MEDIUM-TERM FLUVIAL ISLAND EVOLUTION IN A DISTURBED GRAVEL-BED RIVER (PIAVE RIVER, NORTHEASTERN ITALIAN ALPS)

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ABSTRACT. River islands are defined as discrete areas of woodland vegetation surrounded by either water-filled channels or exposed gravel. They exhibit some stability and are not submerged during bank-full flows. The aim of the study is to analyze the dynamics of established, building, and pioneer islands in a 30-km-long reach of the gravel-bed Piave River, which has suffered from intense and multiple human impacts. Plan-form changes of river features since 1960 were analyzed using aerial photographs, and a LiDAR was used to derive the maximum, minimum and mean elevation of island surfaces, and maximum and mean height of their vegetation. The results suggest that established islands lie at a higher elevation than building and pioneer islands, and have a thicker layer of fine sediments deposited on their surface after big floods. After the exceptional flood in 1966 (RI > 200 years) there was a moderate increase in island numbers and extension, followed by a further increase from 1991, due to a succession of flood events in 1993 and 2002 with RI > 10 years, as well as a change in the human management relating to the control of gravel-mining activities. The narrowing trend (1960–1999) of the morphological plan form certainly enhanced the chance of islands becoming established and this explains the reduction of the active channel, the increase in established islands and reduction of pioneer islands.

Key words: river islands, gravel-bed rivers, Piave River

Introduction

River islands are defined as discrete areas of woodland vegetation surrounded by either water-filled channels or exposed gravel (Ward *et al.* 1999), which exhibit some stability (Osterkamp 1998) and are not submerged during bankfull flows. Islands have the potential to enhance the biodiversity within the riparian zone, because their shorelines are characterized by a mosaic of habitats of different ages and have a level of disturbance and geomorphology that are uncommon features along heavily managed riverbanks (Gurnell *et al.* 2001). Because islands are separated from the floodplain, they can offer a safe refuge for wildlife from many predators. As a consequence, river management strategies that reduce the total island area could have negative implications for migratory fowl. Arscott *et al.* (2000) found that in the Tagliamento River, aquatic habitat complexity was greater in the island-braided section than in the island-devoid section. On the same river, Van der Nat *et al.* (2003) showed that aquatic habitats were more established in areas of vegetated islands even compared with bar-braided areas. Stanford *et al.* (1996) showed that islands are most likely to be found in areas of highly dynamic fluvial processes that would account for high species diversity within a wide range of riparian habitats.

The dynamics of islands are closely related to gravel bar dynamics, so many researchers are inclined to define islands as vegetated bars (Hooke 1986; Church and Rice 2009; Rice *et al.* 2009; Hooke and York 2011; Kiss *et al.* 2011). For instance, Hooke and York (2011) defined mid-channel bars as free bars in the middle of the channel that can be vegetated at a later stage, recognizing the process that can lead a gravel bar to evolve into a vegetated island that could persist for long periods and, in some cases, merge with the floodplain.

An early classification of straight, braided and meandering channel patterns (Leopold *et al.* 1964) implicitly incorporates island development through two different processes: the evolution of relatively

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established medial bars on which vegetation can become established within braided channels; the isolation of a section of vegetated floodplain through avulsion and cut-off along meandering channels. Kellerhals *et al.* (1976) further discriminated between occasional, frequent, split and braided island patterns. The downstream changes in tree species, sediment, climate and subsurface hydrology dictate the strategies available for vegetation establishment and the rate at which it can develop. Islands can remain in place for over a decade (Gurnell *et al.* 2001; Hooke and York 2011), being defined as established if they persist after high flows (Wyrick 2005).

The type of islands in a riverine system can also help in describing the ongoing river processes. Gurnell and Petts (2002) determined that most European rivers were once island 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 the Tagliamento River in northeast Italy (Ward *et al.* 1999). Also, the presence of certain plant species on an island can help determine the flow conditions that have generated and influenced its formation. In fact, some species require specific growth conditions, such as flooding time and duration, gradient, and particle size (Picco *et al.* 2012).

Nearly all large European rivers are flow regulated to some degree. This can have implications for fluvial island development and stability. Dams reduce flood peaks, increase base flow, and store sediments (Kondolf 1997; Braatne *et al.* 2003). The sediment transported downstream from a dam can only be a fraction of the sediment transported from upstream. The reduced flow peaks downstream from a dam eliminate most processes of channel erosion, overbank deposition, and sediment replenishment. The biological habitats, diversity, and interactions between biotic and hydrologic processes are also generally reduced (Poff *et al.* 2007). While dams can reduce the erosion and destruction of fluvial islands, they also promote bank attachment by decreasing the sediment supply and reducing the downstream transport capacity, leading to deposition of tributary input sediment.

Osterkamp (1998) described several scenarios in which islands could disappear, distinguishing two key processes: perimeter sediment deposition and floods. Perimeter sediment deposition can eliminate an island through several mechanisms, such as preferential in-filling of one of the side channels; sedimentation around the whole island perimeter until it eventually coalesces with other nearby islands or the floodplain; and flow preferentially incising one of the side channels and leaving the other anabranch ‘high and dry’. On the other hand, floods can eliminate an island by two processes: increasing the flows to levels high enough that the entire island is eroded away; and changing the main direction of the flow during a flood, thereby altering the angle of attack from the water and gradually wearing away the island by abrasion (Wyrick 2005).

The aim of the present study is to analyze the changes in the characteristics of islands over a medium-term period along a sub-reach of the Piave River, which has suffered intense and multiple human impacts, especially alteration of the sediment regime, due to dam building and in-channel gravel mining. The multi-temporal analysis, covering 46 years (from 1960 to 2006), takes advantage of a sequence of six aerial photographs that allow the variation in number and size of three different types of islands to be analyzed. In order to recognize differences between the development stages, the surface characteristics of the proposed island types are also analyzed using LiDAR data. The influence exerted by floods and the importance of fine sediments deposit are discussed.

Study area

The study was conducted on the Piave River, which flows from its source in the Dolomites at 2037 m a.s.l. for 222 km to the Adriatic Sea (Fig. 1). The drainage basin has an area of 4500 km^2 and is composed mainly of sedimentary rocks (predominantly limestone and dolomite). Morphologically, the river can be divided into an upper, middle, and lower course. The upper course, where the river is generally incised in bedrock and therefore has a quite narrow channel, extends from the source to Longarone. The middle course, where the river is very wide and characterized by a multithreaded channel pattern, extends from Longarone to Ponte di Piave. The lower course, where the river meanders have been artificially straightened in places, extends from Ponte di Piave to the mouth (Surian 1999). The study reach (Fig. 1) is 30 km long and is located along the middle course of the Piave River, within the mountain district. The average valley gradient is about 0.004 m m^{-1} and the channel width ranges from 100 m to 1000 m. The study reach can be described as transitional between a wandering and braided river. The median grain size varies between 20 and 50 mm.

The nearest flow recording site is located at Belluno (Table 1). Big floods occurring during the study period are listed in Table 1 (Da Canal 2011). Fig. 2 shows the maximum annual peak discharges measured at the Belluno gauging station, identifying the formative discharge ($Q = 1606$ m^3 s^{-1}; *recurrence interval* (*RI*) = 10 years) able to generate morphological and morphometric variations along the study reach.

Within the 30-km-long study reach another level of 5-km-long sub-reaches was then analyzed. The smaller scale of analysis consists of three sub-reaches characterized, from upstream to downstream, by braiding (sub-reach 1), wandering (sub-reach 2), and braiding (sub-reach 3) morphology (Fig. 3). The average valley gradient of sub-reach 1 is about 0.0033 m m^{-1} and the channel width ranges between 100 m and 550 m; in sub-reach 2 the average gradient is about 0.0048 m m^{-1} and the channel width ranges between 100 m and 620 m; and finally the average gradient of sub-reach 3 is about 0.0034 m m^{-1} and the channel width ranges between 160 m and 1000 m.

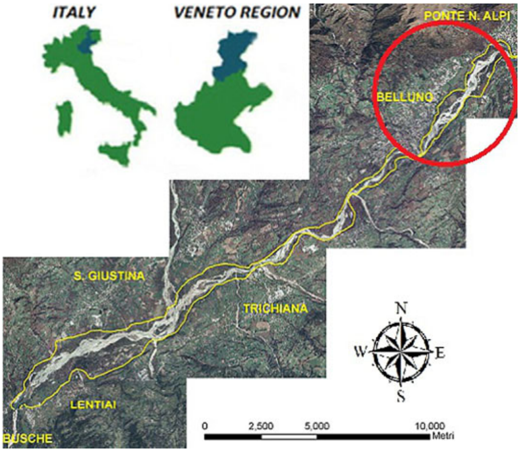

Fig. 1. Location of the Piave River basin and the 30-km-long study reach. The red circles indicate the smaller scale 5-km-long sub-reaches (modified after Picco *et al.* 2012).

The Piave River features a complex pattern of vegetation distribution along the analyzed study reach (Picco *et al.* 2012) (Table 2), which is far more composite than those identified in less disturbed river systems (Hupp and Osterkamp 1996; Tabacchi *et al.* 1998; Bendix and Hupp 2000; Gurnell and Petts 2002).

Materials and methods

River plan-form changes and island characteristics were studied over the period 1960–2006. Plan-form changes were analyzed using six aerial photographs taken in 1960, 1970, 1982, 1991, 1999, and 2006. They range in scale from 1:8.000 to 1:33.000 and were taken when flow conditions were comparable and low (Table 3). Photos were scanned at a resolution of 600 dpi in order to obtain an average virtual resolution of 1 m or smaller. They were then rectified and co-registered on a common mapping base at 1:5000 by a GIS software (Esri ArcGIS 9.2). Approximately 30 ground-control points were used to rectify each frame, and second-order polynomial transformations were then applied, obtaining root mean square errors ranging from 2 to 4 m. The active channel area and width were calculated from the photos and correspond to the area of water and un-vegetated sediment bars.

The analysis was conducted on the whole study area and at sub-reach scale in order to better

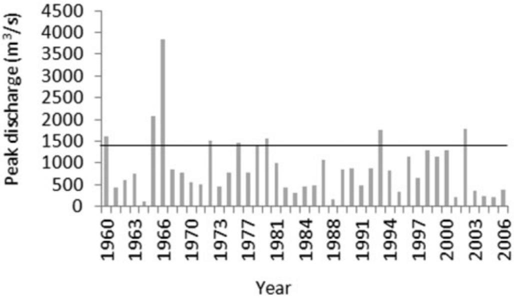

Fig. 2. Maximum annual peak discharges (1960–2006) measured at the downstream end of the study reach. Flow discharges with a recurrence interval = 10 years (Q10) are also shown (after Comiti *et al.* 2011).

Table 1. Main flood events in the Piave river during the study period.

Year	1960	1965	1966	1976	1978	1980	1993	1998	2000	2002
Q (m^3 s^{-1})	1605	2599	4091	1456	1419	1565	1752	1300	1282	1775
RI	9.5	43	280	7.4	6.9	8.9	12.1	5.7	5.5	12.5

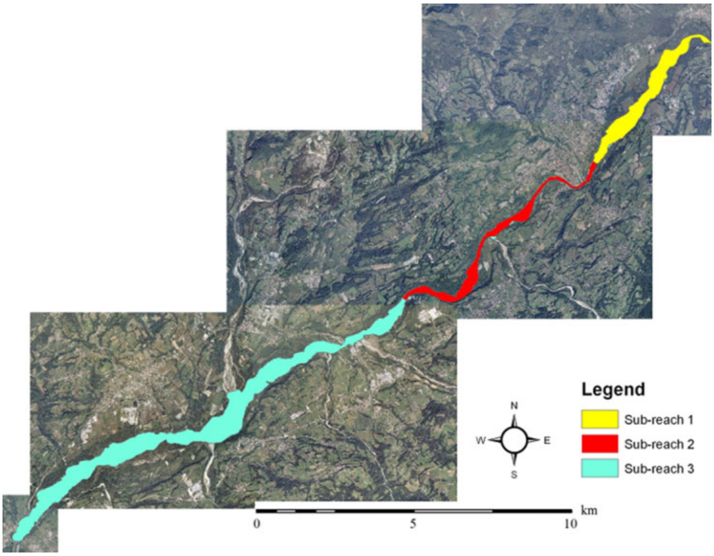

Fig. 3. Location of the three analyzed sub-reaches within the 30-km-long study reach (after Picco *et al*. 2012).

Table 2. Dominant species on islands and floodplain along the Piave River study reach (after Picco *et al*. 2012).

Species	Island	Floodplain
Acer campestre	x	x
Acer pseudoplatanus	x	
Alnus glutinosa	x	
Alnus incana	x	
Amorpha fruticosa	x	x
Buddleja davidii	x	x
Carpinus betulus	x	x
Cornus mas	x	
Cornus sanguinea	x	
Corylus avellana	x	x
Euonymus europaeus	x	
Frangula alnus	x	
Fraxinus angustifolia	x	
Fraxinus excelsior	x	x
Fraxinus ornus	x	x
Juglans nigra	x	
Ligustrum vulgare		x
Ostrya carpinifolia		x
Picea abies	x	
Pinus sylvestris	x	
Platanus acerifolia	x	
Populus alba	x	x
Populus nigra	x	x
Prunus domestica	x	
Robinia pseudoacacia	x	
Salix alba	x	x
Salix daphnoides	x	x
Salix eleagnos	x	x
Salix glaucosericea		x
Salix purpurea	x	x
Salix triandra	x	x
Tilia cordata	x	

Table 3. Discharge when aerial photos were taken.

Year	Discharge (m^3 s^{-1})
1960	23
1970	24
1982	22
1991	25
1999	27
2006	32

understand the differences between the three sub-reaches as their dominant morphological characteristics differ.

In order to distinguish, from aerial photo interpretation, the different vegetated areas in the active channel, a relationship between the age (tree ring measurements) and height of the plants was developed using field data surveyed in 2006 (Fig. 4). This relationship was then extended and applied to the set of historical aerial photos. Assuming the conceptual model of island evolution proposed by Edwards *et al*. (1999), vegetated bars and pioneer islands were identified as distinct morphological units, the latter being areas with vegetation taller than 3 m. Pioneer, building and established islands were distinguished based on the maturity and size of the vegetation, according to Kollman *et al*. (1999), who define how vegetation is generally a good indicator of stability. In the aerial photos, distinction between arboreal and shrubby vegetation was made by

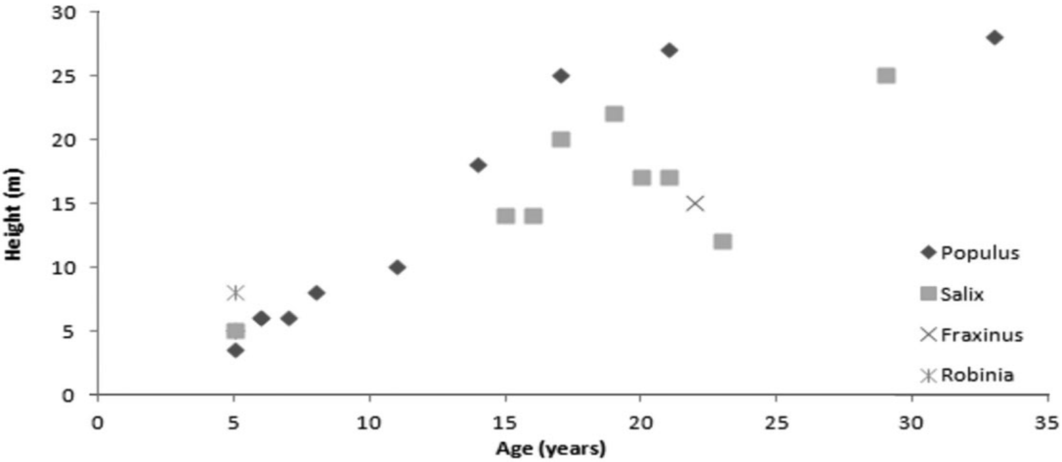

Fig. 4. Relationship between tree heights and ages for different species (modified after Picco *et al.* 2012).

estimating vegetation height based on canopy texture, shape, and shadows. Pioneer islands, defined as an initial stage of development of vegetated patches in rivers (Mikus *et al.* 2012), were described as surfaces on bars with patchy vegetation 3–5 m high, following Thompson *et al.* (1997). These authors proposed that vegetation growing along the regulated braided gravel-bed Waitaki River (New Zealand) could be managed by releasing floods around the bankfull level every three years in order to maintain a bare gravel, braided fairway. This "return period" was suggested to avoid strong rooting of plants. Building islands are an intermediate stage of development, characterized by an increasing stage and extent (Mikus *et al.* 2012). Finally, established islands are defined as surfaces existing after high flow events (Wyrick and Klingeman 2011) and characterized by areas with a tall dense vegetation cover (Gurnell and Petts 2002). In a natural braided gravel-bed river, these landforms rarely survive more than 20 or 25 years (Gurnell *et al.* 2001).

An airborne LiDAR flight, carried out by the *Autorità di Bacino dell'Alto Adriatico* during fall 2003 (adopting orthometric elevations, estimated vertical error ± 20 cm), allowed this approach to be confirmed and the vertical characteristics of the surface and vegetation to be analyzed in detail. A point density of 2–3 m^{-2} was reached after filtration. The *digital terrain model* (*DTM*) and *digital surface model* (*DSM*) were created at 1 m resolution using the tool "3D-analyst" of ArcGIS 9.2. Canopy height derived from the LiDAR was used to complement the aerial photographs (Zanoni *et al.* 2008). Based on the 1 m LiDAR resolution the raster subtraction of the original DTM layer and the DSM layer generated the canopy height model, which was used to obtain the maximum, minimum, and mean elevation of island surfaces and the maximum and mean height of the island vegetation for sub-reach 2 in 2003 (Picco 2010).

Lastly, information on the thickness of the fine sediment on islands was collected in the field in order to analyze differences between the three types of islands. These field measurements were taken all over sub-reach 1, using a random scheme, by digging vertical holes until reaching the gravel layer.

Results

Fig. 5 shows the maximum vegetation height on the different types of islands, as derived from the canopy analysis conducted using the 2003 LiDAR survey. Established islands feature the tallest vegetation cover (median value around 17 m), with a maximum height of around 25 m. Building islands instead show a median value around 7 m, with most values ranging from 5 to 12 m. Pioneer islands feature a median height of about 2.5 m, and maximum values (excluding outliers) of about 7 m. This supports the choice of distinguishing island types using photogrammetry, as the three types of island show values included in the range defined above.

Concerning the morphological modification of the study reach, the active corridor area on the Piave River increased from 13.4 km^2 in 1960 to 14.2 km^2

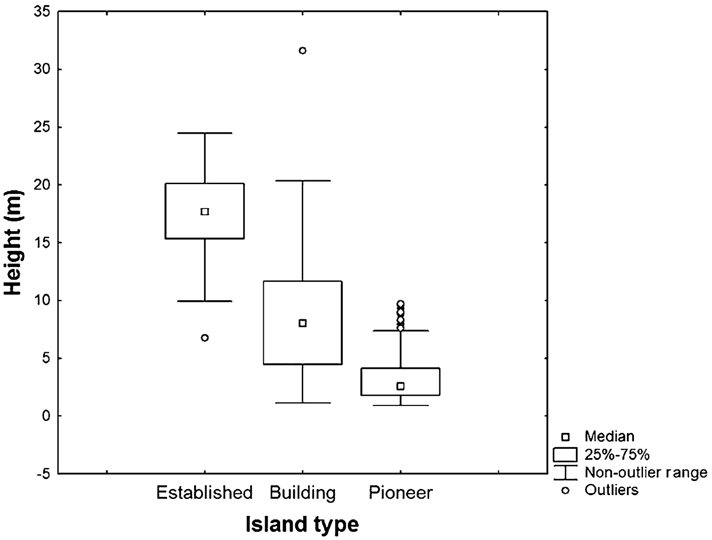

Fig. 5. Maximum height of established, building and pioneer islands derived from analysis of the 2003 LiDAR survey (modified after Picco *et al.* 2012).

in 1970, most likely as a result of an exceptional flood in 1966, and then decreased substantially until 1991, reaching 9.3 km^2. After this, the active corridor area increased gradually, reaching 10.6 km^2 in 2006. Within the active corridor area, the dynamics of the island extent showed complex tendencies. From 1960 to 1970 the area of established islands remained relatively unchanged (1.6% and 1.5% of the active corridor area), then increased to 4.1% in 1982, fluctuating afterwards around 3%, and becoming lower only in 2006 (Fig. 6).

Interestingly, the number of established islands remained around 2 to 2.5 per km^2 between 1960 and 1999, with a substantial increase from 1999 to 2006, reaching 5.3 per km^2 (Fig. 6). Building islands show a similar tendency, with a strong decrease from 1960 (5.7%) to 1970 (1.5%) and then a substantial increase until 1991 (6.2%), followed by a strong decrease until 2006 (2.8% of the active corridor area). As for the number of building islands per km^2, this decreased substantially from 1970 to 1982 (18.5 to 8.3), and significantly expanded during the following period up to 1991 (13.4 building islands per km^2). Finally, the extent of pioneer islands decreased from 1960 to 1970 (1.5% to 0.4%) and then increased until 1991 (1.4%), with a final contraction phase until 2006 (0.9%). In this case, the number of pioneer islands per km^2 decreased constantly from 1960 to 1999 (83.8 to 25.3), with a final expansion trend up to 2006 (38.4).

The area of the active channel surface along sub-reach 1 remained quite constant over time (Fig. 7), whereas sub-reach 2 experienced a slight and constant decrease until 1991, followed by a constant trend between 1960 and 1970. From 1991 to 2006 sub-reach 2 showed a new phase of active channel widening (Fig. 7). Sub-reach 3 changed quite dramatically over the study period. In fact, after a moderate widening phase from 1960 to 1970, there was a strong and continuous decrease in the active channel area until 1991, with an established trend from 1991 to 1999, and then again an increase from 1999 to 2006 (Fig. 7).

Along sub-reach 1, there were a minimal number of established islands until 1982, followed by a strong increase in their extent up to a maximum in 1999 (5.6%), then another decrease in 2006 (3.8%) (Fig. 8). Building islands decreased from 1960 (2.7%) to 1970 (0.5%), and then increased up to a maximum value recorded in 1991 (8.5%), followed by a further contraction phase. Pioneer islands are represented by a very limited area during the entire period under analysis. If the number of islands is normalized using the active channel area (Fig. 8), it appears that the number of established islands (N) was relatively constant over time, at least until the very recent increase phase (15.4 N km^{-2}). The number of building islands decreased from 1960 to 1982, subsequently increased until 1991 (25.2 N km^{-2}), and then

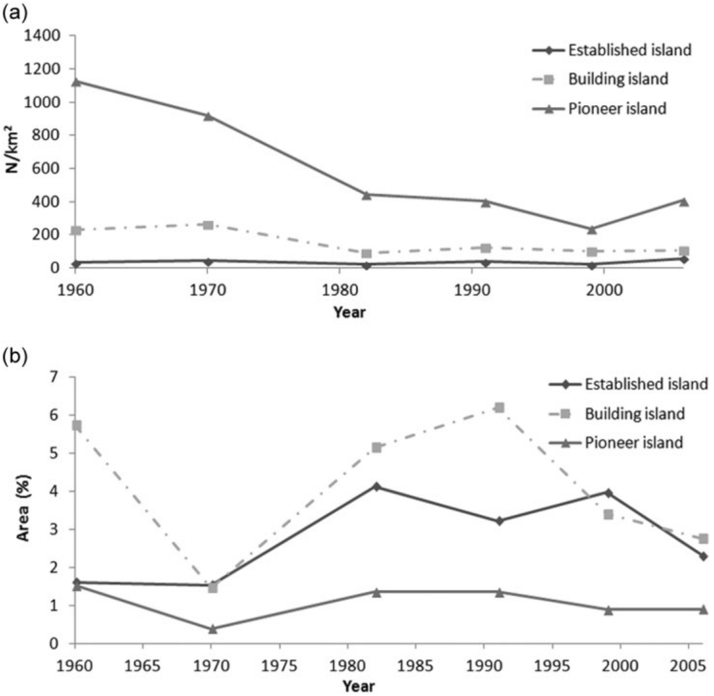

Fig. 6. Extent of islands in the Piave River, expressed in terms of percentage of the active corridor area (a) and number per km^2 (b) (modified after Picco *et al.* 2012).

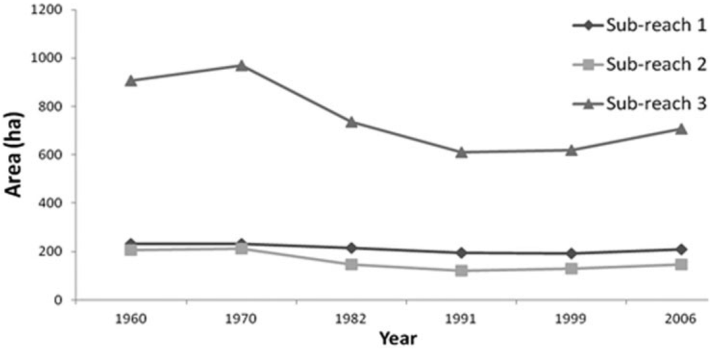

Fig. 7. Active channel area variation of different sub-reaches along the Piave River over the study period (after Picco 2010).

decreased until 1999 (15.6 N km^{-2}), with a very slight recent increase in 2006. Pioneer islands show a clear increase between 1960 and 1970, followed by a sudden decrease until 1982 (53.2 N km^{-2}), and a new increase until 1991 (N km^{-2}).

Along sub-reach 2, the extent of established islands decreased from 1960 (1.1%) to 1970 (0.7%), then increased up to the maximum value in 1982 (3.7%) (Fig. 9). Building islands decreased from 1960 (5.6%) to 1970 (1.2%); there was then a slow decrease until 1980 (0.9%). This was followed by another increase until 1991 (2.1%) and a subsequent slow and constant decrease until 2006 (1.7%). Pioneer islands experienced a relatively constant trend fluctuating around quite low values.

The number of established islands along sub-reach 2 decreased from 1960 (3.9 N km^{-2}) to 1970 (0.9 N km^{-2}). After that, there was an increase until 1982 (2.1 N km^{-2}), a subsequent decrease until 1999 (0.8 N km^{-2}), and a final strong increase until 2006 (2.7 N km^{-2}) (Fig. 9). Building islands

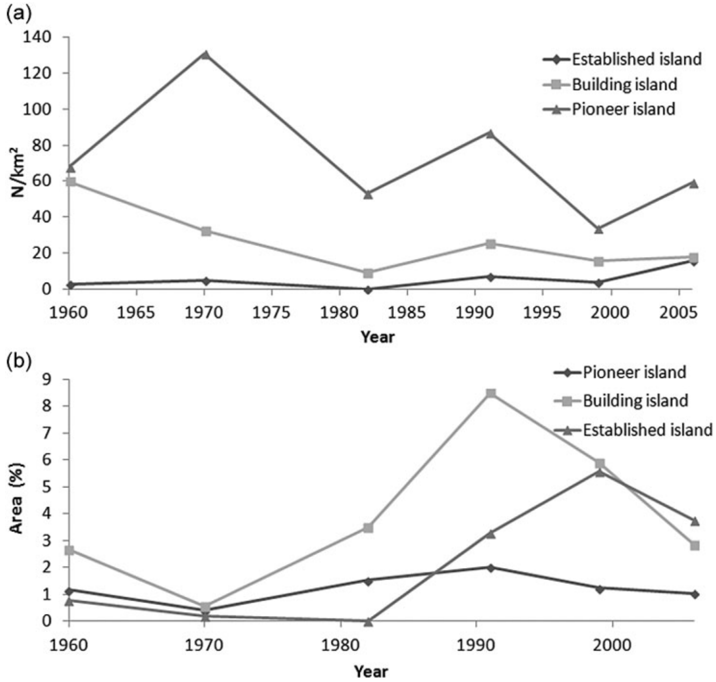

Fig. 8. Extent of islands in sub-reach 1, expressed in terms of number per km^2 (a) and percentage of the active corridor area (b) (modified after Picco *et al*. 2012).

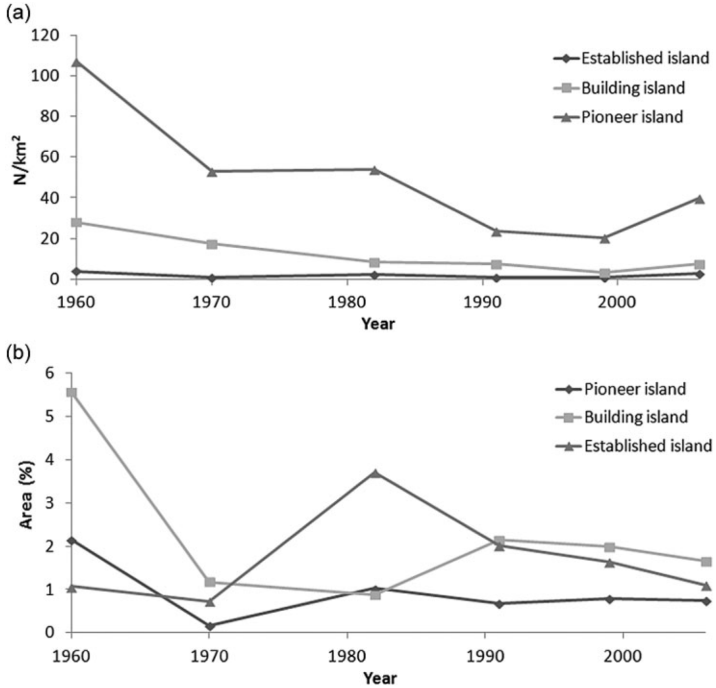

Fig. 9. Extent of islands in sub-reach 2, expressed in terms of number per km^2 (a) and percentage of the active corridor area (b) (modified after Picco *et al*. 2012).

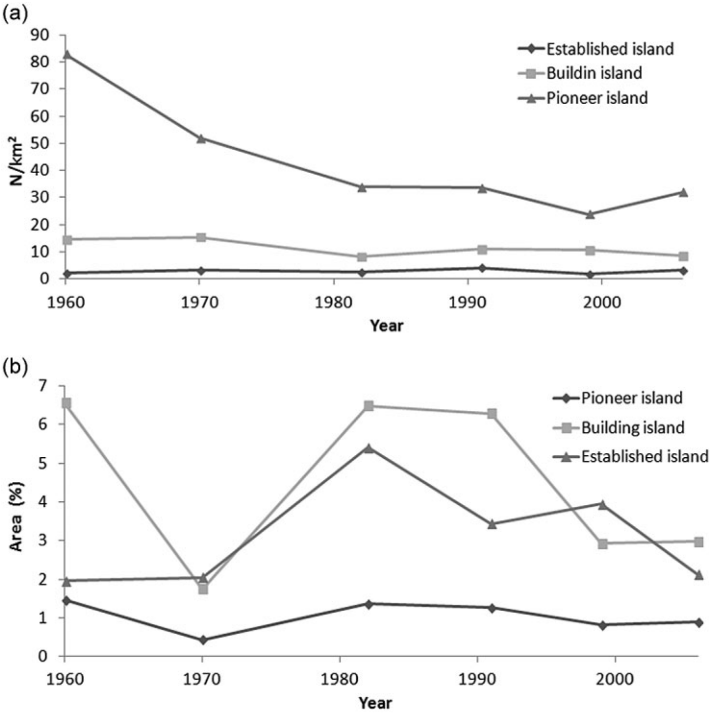

Fig. 10. Extent of islands in sub-reach 3, expressed in terms of number per km^2 (a) and percentage of the active corridor area (b) (modified after Picco *et al.* 2012).

decreased from 1960 (28 N km^{-2}) to 1999 (3.1 N km^{-2}), and then increased until 2006 (7.5 N km^{-2}). The number of pioneer islands decreased substantially from 1960 (107 N km^{-2}) to 1999 (20.2 N km^{-2}), followed by a steep increase until 2006 (396 N km^{-2}).

Along sub-reach 3, the surface area of established islands was quite constant between 1960 (2%) and 1970 (2%), followed by an increase up to the maximum value recorded in 1982 (5.4%); there was then a progressive decrease until 2006 (2.1%), being the only sub-reach experiencing a contrasting trend in 1999 (4%) (Fig. 10). The extent of building islands fluctuated, with a decrease between 1960 (6.6%) and 1970 (1.7%), an increase until 1982 (6.5%), a steady phase until 1991 (6.3%), and a final decrease until 2006 (3.0%).

The number of established islands in sub-reach 3 showed quite a complex trend, fluctuating between a maximum in 1991 (4.1 N km^{-2}) and minimum in 1999 (1.9 N km^{-2}) (Fig. 10). Building islands increased from 1960 (14.6 N km^{-2}) to 1970 (15.4 N km^{-2}), followed by a strong decrease until 1982 (8.1 N km^{-2}); there was then a moderate increase up to 1991 (11 N km^{-2}) and a subsequent slow and constant decrease until 2006 (8.5 N km^{-2}). The number of pioneer islands decreased from 1960 (82.9 N km^{-2}) to 1999 (23.9 N km^{-2}), and then increased until 2006 (32 N km^{-2}).

In 2003 there were 317 islands in sub-reach 2, 75% of which were pioneer, 17% building, and 8% established. The elevations of island surfaces were derived using the DTM obtained from the 2003 LiDAR flight, and their extent is depicted in Fig. 11. Although the median values of the three types of islands were similar, the degree of variation differed between established islands and the other two types.

The established islands feature mean elevations up to 3 m, with most values ranging from 1 to around 1.5 m, whereas most of the building and pioneer islands show a range of mean elevation at lower values (0.5–1.2 m), with the highest islands of these two types being around 2 m (excluding outliers for the building type up to 2.5 m).

Interestingly, the mean elevation of the floodplain being at 1.81 m, it lies higher than the majority of the islands (excluding outliers).

The three types of islands are substantially different in terms of thickness of fine sediments

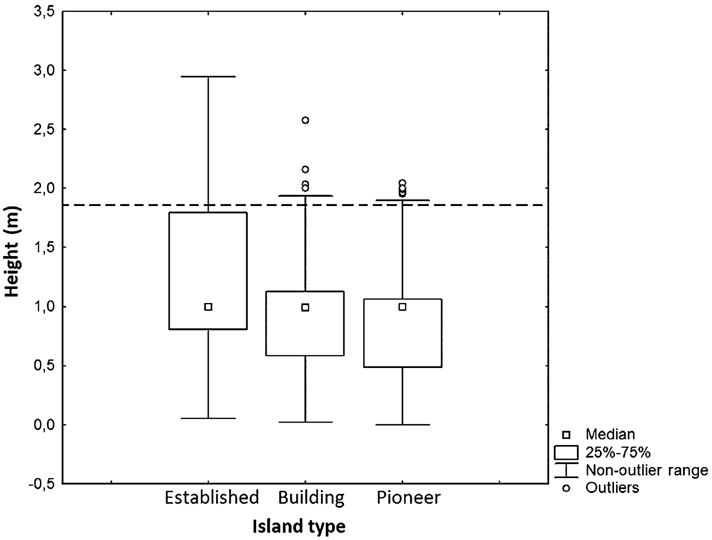

Fig. 11. The elevation of three types of islands in 2003, relative to the low flow water level. The dashed line represents the mean elevation of the floodplain (modified after Picco *et al.* 2012).

deposited on their surfaces, as measured in the field. In fact, the established islands, being older and with a very stable vegetation cover, are able to trap a large amount of sand with a thickness of up to 1 m (Fig. 12).

Discussion

According to the results of the analysis of fluvial islands along the Piave River, there was a predominant and progressive decrease in the active corridor area from 1960 to 2006. After the exceptional flood in 1966 (RI = 280 years) there was a moderate increase in the extent and number of islands, followed by a further increase from 1991, due to flood events in 1993 and 2002, both with RI = 12 years, as well as a change in human management relating to the control of gravel-mining activities. Established islands increased from 1970 to 1982 due to a period of stability that corresponded to a decrease in the active corridor area. After 1982, there was a decrease in their percentage area because established islands presumably merged with the floodplain vegetation, as previously reported in the literature (Osterkamp 1998; Wyrick 2005; Comiti *et al.* 2011; Kiss *et al.* 2011). The flood event in 1993 (RI = 12 years) caused a further increase in established islands until 1999, likely due to the reactivation of abandoned secondary channels and thus the detachment of established sections of riparian vegetation from the floodplain. In this case, an increase in the percentage surface area is not always related to an increase in island number, but is mainly due to the formation of "macro-islands". This occurs because adjacent islands tend to merge through the transition of parts of the younger islands to other types and/or the opening of new channels in the floodplain (Osterkamp 1998). After the 1966 flood, both the surface area and number of pioneer islands decreased until 1970. Subsequently, the extent of pioneer islands increased until 1991 due to the lack of major floods, and then decreased until 1999 due to a succession of moderate flood events.

As expected, established islands lie at higher elevation and have a thicker layer of fine sediments deposited on their surfaces than building and pioneer islands, although not as deep as shown by Church and Rice (2009), who reported a fine sediment thickness of up to 3 m. The thicker sediment is due to the fact that older vegetation growing on established islands allows the deposition of fine sediments which, in turn, enhances the conditions for vegetation establishment and growth.

As for the vegetation height, there is a clear differentiation between the three types of islands. The data obtained analyzing the LiDAR data are confirmed by field surveys. A dendrochronological analysis (Mao, L., Picco, L., Sitzia, T. and Lenzi, M.A., unpubl.) also showed that pioneer islands are

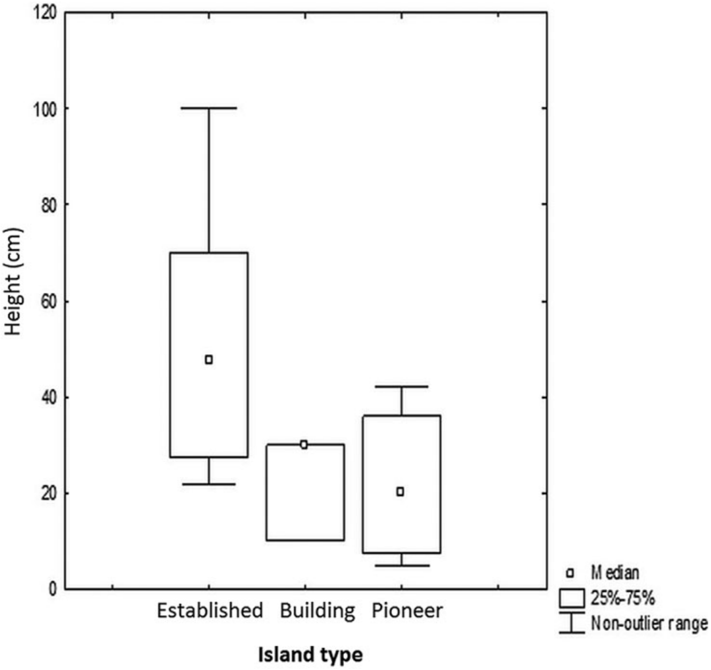

Fig. 12. The thickness of fine sediments on established, building and pioneer islands from 2003 LiDAR surveys (modified after Picco *et al.* 2012).

dominated by vegetation ranging between 3 and 5 years old, building islands are dominated by plants aged between 5 and 15, whereas established islands are vegetated by trees older than 15 years. The oldest plants identified in the reach can be dated back 33 years.

With reference to the long-term morphological evolution of the Piave River, it has already been reported that the study reach suffered from intense and multiple human impacts (Comiti *et al.* 2011), which caused substantial active channel narrowing and incision during most of the twentieth century. Within this context, the dynamics of the islands is certainly influenced by the factors determining the long-term channel narrowing and incision and the recent widening phase (Comiti *et al.* 2011). The narrowing trend (1950 up to 2000), coupled with the lack of flood events capable of changing the size of channels, certainly enhanced the chance of islands becoming established (Fig. 13). This explains the increased reduction of active channels (via floodplain vegetation growth and the merging of established islands with the floodplain), the increase in established islands, and reduction of pioneer islands (becoming progressively building then established islands).

Although a general channel widening is apparent in the study reach between 1999 and 2006, there were no clear indications of a widespread, concomitant aggradation phase. The extreme 1966 event (RI = 280 years) reduced the island-to-channel area ratio to its lowest values, which then soared in concomitance with channel narrowing and bed incision (Comiti *et al.* 2011). Subsequently, floods in 1993 and 2002 (RI = 12 years) determined relevant drops in island cover as well as erosion of riparian vegetation (Comiti *et al.* 2011). These observations match those made by Bertoldi *et al.* (2009) on the Tagliamento River, a braided river similar in many aspects to the Piave, but with virtually unregulated flows and sediment regimes. In fact, the island dynamics in the Tagliamento River were found to be strictly associated with the occurrence of major floods (RI > 10–15 years), which are the only ones able to generate substantial island erosion.

Along the Piave River, the total island area and the large extent of established and pioneer islands during the 1990s was a consequence of an altered sediment regime, determined by gravel mining leading to bed incision, in turn causing vegetation establishment and accelerated island coalescence.

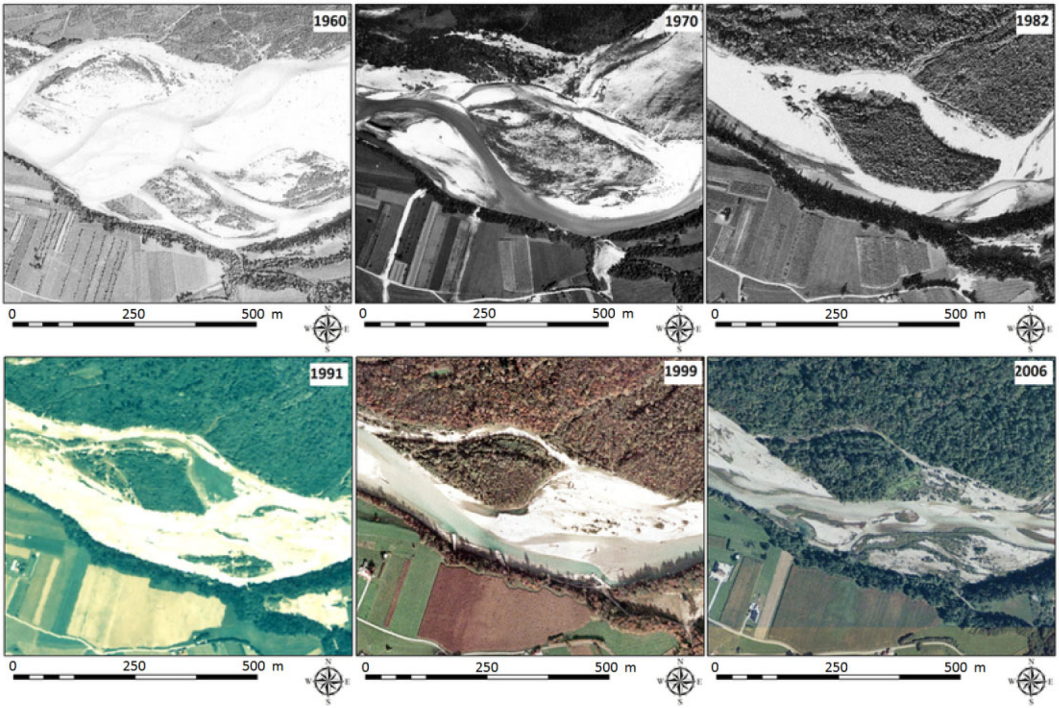

Fig. 13. Gravel bars and island evolution in the Piave River during the study period. The area of the island increased from 1960 to 2006, resulting in a complete merging with the floodplain.

According to what was shown by Church and Rice (2009) along the Fraser River, bars located close to vegetated areas can survive to a much greater age, stabilizing and evolving into vegetated bars, and finally, islands.

The analysis at the scale of sub-reach revealed that only sub-reach 3 was actually affected by a substantial change in the active corridor extension (Fig. 7). This is likely due to the fact that sub-reach 3 is located at the downstream end of the study area, where avulsions and channel wandering are still possible because of the wide floodplain area unprotected by longitudinal banks. A further analysis, concerning the number of islands and their surface area within the three analyzed sub-reaches, revealed a significant difference between values obtained in the wandering and braiding sub-reaches. In fact, along sub-reach 2 (Fig. 14), characterized by a wandering morphology, the constant and significant decrease in island number and area was probably due to the merging of islands with the riparian vegetation and the floodplain (Fig. 15), following natural reforestation of inactive channels and the simplification of the multithread channel pattern, a process already reported by Gurnell *et al.* (2001) and Hooke and Yorke (2011).

Along the two braided sub-reaches (sub-reaches 1 and 3, Figs 16 and 17, respectively) there was an increase in the island areas until 1999, due to the higher dynamic tendency of braided environments. In fact, the presence of islands and bars is typical of active environments such as braided rivers or systems in transition to this morphology (Leopold and Wolman 1957; Hooke 1986, 2010; Hooke and York 2011), and increases the diversity and number of habitats (Crosato and Mosselman 2009).

It is interesting to note that between 1991 and 1999 there was a strong decrease in the building island area and an increase in the established island area along both sub-reaches. This is mainly due to the progressive stabilization and merging of building island patches. Finally, it is worth pointing out that the islands can strongly influence water and sediment transport in the river network and can have important impacts on the type and rate of the river plan-form style adjustments as well as the resistance of river styles to subsequent change

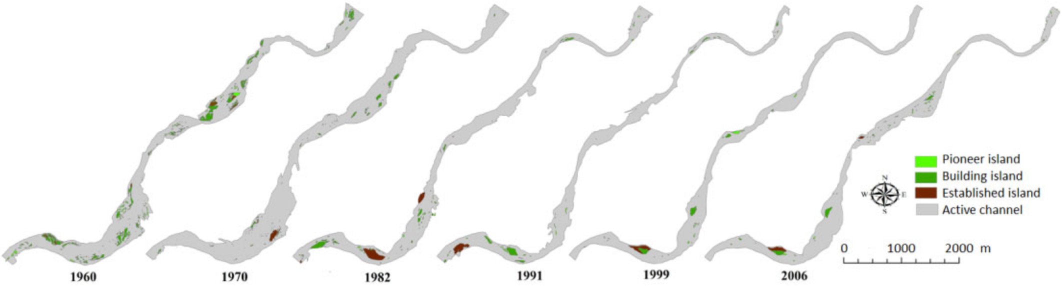

Fig. 14. Historical evolution of sub-reach 2 along the Piave River between 1960 and 2006.

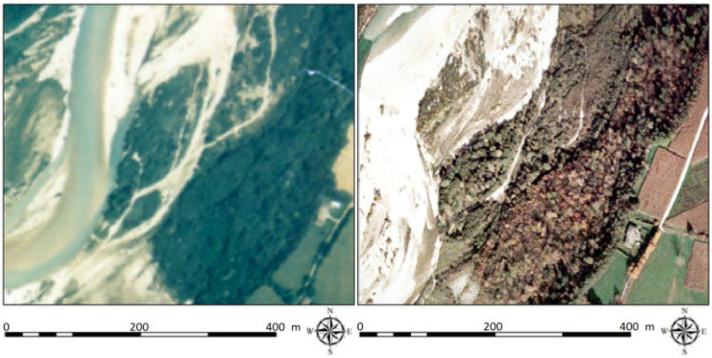

Fig. 15. Merging of a fluvial island with the floodplain along the Piave River sub-reach 2, occurred between 1991 and 1999.

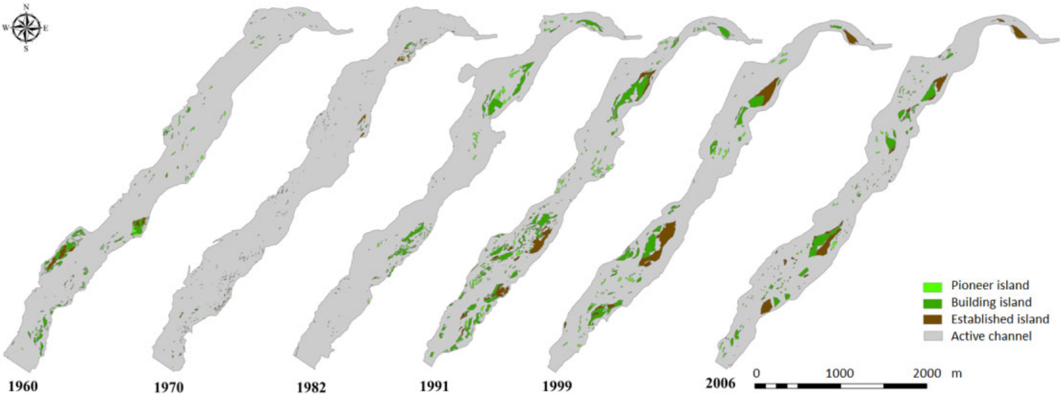

Fig. 16. Historical evolution of sub-reach 1 along the Piave River between 1960 and 2006.

(Gurnell *et al*. 2009). Changes in discharges (therefore its regulation) and vegetation growing within the river corridor both contribute to determine morphological changes of a river reach. A decrease in discharge causes a lower sediment transport as well as an increased tendency of vegetation to grow in the riverbed. Furthermore, established in-channel vegetation affects the sediment transport by stabilizing banks and bars, thus limiting erosion and channel migration. This leads to channel incision (Picco 2010; Comiti *et al*. 2011), which further increases the stability of islands. The lack of major and formative floods or a decrease in their frequency contributes to stabilizing both islands and riparian vegetation, which increase overall flow resistance within the floodplain.

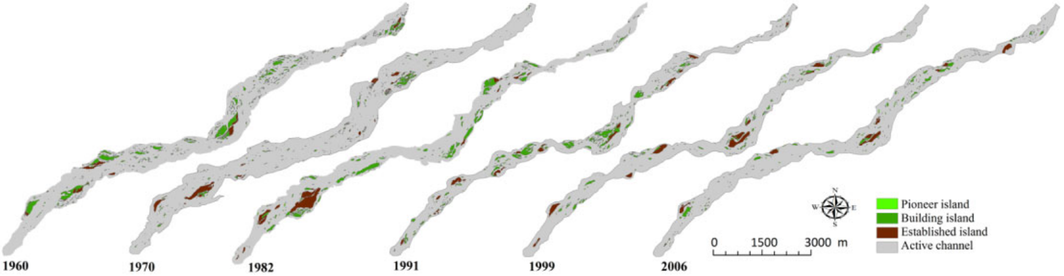

Fig. 17. Historical evolution of sub-reach 3 along the Piave River between 1960 and 2006.

Final remarks

The characteristics and extent of fluvial islands are the results of a complex interaction between vegetation growth during inter-flood periods and the erosional effects of floods of different magnitude and duration. The long-term lack of formative discharges or the lack of sediment supply due to human disturbance can produce a consistent increase in size and stability of fluvial islands. Reduced floods also cause established island to merge with floodplain vegetation reducing the area of active channel. The results gathered from a 40-year multi-temporal analysis of island evolution along the Piave River highlight that pioneer, building, and established islands have different responses to the occurrence of flood events. It is therefore important for river managers to recognize the progression of island development. This could be useful to better define flood management programs and precautionary action, such as the removal of the biggest trees from the islands located close to critical sections.

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