for channel recovery

The study reach of the Brenta River was characterized by a period of strong narrowing of the active channel (from 1981 to 1990) followed by a general stability and an initial, low recovery phase (Figure 5). A similar situation was found in the Piave River (Comiti *et al*., 2011). Analyzing in detail this trend, five periods can be identified (1981-1990, 1990-2003, 2003-2008, 2008-2010 and 2010-2011). Comparing the surface extension of the active channel at the beginning and at the end of each series, it was possible to highlight and calculate erosion and deposition areas. Figure 5 reports enlargement and narrowing areas and the total areal variation of the active channel. In the first nine years (1981-1990), the active channel decreases of ~ 225 ha, equal to 19% of the total area, with a variation rate of 25 ha year^{-1} which represents the smaller historical extension. This period corresponds to a series of ordinary flood events (average annual hourly peak discharge 1981-1990 = 426 m^3 s^{-1}, maximum Qh = 682 m^3 s^{-1}) and still relevant human impacts. The 1990s coincide with the end of the narrowing phase, commonly associated, for Italian rivers, to sediment mining activities (Surian *et al*., 2009b). Some differences are noticeable with other Alpine regions where floodplain reforestation (following changes in the land use), along with sediment mining, is considered a major cause of channel erosion (Liébeault and Piégay, 2001, 2002; Rinaldi *et al*., 2011). As showed by the most recent channel evolution of the Brenta River, Surian and Rinaldi (2004) identified a phase of channel widening in several Italian rivers and Surian *et al*., (2009b) pointed out that such phase is often associated with aggradation, even if it can also occur without significant bed level changes. A similar phase in our study site can be recognized from 1990 to 2003. In this period, there was a partial recovery of the active channel width of ~ 135 ha (11% of total area, 11 ha year^{-1}), eventually due to flood events (e.g. 2002 and 1996) and/or a partial recovery of the natural dynamics (in relation with the decrease of gravel mining and human pressure). During these 12 years, in fact, we can observe an increase of the most intense flood events (average annual hourly peak discharge 1990-2003 = 572 m^3 s^{-1}, maximum Qh 1990-2003 = 860 m^3 s^{-1}and 6 floods with RI ≥ 5 year). During the third period (2003-2008), the trend changes one more time as demonstrated by the multi-temporal analysis of the aerial photos (Figure 5 and 9): the active channel surface reduces of ~ 70 ha (14 ha year^{-1}) which corresponds to about 6% of the total area. In this period, the flows decrease their intensity (average annual hourly peak discharge 2003-2008 = 425 $m^3 s^{-1}$, maximum Qh 2003-2008 = 618 $m^3 s^{-1}$), and no flood events with RI > 4 years occur. Observing the fourth period (2008-2010), we can notice a new little expansion of 10 ha, that corresponds to about 1%, due to two subsequent floods of around 327 $m^3 s^{-1}$ and 676 $m^3 s^{-1}$, in 2008 and 2009, respectivelly. During the last period (2010-2011) there was a consistent enlargement of about 41 ha, that correspond to about 3%, due to the significant 2010 flood (Qh = 863 $m^3 s^{-1}$; Qd = 759 $m^3 s^{-1}$ with RI = 10 years). In correspondence to this enlargement, a low channel incision in the upper part of the study reach is recognizable. On the contrary, in the second half of the reach a relative phase of equilibrium or smooth aggradation can be distinguished (see section 4.2 and Figure 3). Contrary to the Piave River which is currently showing a certain morphological recovery (Comiti *et al*., 2011); the Brenta River is not entirely in a morphological recovery trajectory. Even though in the downstream area of Bassano Del Grappa the abandonment of gravel mining activities has led to a decrease of erosion and narrowing processes starting from the early 1990s, a low morphological degradation of the river is still undergoing. The main recognizable driving factors seem to be: i) the very scarce availability of bedload transported sediment from upstream (as highlighted also in Surian and Cisotto, 2007); ii) the absence of tributaries which can supply sediment; iii) the higher bedload transport capacity consecuent to the increase of slope registered from 1997 until so far (+ 0.3 ‰). In the downstream part, otherwise, the active channel results much more stable, either in width and elevation terms due to: i) the higher availability of sediment which derives from the upstream part as consequence of bank and bed erosion; ii) the lower slope (reduction of 0.6‰) of the active channel if compared to 1997 from section 6 ahead; iii) the greater presence of stable riparian vegetation; iv) the reduction of sediment mobility carried out by numerous infrastructures as bridges and dam structures (Carturo dam built up in the 1970s). The recent variations of morphology and vegetation are related to the episodic severe flood events, in association with the effects of human actions acting both at reach- (in the past) and basin-scale (nowadays).

In order to avoid the adverse effects associated with the morphological deterioration experienced by the river over the past, it seems that the management strategy should pursue channel aggradation and promote bankfull expansion. These objectives could be achieved through a proper management of sediment with measures oriented to: i) prevent the extraction of gravel from the active channel and, if possible, locate these activities upstream of the dams, favoring the transfer to downstream of trapped sediment in the reservoir (Palmieri *et al.*, 2001); ii) rethink about torrent control measurements, promoting open check-dams with hydrodynamic filtering mechanism (Conesa-Garcìa and Lenzi, 2010; D'Agostino *et al.,* 2004); iii) promote the formation of an erodible river corridor (Piégay *et al.,* 2005), avoiding to occupy areas within the levees with historical structures or agricultural 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 that the Brenta River is experiencing, especially in the second half of the downstream reach analyzed (Surian *et al.,* 2009b), is likely to continue and increase only if a combinations of the actions described above will be applied.

6. Conclusion

The medium and short-term morhological dynamics, channel width, channel slope and islands of the study reach of Brenta River are remarkably complex due to the occurrence of spatially variable natural processes and human disturbances. During the study period a widening phase of the active channel has been observed, along with a reduction of island extension from 1990 to 2003 and from 2008 to 2011. On the other hand, from 1981 to 1990 and from 2003 to 2008, the river experienced channel narrowing and island expansion. However, due to the relevant spatial variability of morphological patterns, slope, and extent of human structures and disturbances these dynamics and temporal trends are quite different along the study reach, that results in a different morphological evolution in terms of channel width and island extent. Also, the channel slope increased in the upper portion from 0.495 % to 0.526 % and decrease in the lower portion of the study reach from 0.429 % to 0.374 %. Overall, it seems that the evolution trends of these two portion depend on sediment supply from upstream reaches and from the types and degree of local human disturbances and infrastructures.

Alteration on sediment supply that drives recent channel and islands changes is related to the extraction of sediment, indeed after the abandonment of mining in the river bed (90s), the Brenta River has partially recovered its morphology. However, this trend is not yet stable and not distributed along the whole study reach. In the upstream area there are still incision and widening processes of the active channel as a result of bank erosion. Recent changes in the active channel dimension are related to the rates of flood events. The analysis of the relation between active channel adjustement and the occurrence of flood highlights that severe flood events (RI >8-10 years) cause substantial morphological modifications and erosion tends to reduce along downstream reaches. A more detailed and thoughtful sediment budget assessment, to be compared with field measurements of sediment transport, is currently in progress and will be part of a future publication.

The study suggests that restoration strategies could enhance channel recovery, but their effectiveness will likely depend on the local human impacts and sediment availability from upstream reaches. The upper reach (around section 2) is characterized by a very reduced sediment supply from upstream due to a transversal barrier and by numerous longitudinal defenses, which will prevent a natural widening and recovery. Moreover, the region at the knick point in slope is still subject to a little degradation, indicated that the river in this part is not entirely at equilibrium conditions. Instead, in the downstream, is already widening and aggrading due to sediment supply from the upper and middle reaches, the stabilization of the bed slope and the lower human disturbances, thus restoration strategies (e.g. elimination of bank defenses) will probably increase these natural tendencies.

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Tables

Table 1. Technical specifications of aerial image series used in the study. Px: pixel size; Hf: height of flight; Fcl: focal, Q: Daily discharges ($m^3 s^{-1}$).

Year	Px (m)	Aprox. Scale	Hf (m)	Fcl (mm)	Date flight	Company	Q ($m^3 s^{-1}$)
1981	1.00	1:17000	2600	153.13	April 15	CGR Parma	38
1990	1.00	1:20000	3000	152.82	April 15	CGR Parma	31
1994*	0.35	1:20000	8000	305.38	20 Sept.	CGR Parma	88
1999	1.00	1:16000	2500	153.26	July 23	CGR Parma	36
2003	0.50	1:10000	5400	150.00	May - Nov.	CGR Parma	62
2006	0.50	1:10000	5400	150.00	May - Nov.	CGR Parma	69
2008 A	0.40	1:8000	1250	153.64	July 15	Rossi -	75
2008 B	0.75	1:16000	2400	153.64	July	CGR Parma	85
2010	0.15	1:12000	2000	100.47	August 30	CGR Parma	55
2011	0.15	1:12000	2000	50 - 35	April 12	OGS	69

*1994 flight does not include the upper part of the study reach.

Table 2. Temporal variation of the active channel (AC) width (m) and the talweg (Tw) elevation (m a.s.l.) in the cross-sections (CS). It 'also shows the lateral (ΔAC) and vertical adjustments (ΔTw).

	1923		1997		2010		1997-1923		2010-1997	
	AC (m)	Tw (m a.s.l.)	AC (m)	Tw (m a.s.l.)	AC (m)	Tw (m a.s.l.)	ΔAC (m)	ΔTw (m)	ΔAC (m)	ΔTw (m)
CS 1	248	91.6	87	92.2	90	90.4	-161	0.6	3	-1.8
CS 2	401	85.1	158	83.9	230	82.6	-243	-1.2	72	-1.3
CS 3	838	75.1	427	73.3	572	72.6	-411	-1.8	145	-0.7
CS 4	699	67.6	413	63.8	506	63.4	-286	-3.8	93	-0.4
CS 5	409	59.8	263	56.0	310	55.0	-146	-3.8	47	-1.0
CS 6	541	54.6	514	50.0	520	49.1	-27	-4.6	6	-0.9
CS 7	752	43.9	479	37.6	480	38.3	-273	-6.3	1	0.7
CS 8	303	37.9	258	33.6	242	33.4	-45	-4.3	-16	-0.2
CS 9	744	34.7	482	24.6	477	24.8	-262	-10.1	-5	0.2
CS 10	409	29.9	359	22.1	361	22.1	-50	-7.8	2	0.0

FIGURE CAPTIONS

Figure 1. General view of the Brenta River context, the study reach and the cross-sections.

Figure 2. Water discharges (mean daily) at the Barzizza gauging station (Bassano Del Grappa, drainage area = 1567 km^2), from 1924 until June 2011; Flow discharges featuring RI = 1.5 years ($Q_{1.5}$), and RI = 10 years (Q_{10}) are also shown.

Figure 3. (a) Longitudinal profiles of the Brenta river from 1932 and 1997 survey (Surian and Cisotto, 2007) and 2010. Best equations (exponentials) of the longitudinal profiles are reported (the all three profiles $r^2 > 0.95$); (b) variation of average bed elevation as derived from the comparison of cross-sections along the study reach from section 1 to 10 are shown: negative values of vertical adjustments indicate an incision of streambed whereas positive values indicate an aggradation. 2011 sections are derived from LiDAR survey (Moretto *et al.*, 2012) and are available only for sections 2, 5, and 7.

Figure 4. Evolution of historical cross sections 2, 5, and 7 for the years 1932, 1997, 2010, and 2011. The horizontal line represents the bankfull stage for the sections measured in 2010.

Figure 5. Temporal variation with error bars of the surface of the active channel, floodplain and islands in the analyzed reach of the Brenta River.

Figure 6. Active channel evolution over the last 30 years divided in five significant periods characterized by different morphological trends.

Figure 7. Fluvial Island evolution over the last 30 years divided in five significant periods characterized by different morphological trends of active channel.

Figure 8. Relationship between the changes of elevation of the bankfull stage and changes of active channel width evaluated in 10 historical cross-sections. The two reported series refer to the periods 1932-1997, and 1997-2010. Negative values mean narrowing or incision, while positive values correspond to widening or aggradation.

Figure 9. Time evolution of the average active channel width and RI of flood events. (a) Bar chart represents the maximum hourly discharge registered in the year (Qh) and the maximum annual values of the mean daily water discharge (Q); dashed line (Qh_{mean}) represents the average of the annual Qh over a period between two aerial photo-interpretation. Flow discharges featuring RI = 1.5 years ($Q_{1.5}$), and RI = 10 years (Q_{10}) are also shown. (b) Adjustments of the average active channel width (whole reach and sub-reaches). Maximum annual peak discharges value was not available at the Barzizza gauging station for the year 1985.

Figure 10. Rate of active channel width variation (m $year^{-1}$) in relation of the average of annual daily peak discharge (Qh m^3 s^{-1}) over photo periods and the corrispondent RI.

Figure 11. Lateral adjustment rate versus the number of the days per year with Qd over 450 m^3 s^{-1} for the photo period .

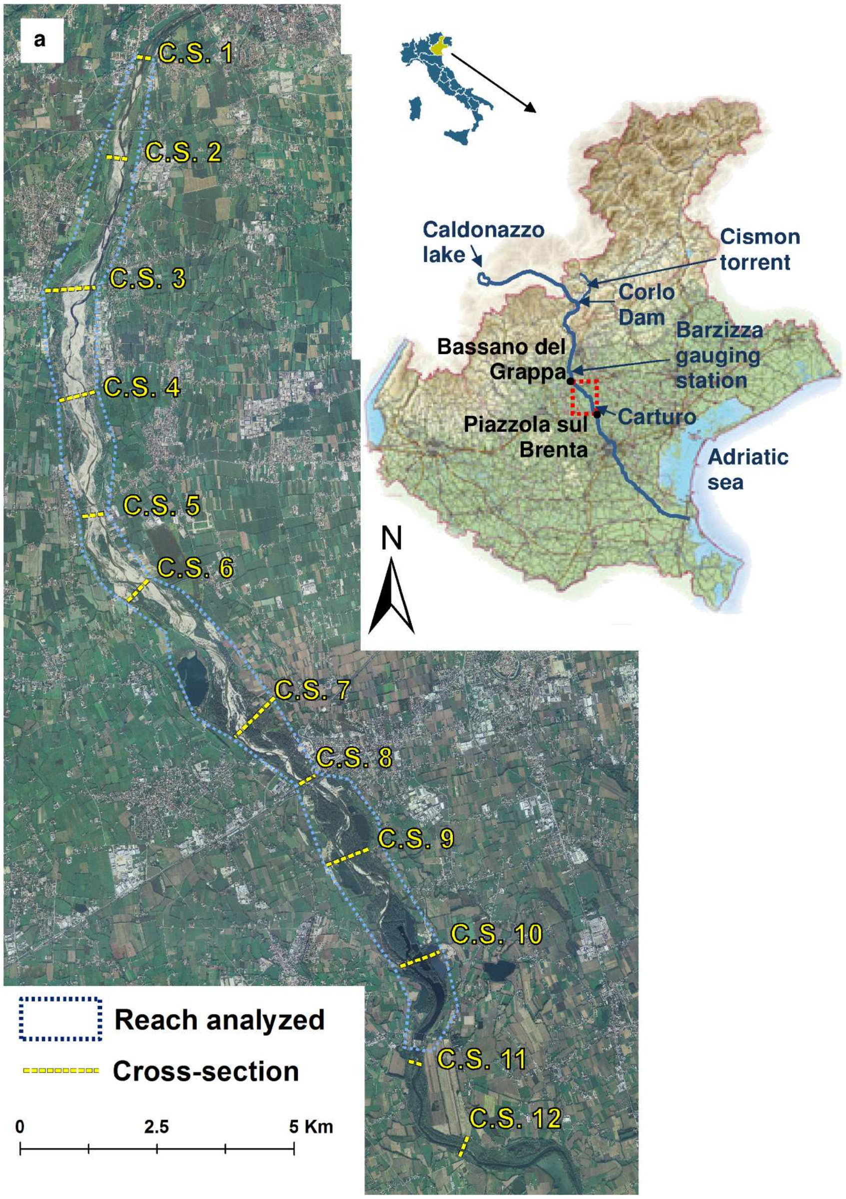
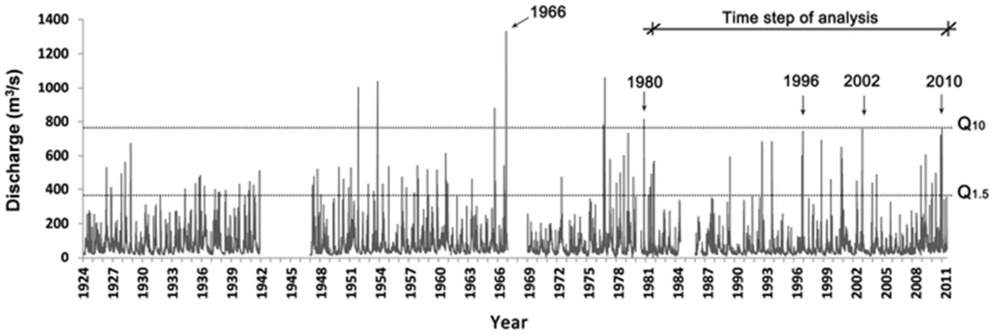


Figure 1. General view of the Brenta river context, the study reach and the cross-sections.
230x324mm (300 x 300 DPI)



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61x20mm (300 x 300 DPI)

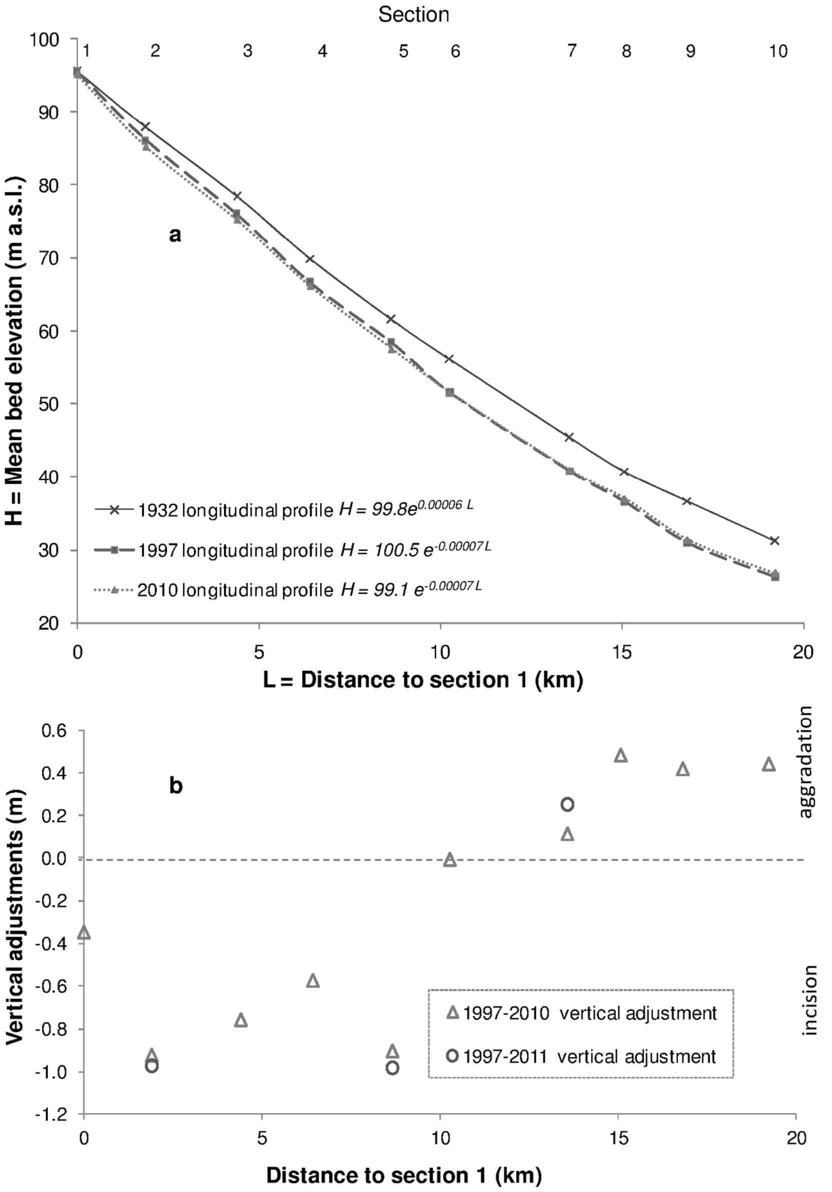

Figure 3. (a) Longitudinal profiles of the Brenta river from 1932 and 1997 survey (Surian and Cisotto, 2007) and 2010. Best equations (exponentials) of the longitudinal profiles are reported (the all three profiles $r^2 > 0.95$); (b) variation of average bed elevation as derived from the comparison of cross-sections along the study reach from section 1 to 10 are shown: negative values of vertical adjustments indicate an incision of streambed whereas positive values indicate an aggradation. 2011 sections are derived from LiDAR survey (Moretto *et al.*, 2012) and are available only for sections 2, 5, and 7.
151x216mm (300 x 300 DPI)

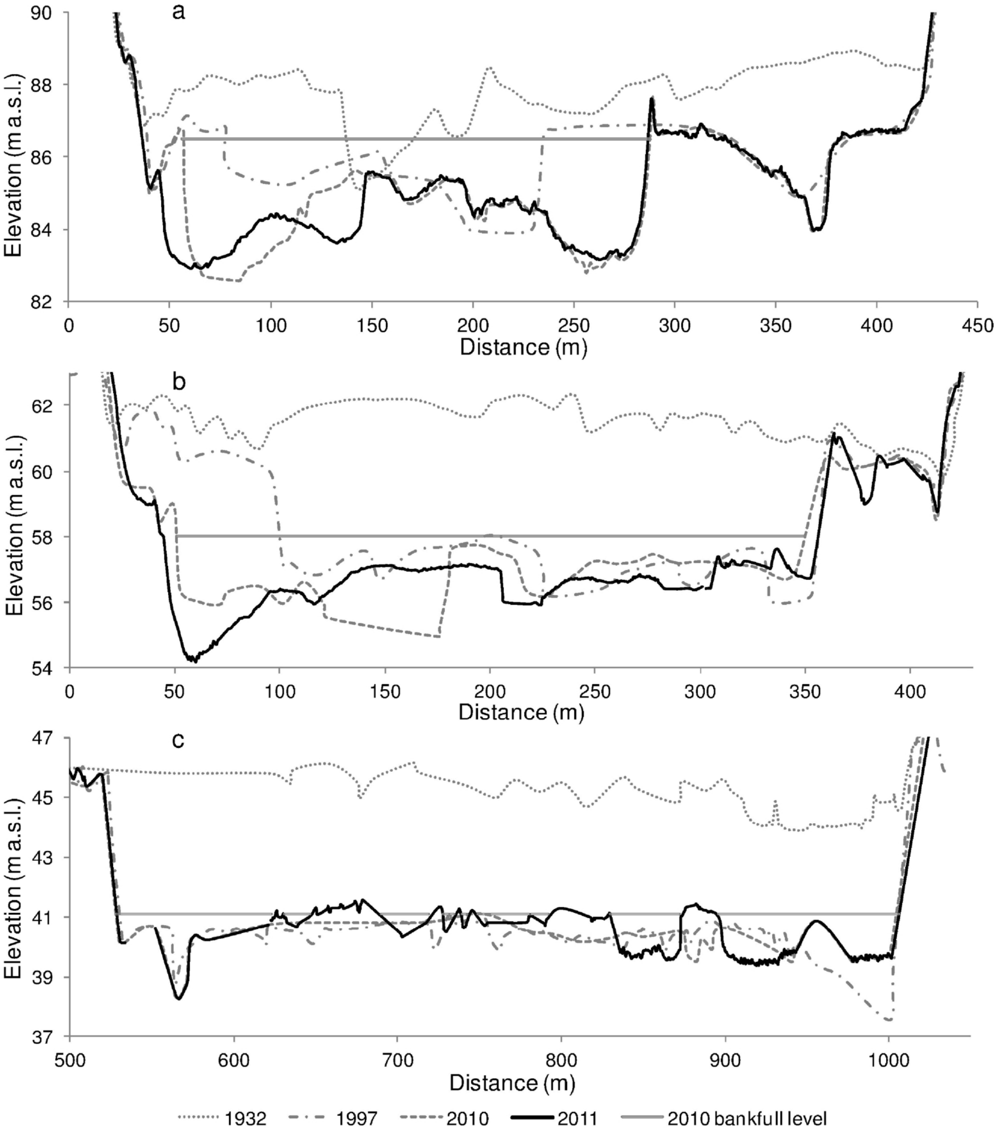

Figure 4. Evolution of historical cross sections 2, 5, and 7 for the years 1932, 1997, 2010, and 2011. The horizontal line represents the bankfull stage for the sections measured in 2010.
193x223mm (300 x 300 DPI)

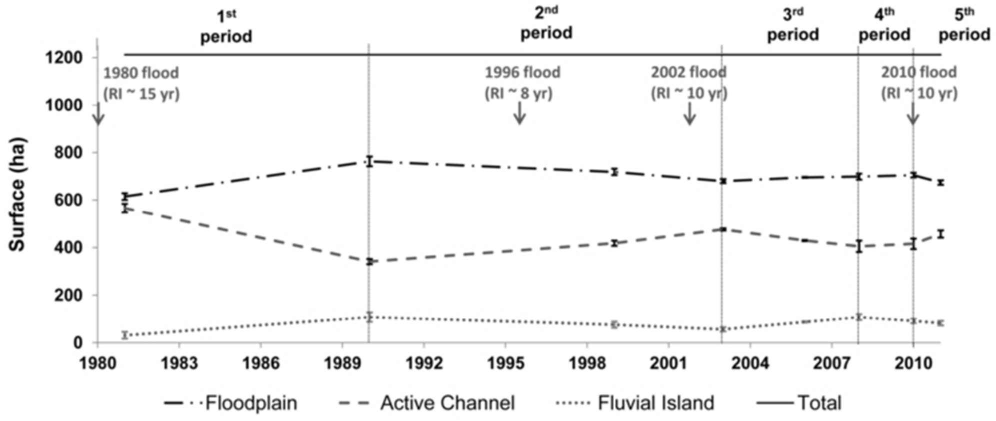

Figure 5. Temporal variation with error bars of the surface of the active channel, floodplain and islands in the analyzed reach of Brenta River.
62x26mm (300 x 300 DPI)

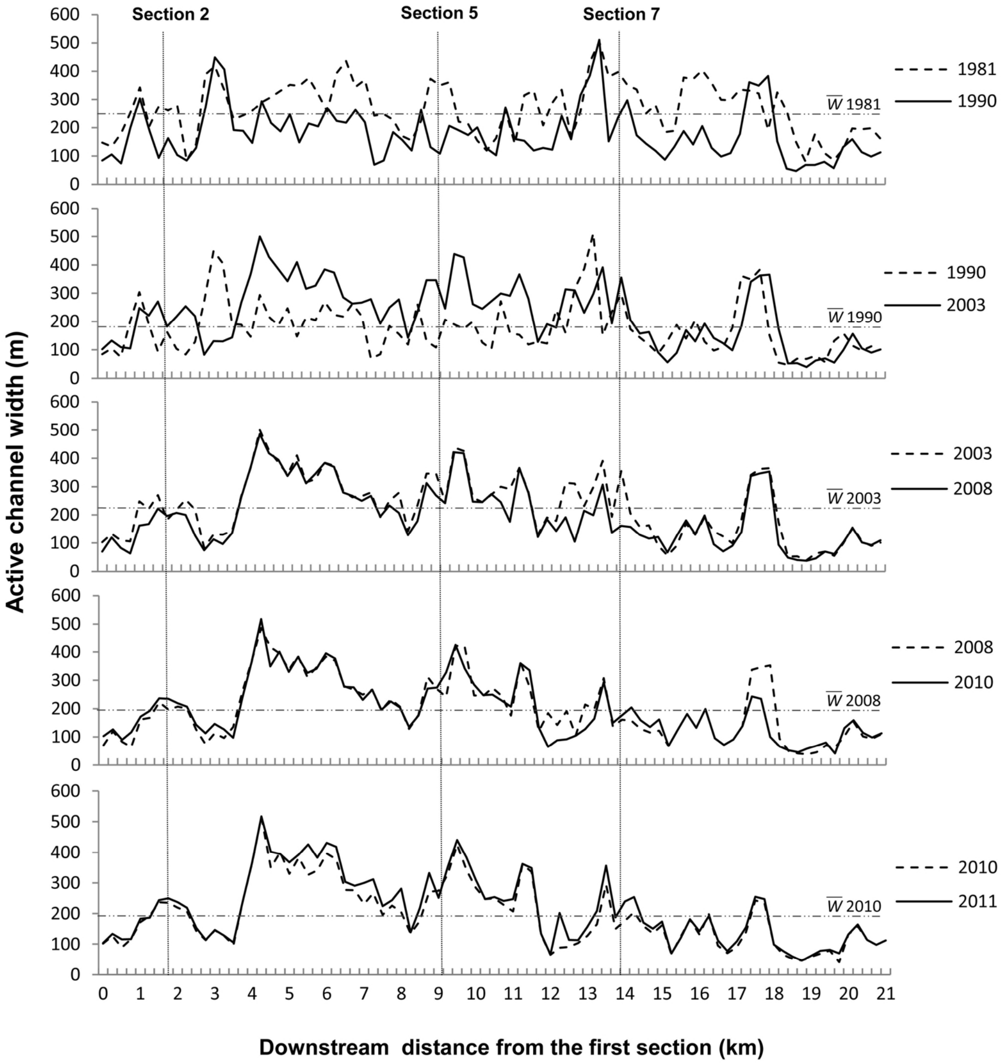

Figure 6. Active channel evolution over the last 30 years divided in five significant periods characterized by different morphological trends.
171x182mm (300 x 300 DPI)

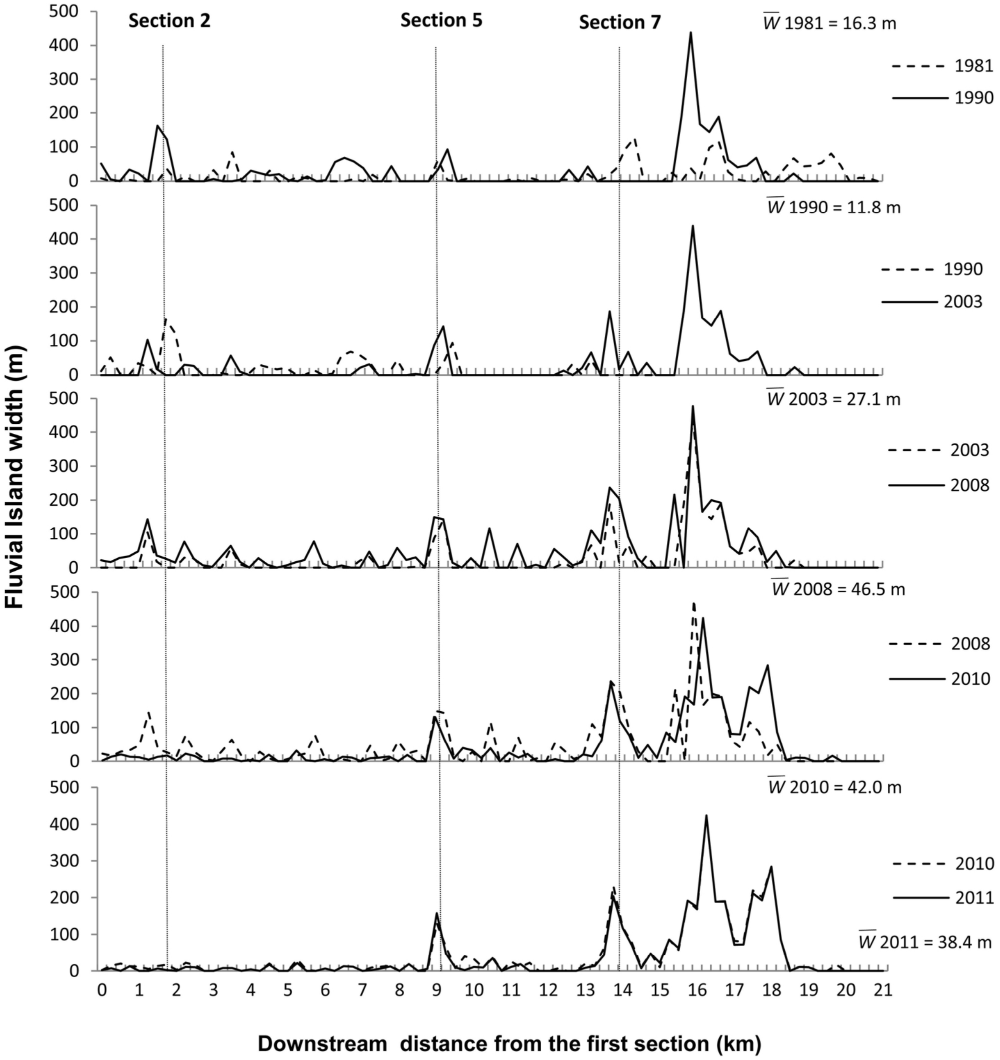

Figure 7. Fluvial island evolution over the last 30 years divided in five significant periods characterized by different morphological trends of active channel.
171x181mm (300 x 300 DPI)

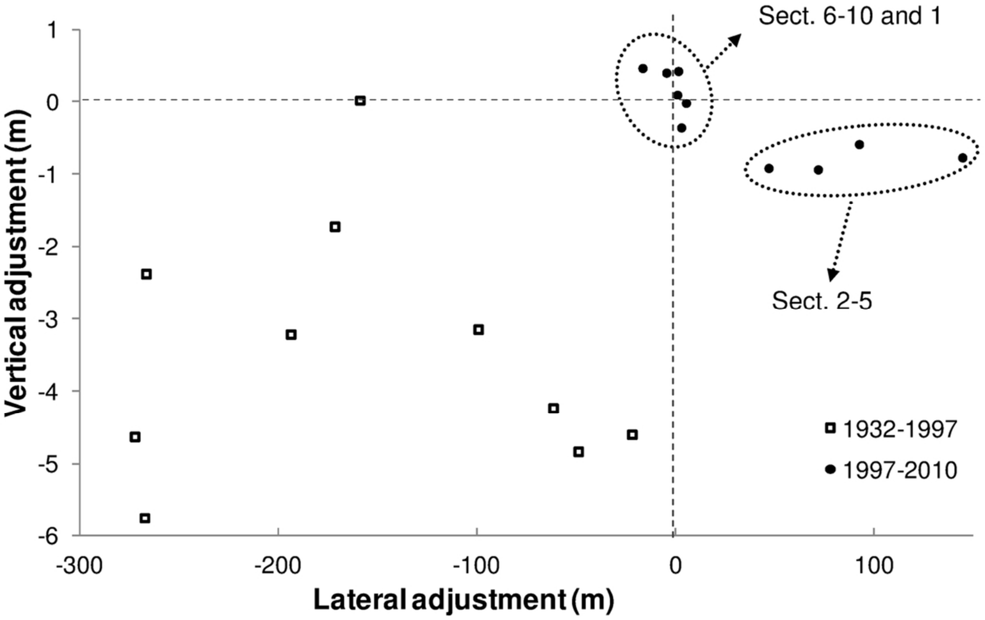

Figure 8. Relationship between the changes of elevation of the bankfull stage and changes of active channel width evaluated at 10 historical cross-sections. The two reported series refer to the periods 1932-1997, and 1997-2010. Negative values mean narrowing or incision, while positive values correspond to widening or aggradation.
105x66mm (300 x 300 DPI)

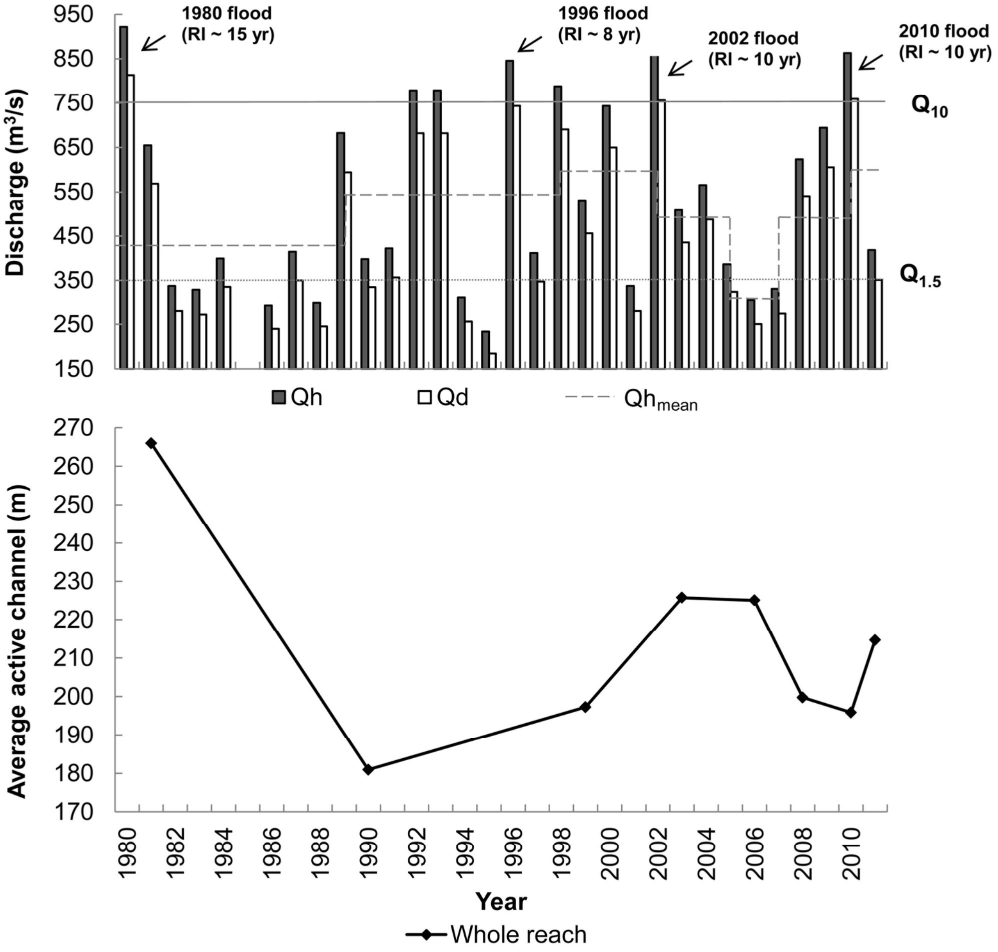

Figure 9. Time evolution of the average active channel width and RI of flood events. (a) Bar chart represents the maximum hourly discharge registered in the year (Qh) and the maximum annual values of the mean daily water discharge (Q); dashed line (Qh_{mean}) represents the average of the annual Qh over a period between two aerial photo-interpretation. Flow discharges featuring RI = 1.5 years ($Q_{1.5}$), and RI = 10 years (Q_{10}) are also shown. (b) Adjustments of the average active channel width (whole reach and sub-reaches). Maximum annual peak discharges value was not available at the Barzizza gauging station for the year 1985.
162x156mm (300 x 300 DPI)

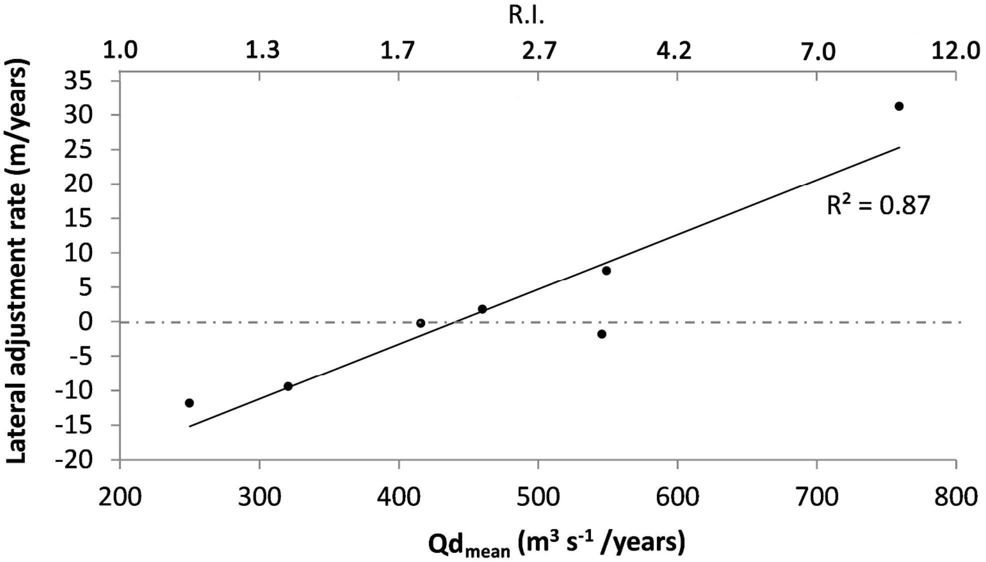

Figure 10. Rate of active channel width variation (m year^{-1}) in relation to the average of annual daily peak discharge (Qd m^3 s^{-1}) over photo periods and the correspondent recurrence interval.
725x412mm (120 x 120 DPI)

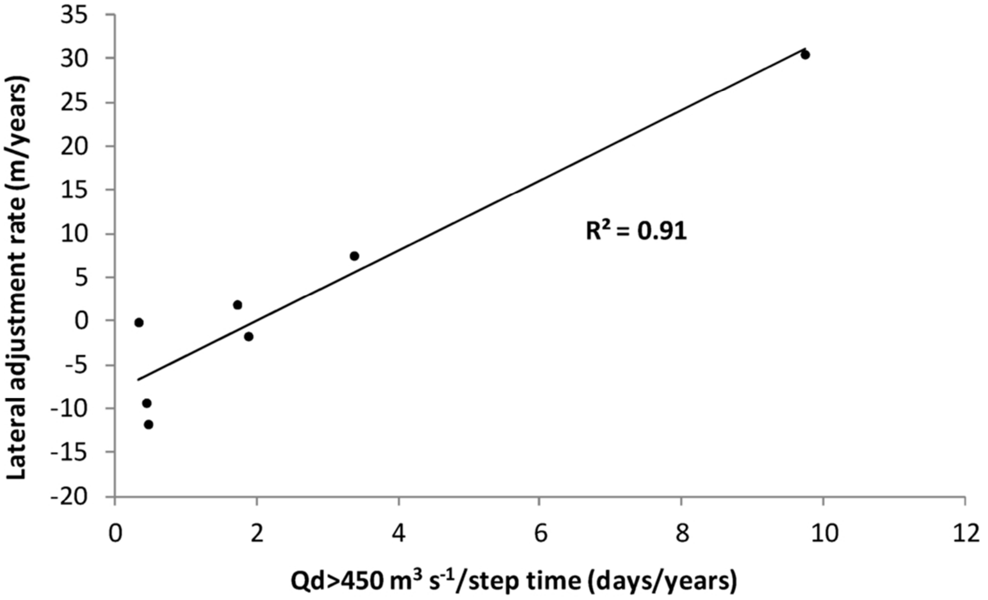

Figure 11. Lateral adjustment rate versus the number of the days per year with Qd over 450 m^3 s^{-1} for the photo period.
90x55mm (300 x 300 DPI)