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Channel adjustments in response to human alteration of sediment fluxes: examples from Italian rivers

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Abstract In response to various types of human impacts, most Italian rivers have experienced considerable channel adjustments during the last two centuries. Human impact includes reforestation, channelization, construction of dams and sediment mining. The most important effect of human impact has been an alteration of sediment fluxes, and specifically a remarkable decrease in sediment supply to river channels. The five rivers selected in northern Italy (Tagliamento, Piave, Brenta, Trebbia and Vara), which have or used to have a braided morphology, have undergone channel narrowing (between 58 and 85%), decrease of braiding intensity and incision (up to 4–5 m). Narrowing and incision have been the dominant processes during the last two centuries, particularly intense from the 1950s to the 1990s; however, recent data suggest that those processes could now be exhausted since other kinds of adjustments, specifically channel widening and (local) aggradation, have occurred during the last 10–15 years.

Key words braided rivers; channel adjustments; channel narrowing; channel widening; human impact; Italian rivers; sediment fluxes

INTRODUCTION

During the last century most of the Italian rivers, like many other rivers throughout the world (e.g. Williams & Wolman, 1984; Wyzga, 1993; Kondolf, 1994; Winterbottom, 2000; Liebault & Piegay, 2001), have experienced considerable morphological changes in response to various types of human interventions. Two recent papers, about the rivers of Tuscany (central Italy) (Rinaldi, 2003) and Italian rivers (Surian & Rinaldi, 2003), have documented that: (a) incision and narrowing have been the dominant processes in river channels; and (b) these processes have been mainly induced by a dramatic reduction in sediment supply. In these papers two classification schemes of channel evolution (for Tuscany and Italian rivers, respectively) were developed.

The aim of this paper, which is based on some recent case studies (Sogni, 2003; Simoncini, 2003; Surian, 2004), is to: (a) improve the existing knowledge about channel adjustments in Italian rivers, and in particular existing temporal trends of width adjustment; (b) analyse the most recent channel changes (the last 10–15 years) for which there is very little known; and (c) try to improve the existing scheme of channel evolution (Surian & Rinaldi, 2003) for rivers with a braided, or initially braided, morphology.

GENERAL SETTING

The five selected rivers are in northern Italy (Fig. 1): three drain from the Alps (Tagliamento, Piave and Brenta) and two from the Apennines (Trebbia and Vara). Their

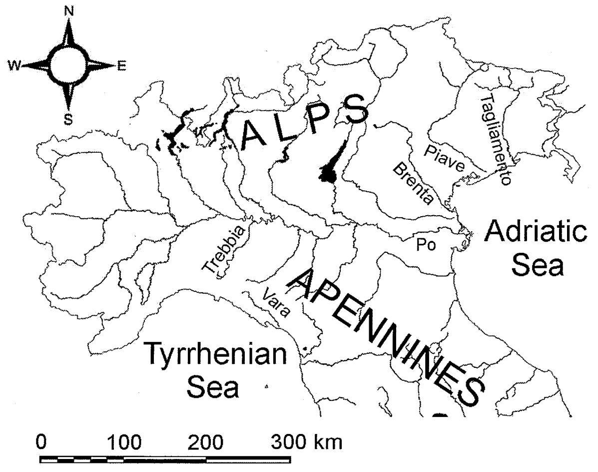

Fig. 1 Location map of the selected rivers.

Table 1 Hydrologic and drainage basin characteristics of the selected rivers.

River	Drainage basin area (km^2)	Length (km)	Length of the study reach (km)	Basin relief (m)	Precipitation (mm year^{-1})	Mean annual discharge (m^3 s^{-1})	Flood peak discharge (m^3 s^{-1})
Tagliamento	2580	178	39	2696	2150	109	4650
Piave	3899	222	23	3162	1330	132	5300
Brenta	1567	174	18	3079	1386	71	2400
Trebbia	1070	116	35	1753	1400	24	3430
Vara	572	62	6	1603	1742	23	820

hydrological and drainage basin characteristics are reported in Table 1. The drainage basin areas range from 572 to 3899 km^2 and river lengths from 62 to 222 km. The basin relief is higher in the Alpine rivers than in those draining from the Apennines (about 3000 m and 1600–1700 m, respectively), whereas precipitation is relatively high in all the rivers (it ranges from 1330 to 2150 mm year^{-1}). Floods are relatively flashy and high in magnitude: the ratio between flood peak discharge and mean annual discharge ranges between 34 (Brenta) and 143 (Trebbia).

In long reaches of their course, these rivers have (or used to have) a braided morphology and have channel beds mainly composed of gravel. The following historical analysis on channel adjustments is focused on those braided reaches (or a part of those reaches), in which channel morphology is very sensitive to changes in sediment fluxes.

HUMAN IMPACT ON SEDIMENT FLUXES

Several human interventions (reforestation, torrent control works, constructions of levees, dams, sediment mining) have taken place in the selected rivers during the past centuries, and in particular during the last one (Table 2). Such interventions have had different impacts on the fluvial system (e.g. runoff changes, decrease of low flows), but the most important

Table 2 Human interventions in the selected rivers.

River	Drainage area upstream from dams (%)	Time of dam closure	Time of intense sediment mining	Construction of levees and other bank protection structures	Reforestation and torrent control works in the drainage basin
Tagliamento	3	1950s	1970s–1980s	19th–20th century	20th century (?)
Piave	54	1930s–1950s	1960s–1980s	14th–20th century	since the 1920s
Brenta	40	1954	1950s–1980s	19th–20th century	since the 1920s
Trebbia	25	1920s–1950s	1950s–1980s	not considerable	not considerable
Vara	36	1930s	1960s–1970s	20th century	20th century

impact on channel processes is the alteration of sediment fluxes, and specifically a remarkable decrease in sediment supply to river channels.

The chronology of human intervention is quite similar in the selected rivers, although there are some differences (Table 2). Reforestation, which occurred after several centuries of intense logging, and torrent control works generally started in the first decades of the 20th century, whereas construction of dams took place between the 1930s and 1950s. Later, between the 1950s and 1980s, sediment mining from river channels was carried out, frequently with extraction rates largely exceeding replenishment rates. These interventions have altered sediment fluxes in different ways, both in relation to the type of intervention (in particular the volumes of sediment affected by the specific intervention) and the location of the intervention (in the drainage basins and within the river channels). For instance, while sediment mining has had a dramatic impact in terms of the volume of sediment removed from the river channel in the short term, the impact of reforestation and dams probably have a greater impact in the long term.

CHANNEL ADJUSTMENTS

A historical analysis of river morphology was performed using maps, aerial photographs, longitudinal profiles and cross sections. Channel width, which was measured on maps and aerial photographs, has undergone dramatic changes during the last two centuries (Fig. 2). Average channel width has decreased by several hundreds of metres. Referring to the original widths in the early 19th or 20th century, a width reduction varying between 58 and 85% was measured (Table 3). It is worth noting that the selected rivers show very similar temporal trends, and in particular two phases of narrowing followed by a very recent phase of widening. As regards narrowing, data clearly show that the process has not been constant through time, and two different periods can be recognized: a first phase of narrowing took place from the early 19th century (in the case of the Tagliamento, Brenta, Trebbia and Vara Rivers) or early 20th century (for the Piave) to the 1950s, whereas a second one took place from the 1950s to the 1990s (Fig. 2). As for the amount of narrowing, in two out of five rivers, about 70% of the whole narrowing occurred in the second phase, whereas in the other three rivers narrowing was almost the same in the two phases (Table 3). The average rate of narrowing has always been higher (between 2.5 and 7.0 times) in the second phase than in the first one (Table 3) (e.g. 5.7 m year^{-1}, in the second period, and 2.5 m year^{-1}, in the first period, in the Vara River and 4.2 and 0.6 m year^{-1} in the Brenta River).

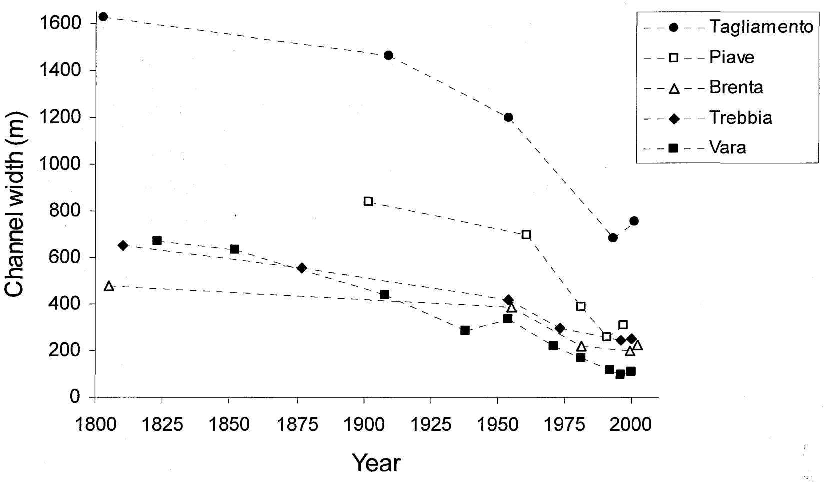

Fig. 2 Changes in channel width during the last 200 years in the selected rivers.

Table 3 Channel narrowing in the selected rivers.

River	Total narrowin g (m)	Total narrowin g (%)	Narrowing in the 1st phase (% of the total)	Narrowing in the 2nd phase (% of the total)	Rate of total narrowing (m year^{-1})	Rate of narrowing in the 1st phase (m year^{-1})	Rate of narrowing in the 2nd phase (m year^{-1})
Tagliamento	942*	58	46	54	5.0	2.8	13.2
Piave	580**	69	25	75	6.5	2.4	14.6
Brenta	276*	58	33	67	1.4	0.6	4.2
Trebbia	403*	62	56	44	2.2	1.6	4.2
Vara	569*	85	58	42	3.3	2.5	5.7

Total narrowing: refers to the period from early 19th (*) or 20th (**) century to the 1990s;
Narrowing in the 1st phase: refers to the period from early 19th or 20th century to the 1950s;
Narrowing in the 2nd phase: refers to the period from the 1950s to the 1990s;
Rate of narrowing: average rate of narrowing estimated over the different time periods considering initial and final channel widths.

Table 4 Channel widening in the selected river.

River	Widening (m)	Period of documented channel widening	Widening compared to original channel width (%)	Widening compared to previous channel width (%)	Rate of widening (m year^{-1})
Tagliamento	72	1993–2001	4	11	9.0
Piave	49	1991–1997	6	19	8.2
Brenta	21	1999–2002	4	10	7.0
Trebbia	4	1996–2000	0.6	2	1.0
Vara	13	1996–2000	2	13	3.3

Widening compared to original channel width: represents the ratio between the amount of widening and channel width in the early 19th or 20th century;
Widening compared to previous channel width: represents the ratio between the amount of widening and channel width at the beginning of the widening process;
Rate of widening: average rate of widening estimated over the different time periods considering initial and final channel widths.

The most recent data point out that channel narrowing has stopped in all the selected rivers and channel widening has been taking place since the 1990s (Fig. 2). The magnitude of widening is low if the original channel width (width in early 19th or 20th century) is considered, but relatively high if the channel width at the end of narrowing is taken as a reference. In this latter case, in four out of five rivers widening is more than 10% (e.g. 19% in the Piave River), with an average rate ranging between 3.3 and 9.0 m year^{-1} (Table 4).

Braiding intensity has also changed considerably. A decrease of braiding indices has occurred in all these rivers, but, differently from channel width, temporal trends show some variability from one river to another (Fig. 3). Braiding indices used to be around 2.0 in two of the rivers and much higher in the other three (5.7, 3.9 and 3.8, respectively in the Tagliamento, Piave and Vara), whereas nowadays they are equal or less than 1.5 in four out of five rivers. Three rivers (Tagliamento, Trebbia and Brenta) show a remarkable decrease of braiding intensity in the period 1950s–1990s (corresponding to the major phase of narrowing), whereas the other two rivers (Piave and Vara) show a less constant decreasing trend in the same period (Fig. 3).

In addition to channel narrowing and decrease of braiding intensity, channel incision has been clearly documented in some of the selected rivers (Castiglioni & Pellegrini, 1981; Surian, 2004). Incision, which has been up to several metres (e.g. 4 and 5 m in the Piave and Brenta), occurred together with the major phase of narrowing, whereas in the last 10–15 years there is evidence, from cross-sections, that bed-level lowering could be over. As for the Vara River, in some reaches incision has been followed by aggradation during the last 10 years, promoted by the construction of some grade control structures. On the contrary, less information is available as regards bed-level adjustments during the 19th century and the first decades of the 20th century.

Such channel adjustments (narrowing, decrease of braiding intensity, incision) have produced significant changes in the channel configuration of those initially braided rivers. In several reaches there has been a modification from braided to wandering, and in some cases

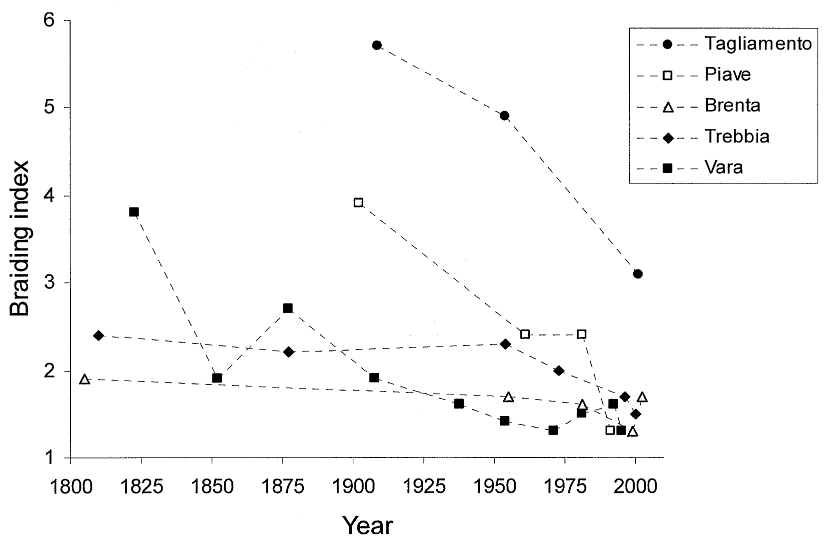

Fig. 3 Changes in braiding index during the last 200 years in the selected rivers.

to a single-thread morphology (e.g. in the Brenta). Only the Tagliamento, notwithstanding significant channel changes, has retained a clear braided morphology along the whole study reach.

DISCUSSION AND CONCLUSIONS

On the basis of the data discussed above, and in particular of the temporal trends of channel width considered in this paper (only the trend of the Piave River was available previously), it is possible to further develop the scheme of channel evolution of Italian rivers originally proposed by Surian & Rinaldi (2003). Four stages of channel evolution can be recognized in the selected braided rivers (Fig. 4). Considering the channel morphology in the early 19th or 20th century as the initial stage (stage I), a second stage of channel evolution can be identified after a first phase of narrowing and incision (in such phase bed-level changes are not well documented, but there is evidence that, at least during the first half of the 20th century, some incision occurred). Stage III represents the channel morphology after the major phase of narrowing and incision, which took place from the 1950s to the 1990s, whereas stage IV represents the present morphology which is the result of some widening processes. The recognition of the very recent channel adjustments occurred in the last 10–15 years (channel evolution from stage III to stage IV), is meaningful since it has pointed out that the relatively long period of narrowing and incision should be exhausted and other processes, in particular channel widening, can become dominant at present.

The causes of these channel adjustments are mainly human interventions, and in particular those interventions, such as sediment mining, dams, reforestation, which have

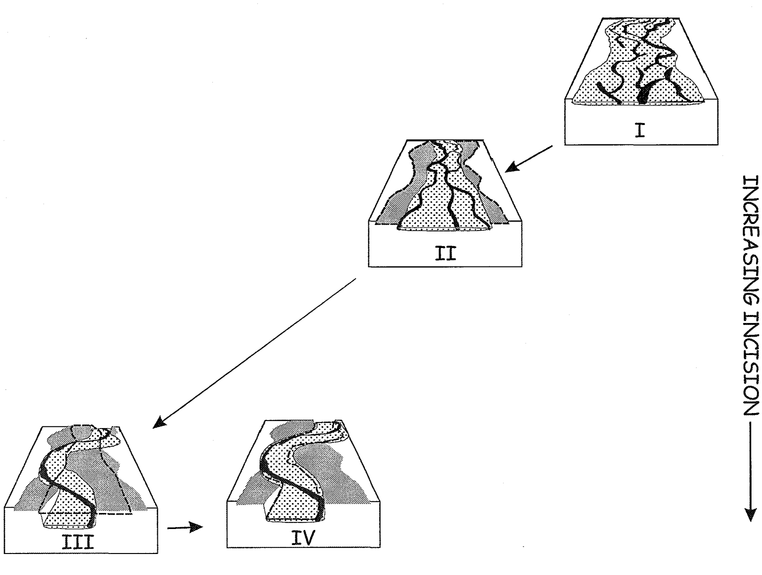

Fig. 4 A channel evolution model for Italian braided rivers; "stage I" represents channel morphology in the early 19th or 20th century, "stage IV" represents the present morphology. Note: active channel is represented by dots and abandoned channel in grey.

induced a remarkable alteration of sediment fluxes. There is a strong temporal relationship between human interventions and channel adjustments as for the main phase of adjustment (from stage II to stage III). Two factors, sediment mining and construction of dams, had a main role in this phase of adjustment, even if some other factors (e.g. reforestation and torrent control works) could have had some effects on sediment fluxes (see also Table 2). On the contrary, there is more uncertainty regarding the first phase of adjustment (from stage I to stage II). Reforestation and torrent control work should have played a significant role during the first half of the 20th century, whereas the construction of bank protection structures (levees, groynes) and climate changes could be significant factors in explaining channel adjustments during the 19th century. The first of the latter factors (bank protection structures) is well documented, whereas at the present stage of the research the second one (climate changes) is only a hypothesis. In fact, the climatic transition occurred during the 19th century, at the end of the Little Ice Age, could have had some effects on sediment fluxes in the selected rivers. Finally, the most recent channel adjustments (from stage III to stage IV) could be due to an increase of sediment availability in river channels (mainly in relation to a remarkable reduction of sediment mining) which promotes the formation of bars and, therefore, widening of the active channel.

Finally, issues that will require further research to improve the present knowledge about channel adjustments in Italian rivers include: (a) bed-level changes: it is necessary to gain more data about these changes during the 19th century and the first half of the 20th century and about the temporal trends of such changes; (b) human interventions: some of them, in particular their development through time, are still not well documented (e.g. reforestation in drainage basins and along river channels, torrent control works); (c) present channel processes and sediment fluxes: since different processes have occurred in the last few years, specifically widening after a long period of channel narrowing, monitoring of present processes is very important as well as information about the present and future sediment fluxes in Italian rivers (for instance in rivers with no dams, or where dam effects are little, an increase of sediment fluxes could take place in the next future).

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