Channel adjustments in northern and central Italy over the last 200 years.

Geological Society of America
3300 Penrose Place
P.O. Box 9140
Boulder, CO 80301
(303) 357-1000 • fax 303-357-1073
www.geosociety.org

Chapter 5: "Channel adjustments in northern and central Italy over the last 200 years" (Surian et al.), *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts: Geological Society of America Special Paper 451.

The Geological Society of America
Special Paper 451
2009

Channel adjustments in northern and central Italy over the last 200 years

Nicola Surian*
Department of Geography, University of Padova, Via del Santo, 26, Padova 35123, Italy

Massimo Rinaldi
Department of Civil and Environmental Engineering, University of Florence, Via S. Marta, 3, Florence, 50139, Italy

Luisa Pellegrini
Department of Earth Sciences, University of Pavia, Via Ferrata, 1, Pavia, 27100, Italy

Chiara Audisio
Franca Maraga
National Research Council, Institute for Geo-hydrological Protection, Strada delle Cacce, 73, Torino, 10135, Italy

Liliana Teruggi
Department of Civil and Environmental Engineering, University of Florence, Via S. Marta, 3, Florence, 50139, Italy

Ornella Turitto
National Research Council, Institute for Geo-hydrological Protection, Strada delle Cacce, 73, Torino, 10135, Italy

Luca Ziliani
Department of Geography, University of Padova, Via del Santo, 26, Padova 35123, Italy

ABSTRACT

This paper deals with channel evolution over the past 200 yr in 12 selected streams in northern and central Italy and aims at reconstructing the evolutionary trends (e.g., trends of channel width and bed elevation) and understanding the causes of channel adjustments. The selected streams have been studied using various sources and methods (historical maps, aerial photographs, topographic surveys, and geomorphological surveys). The selected rivers have undergone almost the same processes in terms of temporal trends; however, the magnitude of adjustments varies according to several factors, such as original channel morphology. Initially, river channels underwent a long phase of narrowing (up to 80%) and incision (up to 8–10 m), which started at the end of the nineteenth century and was intense from the 1950s to the 1980s. Then, over

*nicola.surian@unipd.it

Surian, N., Rinaldi, M., Pellegrini, L., Audisio, C., Maraga, F., Teruggi, L., Turitto, O., and Ziliani, L., 2009, Channel adjustments in northern and central Italy over the last 200 years, *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts: Geological Society of America Special Paper 451, p. 83–95, doi: 10.1130/2009.2451(05). For permission to copy, contact editing@geosociety.org.

the last 15–20 yr, channel widening and sedimentation, or bed-level stabilization, have become the dominant processes in most of the rivers.

Different human interventions have been identified as the causes of channel adjustments in Italian rivers (sediment mining, channelization, dams, reforestation, and torrent control works). Such interventions have caused a dramatic alteration of the sediment regime, whereas effects on channel-forming discharges have seldom been observed. Some notable implications for river management and restoration are (1) the state of rivers before major human disturbances and channel adjustments can rarely be taken as a reference, as at present rivers are far from their pristine condition; and (2) sediment management is and will be a key issue in such fluvial systems.

INTRODUCTION

During the last centuries, and particularly during the second half of the twentieth century, many fluvial systems have been significantly affected by human interventions. Such interventions involve both changes within drainage basins (e.g., land-use changes, torrent control works) and within river channels (e.g., channelization, dams, sediment mining), and may cause substantial alterations of flow and sediment regimes as well as boundary conditions of river channels. Several studies have analyzed the response of rivers to human impact, showing that different channel adjustments, such as incision, aggradation, and changes in channel width and pattern, generally take place (e.g., Leopold, 1973; Petts, 1979; Williams and Wolman, 1984; Knighton, 1991; Wyzga, 1993; Kondolf, 1997; Sear and Archer, 1998; Winterbottom, 2000; Liébault and Piégay, 2001; Marston et al., 2003; Gregory, 2006). These adjustments are generally much larger than those that could be expected from natural channel evolution, although some natural phenomena, such as large floods and volcanic eruptions, or short-term climatic fluctuations, may also have an important role in controlling channel instability and changes (Simon, 1992; Rumsby and Macklin, 1994; Macklin et al., 1998).

Most Italian rivers have undergone widespread channel adjustments, in particular incision and narrowing. Such adjustments have been analyzed in several studies since the 1960s (e.g., Roveri, 1965; Castiglioni and Pellegrini, 1981; Dutto and Maraga, 1994; Castaldini and Piacente, 1995; Capelli et al., 1997; Billi and Rinaldi, 1997; Rinaldi and Simon, 1998; Surian, 1999; Aucelli and Rosskopf, 2000; Rinaldi, 2003), but, as pointed out by a recent review (Surian and Rinaldi, 2003), most of the studies are largely descriptive and lack temporal reconstruction of key parameters such as channel width and bed level. The reconstruction of temporal trends of channel changes is fundamental in order to recognize relations between channel adjustments and their causes, define a channel-evolution model that could explain a sequence of processes regarding most Italian rivers, and understand recent river dynamics. Moreover, understanding evolutionary trends of river channels and their causes is a crucial issue for a sustainable management and restoration of streams that are largely affected by human impact (Downs and Gregory, 2004; Habersack and Piégay, 2008).

The research carried out in Italy during the last few years has focused on the following objectives: (1) reconstructing the channel changes (e.g., changes of channel width, bed elevation, braiding intensity, sinuosity) for several rivers, thereby increasing the relatively small number of case studies available; (2) understanding the relationship between channel adjustments and various human interventions; (3) improving existing conceptual models of channel evolution; and (4) analyzing the implications of channel adjustments in terms of river management and restoration. This paper deals with channel evolution over the past 200 yr in 12 selected streams in northern and central Italy, and it focuses on objectives 1 and 2, with a brief discussion of numbers 3 and 4. The selected streams have been studied using similar sources (historical maps, aerial photographs, topographic surveys, geomorphological surveys), and, most important, the same protocols for collecting, measuring, and processing data. Such an approach has allowed the creation of a homogeneous data set and, therefore, reliable comparisons among the studied rivers.

GENERAL SETTING

The selected streams are in northern and central Italy (Fig. 1): seven drain from the Alps (Stura di Lanzo, Orco, Brenta, Piave, Cellina, Tagliamento, and Torre) and five from the Apennines (Trebbia, Panaro, Magra, Vara, and Cecina). These rivers were selected in order to have a set of rivers representative of the study area, taking into account the following criteria: (1) a relatively wide range in terms of river size, and (2) fluvial systems with different degrees of human impact. The data availability was also important in the selection of the study cases.

The physiographic and hydrological characteristics of the 12 selected streams are reported in Table 1. The drainage-basin areas range from 446 to 3899 km^2, and the river length from 53 to 222 km. The basin relief is higher in the Alpine rivers than in those draining from the Apennines, being up to 3435 m and 2157 m, respectively. As for the discharge regime, there is a significant difference between low and high flows. This difference has been enhanced by stream regulation, which has significantly decreased low flows, but has not altered, in most cases (see next section), the high flows. The floods are relatively flashy and high in magnitude: the ratio between largest flood and mean annual discharge ranges between 34 (Brenta) and 129 (Cecina) (Table 1).

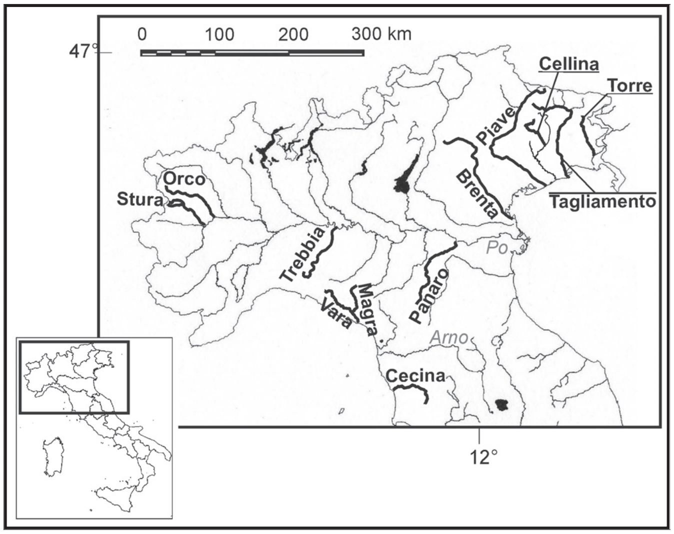

Figure 1. General setting of the selected rivers.

The study reaches, which range in length from 10 to 49 km, are those where major channel adjustments occurred over the past 200 yr and are located in the piedmont plain in most cases. In such reaches the river channels are generally very wide (some hundred meters) and are not confined or only slightly confined. Morphological and sedimentological characteristics of the selected reaches are reported in Table 2. There is a range of channel morphology at present, since several reaches exhibit a downstream transition from braided to single-thread, but originally the braided configuration was dominant in the study reaches. Channel slope is generally in the range 0.002–0.006, but in three reaches it is ~0.01. River beds are composed of gravels, and banks are noncohesive or composite.

HUMAN IMPACT ON FLUVIAL SYSTEMS

A range of human impacts (channelization, sediment mining, dams, reforestation) has taken place in the selected streams during

TABLE 1. PHYSIOGRAPHIC AND HYDROLOGICAL CHARACTERISTICS OF THE SELECTED RIVERS

River	Drainage-basin area* (km^2)	Length (km)	Basin relief (m)	Precipitation ($mm\ yr^{-1}$)	Mean annual discharge ($m^3\ s^{-1}$)	Largest flood ($m^3\ s^{-1}$)
Stura di Lanzo	928 (582)	80	3427	1107	20	2000
Orco	906 (630)	83	3435	1250	20	1650
Brenta	1567	174	3079	1390	71	2400
Piave	3899	222	3162	1330	132	5300
Cellina	446	58	2401	1770	N.A.	950
Tagliamento	2580	178	2696	2150	109	4650
Torre	1105 (168)	69	1679	2280	N.A.	730
Trebbia	1070	120	1406	1440	35	3500
Panaro	1783 (1036)	165	2157	1017	19	1400
Magra	1699 (932)	70	1639	1707	41	1440
Vara	572 (523)	65	1603	1770	23	820
Cecina	905 (634)	53	1018	944	8	1030

*Drainage-basin area—the area upstream of gauging stations, where discharges are measured, is in parentheses.
N.A.—not available.

TABLE 2. MORPHOLOGICAL AND SEDIMENTOLOGICAL CHARACTERISTICS OF THE SELECTED REACHES

River	Reach length (km)	Channel morphology*	Slope (%)	D_{50} of bed sediments (mm)	Type of banks†
Stura di Lanzo	10	B/W	1.3	117	NC/CO
Orco	25	W	0.6	65–80	NC
Brenta	23	B/W/S	0.2–0.5	26–140	NC/CO
Piave (mountain reach)	32	B/W	0.3–0.6	20–48	NC
Piave (plain reach)	22	B/W/S	0.2–0.5	18–28	NC/CO
Cellina	10	B/W	1.2	N.A.	NC
Tagliamento	49	B/W/S	0.1–0.4	20–49	NC/CO
Torre	44	B/W/S	0.3–0.6	N.A.	NC/CO
Trebbia	32	B/W	0.2–0.4	33–80	NC
Panaro	38	W/S/M	0.05–0.4	27–90	CO/C
Magra (upper reach)	10	W	0.9	45–91	NC
Magra (lower reach)	11	W	0.15–0.4	21–40	CO
Vara	22	W/S	0.3–0.5	12–52	NC/CO
Cecina	40	W/S	0.2–0.5	12–34	NC/CO

*Channel morphology—braided (B), wandering (W), sinuous (S), meandering (M).
†Type of banks—noncohesive (NC), cohesive (C), composite (CO).
N.A.—not available.

the past centuries, particularly during the past 100 yr (Table 3). These interventions have both direct (e.g., levees and groins) and indirect (e.g., reforestation) effects on channel dynamics.

The chronology of human interventions is similar in the selected rivers, although some small differences exist (Table 3). In most cases, channelization started during the nineteenth century, initially with the construction of levees, and then, during the twentieth century, also with the construction of groins and other bank-protection structures. Reforestation and torrent control works are not well documented, but the available data suggest that both interventions generally started in the 1920s–1930s. Reforestation occurred after several centuries of intense deforestation, and it is still ongoing (Lamedica et al., 2007). Dams were constructed in 9 out of the 12 streams selected. Some were closed in the 1930s, but most of the dams were built during the 1950s. Since then, several millions of cubic meters of sediment have been trapped in reservoirs, especially in those river systems with a large impounded drainage area (e.g., Brenta, Piave, Cellina, and Vara). Gravel mining was intense between the 1950s and the 1980s. During relatively short periods of time (20–30 yr) large volumes of sediments were removed from the channels, e.g., 8.6×10^6 m^3 in the Brenta from 1953 to 1977, 24×10^6 m^3 in the Tagliamento from 1970 to 1991, 15×10^6 m^3 in the Torre from the 1950s to the 1970s, 24×10^6 m^3 in the Magra and Vara from 1958 to 1973, and 5.9×10^6 m^3 in the Panaro from 1962 to 1980 (such values are underestimates, because they come from official data, which commonly do not correspond to the real volumes extracted).

Such interventions have dramatically altered the sediment regime, although by different magnitudes and timing. A major effect has been produced by gravel mining, which has significantly decreased or ceased in the past 20 yr or so. Although several difficulties exist for obtaining reliable bed-load-transport calculations, as well as the volume of the sediment extracted, we estimated that when mining was most intense the extraction rates exceeded replenishment rates by 10 or more times (e.g., Surian and Cisotto, 2007). The other interventions (e.g., dams, reforestation) likely have a lower, but more extended, effect on sediment regime.

Dams and diversions have markedly reduced low flows, but no reductions have occurred in channel-forming discharges of the selected rivers, according to previous works (Maraga, 1983; Surian, 2006; Surian and Cisotto, 2007). Historical trends of maximum annual discharges are available for six rivers (Fig. 2). These trends show that no significant changes occurred in four rivers (Brenta, Piave, Tagliamento, and Magra), whereas some changes occurred in the Cellina and Cecina. With regard to the Cellina, the decrease of maximum annual discharge is due to the construction of a dam in 1954, whereas the decrease in the Cecina could be due to climate changes, since there is no notable regulation along this river.

METHODS AND DATA SOURCES

Historical Maps and Aerial Photographs

The analysis of historical maps and aerial photographs, carried out using geographical information systems (GIS), has allowed us to examine channel changes over the past 200 yr. The maps are at scales ranging between 1:25,000 and 1:86,400 and refer to the nineteenth century and the first half of the twentieth century. The aerial photographs are at scales ranging from 1:7,000 to 1:33,000 and cover the period from the 1950s to the present. The historical maps are available from the beginning of the nineteenth century in 7 streams out of 12, whereas in the other cases from the 1870s or the 1880s. For each river reach, 9 dates

TABLE 3. HUMAN IMPACT IN THE SELECTED RIVERS

River	Drainage area upstream from dams (%)	Dates of dam closure	Dates of intense sediment mining	Construction of levees and other bank protection structures	Reforestation in the drainage basin
Stura di Lanzo	31	1931–1933	1960s–1980s	Since end of 19th century	N.A.
Orco	13	1927–1959	1960s–1980s	19th–20th century	20th century
Brenta	40	1954	1950s–1980s	19th–20th century	Since 1920s–1930s
Piave	54	1930s–1950s	1960s–1980s	15th–20th century	Since 1920s–1930s
Cellina	87	1954	1970s–1980s	19th–20th century	N.A.
Tagliamento	3	1950s	1970s–1980s	19th–20th century	20th century (?)*
Torre	8	1900	1960s–1970s	19th–20th century	N.A.
Trebbia	24	1950s–1970s	1960s–1980s	19th–20th century	Since 1940s
Panaro	3	1950s	1960s–1990s	1920s–1960s	Since 1920s–1930s
Magra	4	1950s	1960s–1970s	Since 1920s	Since 1920s–1930s
Vara	43	1930s	1960s–1970s	Since 1920s	Since 1920s–1930s
Cecina	0	–	1970s	Since 1920s–1930s	Since 1920s–1930s

*(?)—data with a higher degree of uncertainty.
N.A.—not available.

were analyzed on average, from a minimum of 6 (Stura di Lanzo) to a maximum of 12 (Vara and Tagliamento).

The digital maps and aerial photographs were co-registered using maps at 1:5,000 or 1:10,000 scale as base layers. Then, channel features were digitized in order to analyze planform characteristics (channel width, braiding index, sinuosity). As for channel width, both the "total channel width," that is, including islands, and the "active channel width," that is, the width of the single low-flow channels plus that of unvegetated or sparsely vegetated bars, were measured. It is worth noting that the measured width is affected by some errors owing to georectification and digitization. According to some preliminary assessment and to previous works (e.g., Gurnell, 1997; Winterbottom, 2000; Hughes et al., 2006), maximum errors of 15–20 m and 5–6 m were estimated, respectively, for measurements on maps and aerial photographs.

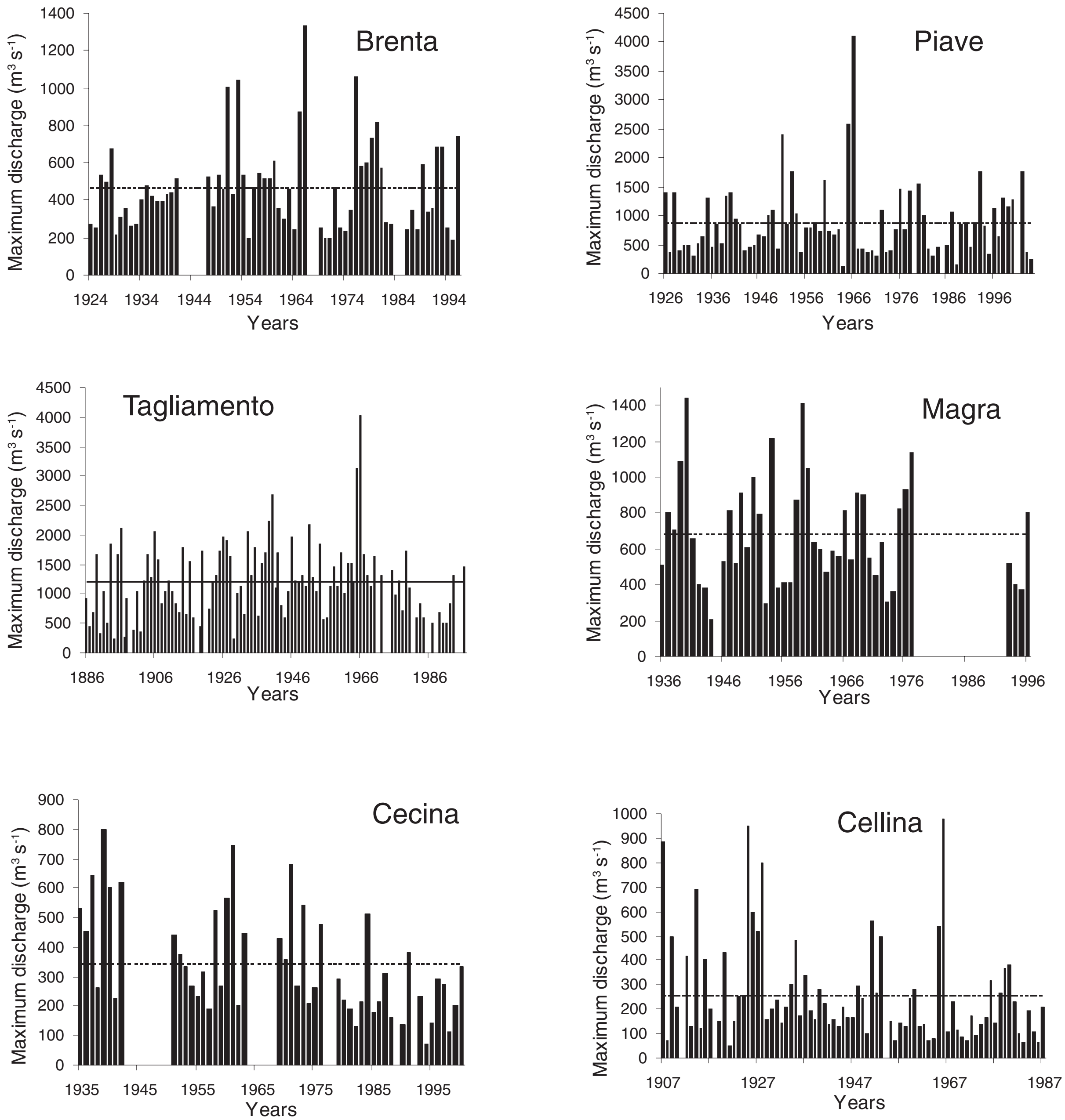

Figure 2. Historical trends of maximum annual discharge for six of the selected rivers (Brenta, Piave, Tagliamento, Magra, Cecina, and Cellina). Dashed line represents the average maximum discharge for the examined period. Some gaps do exist, in particular for Magra and Cecina, because data were not available.

Topographic Data

Longitudinal profiles and cross sections were available for all the selected streams, but they did not allow as detailed reconstructions of bed-level changes as was possible for planform characteristics. Several surveys are available only for the Magra and Brenta Rivers: six for the Magra, from 1914 to 2006, and seven for the Brenta, from 1932 to 1997. Besides the fact that few surveys are available for most of the study reaches, such topographic data refer to a limited period of time. The first surveys date back to the first decades of the twentieth century in 3 cases out of 12 (Brenta, Piave, and Magra), whereas for the other streams they date back to the 1950s–1970s.

Geomorphological Survey

Geomorphological surveys were carried out using standardized forms specifically designed to record measurements and observations of channel changes (Rinaldi, 2007). Data collected through such surveys should integrate those coming from the other sources (maps, aerial photographs, and topographic data) and are crucial in quantifying bed-level changes. In particular, the geomorphological surveys have allowed us to infer short-term channel changes, according to a number of morphological and sedimentological features (e.g., differences in elevation between bars and floodplain, presence-absence of sediment lobes, presence-absence of armoring, etc.).

RESULTS

Channel-Width Changes

The use of historical maps and aerial photographs has allowed a detailed analysis of channel-width change during the last 100–200 yr (Fig. 3; Tables 4, 5). Because the study reaches are relatively long and not homogeneous in terms of channel morphology, most of the reaches were divided into two or three sub-reaches. This division led to a total of 27 sub-reaches, which

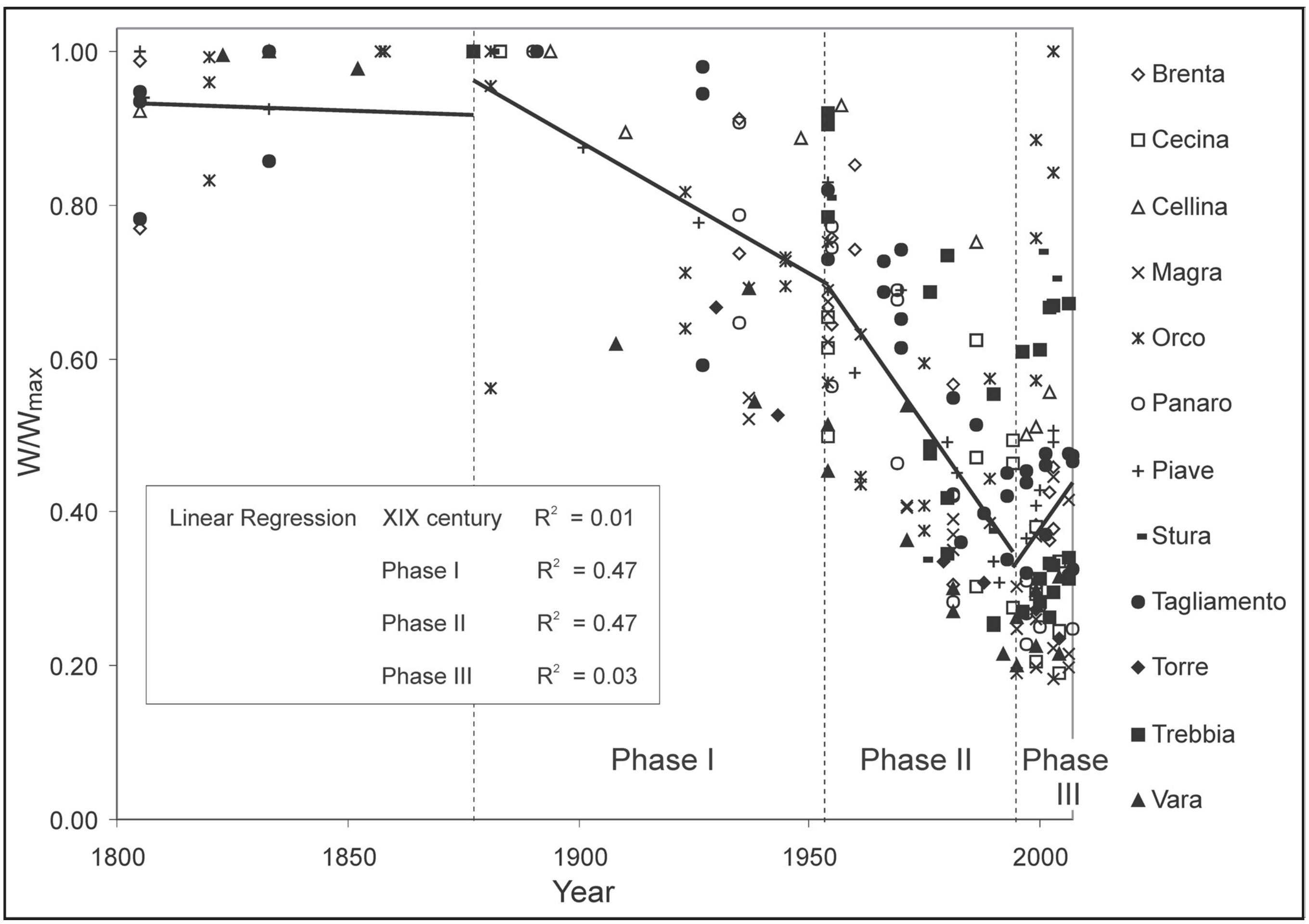

Figure 3. Channel width variations in 27 sub-reaches over the past 200 yr. In order to compare the 12 selected rivers a dimensionless width "W/W_{max}" is used, in which W is the width measured on the different dates, and W_{max} the maximum width, for each sub-reach, for the study period. The three phases of channel adjustment that have occurred from the end of the nineteenth century to the present are pointed out.

TABLE 4. WIDTH CHANGES FROM THE BEGINNING OF THE NINETEENTH CENTURY TO THE 1980s/1990s

River	Reach	Width change in the 19th century			Width change in the 1st phase of adjustment (1880s–1950s)			Width change in the 2nd phase of adjustment (1950s–1980s/1990s)			Total width change (since the beginning of 19th century)	
		(m)	(%)*	($m\ yr^{-1}$)†	(m)	(%)	($m\ yr^{-1}$)	(m)	(%)	($m\ yr^{-1}$)	(m)	(%)
Stura di Lanzo		N.A.	N.A.	N.A.	–54	–19	–0.7	–134	–47	–6.4	–188	–66
Orco	Upper	–22	–9	–0.4	–58	–25	–0.8	–26	–11	–0.7	–105	–46
	Middle	–38	–17	–0.6	62	28	0.9	–120	–54	–3.4	–96	–43
	Lower	–57	–16	–0.9	–134	–36	–1.8	–60	–16	–2.9	–251	–68
Brenta	Upper	47	10	0.5	–122	–27	–1.9	–200	–44	–7.7	–275	–60
	Lower	n.c.			–82	–20	–1.3	–193	–46	–4.4	–275	–69
Piave	Mountain	40	7	0.5	–272	–45	–3.9	–160	–26	–5.3	–392	–64
	Plain	–120	–12	–1.2	–143	–15	–2.7	–437	–46	–11.8	–699	–73
Cellina		–89	–11	–1.0	–51	–6	–0.8	–310	–38	–7.8	–450	–55
Tagliamento	Upper	–224	–12	–2.6	–295	–16	–4.7	–606	–32	–15.5	–1125	–60
	Middle	273	28	3.2	–341	–35	–5.4	–415	–42	–12.2	–483	–49
	Lower	29	7	0.3	–41	–10	–0.6	–264	–63	–6.1	–275	–66
Torre		N.A.	N.A.	N.A.	–267	–47	–2.4	–142	–25	–2.5	–409	–73
Trebbia	Upper	N.A.	N.A.	N.A.	–23	–8	–0.3	–105	–37	–2.9	–127	–45
	Middle	N.A.	N.A.	N.A.	–197	–22	–2.6	–482	–53	–13.4	–679	–75
	Lower	N.A.	N.A.	N.A.	–54	–10	–0.7	–363	–65	–10.1	–417	–75
Panaro	Upper	N.A.	N.A.	N.A.	–66	–25	–1.0	–113	–44	–2.7	–179	–69
	Middle	N.A.	N.A.	N.A.	–87	–23	–1.3	–192	–50	–4.6	–278	–73
	Lower	N.A.	N.A.	N.A.	–112	–44	–1.7	–86	–34	–2.1	–198	–77
Magra	Upper	N.A.	N.A.	N.A.	–106	–33	–1.4	–120	–37	–2.9	–226	–70
	Middle	N.A.	N.A.	N.A.	–247	–38	–3.2	–279	–43	–6.8	–526	–81
	Lower	N.A.	N.A.	N.A.	–268	–34	–3.5	–324	–41	–7.9	–593	–75
Vara	Upper	N.A.	N.A.	N.A.	–125	–49	–1.6	–65	–25	–1.6	–189	–74
	Lower	n.c.			–301	–55	–3.9	–140	–26	–3.4	–441	–80
Cecina	Upper	N.A.	N.A.	N.A.	–63	–35	–0.9	–30	–16	–0.7	–93	–51
	Middle	N.A.	N.A.	N.A.	–72	–50	–1.0	n.c.			–72	–54
	Lower	N.A.	N.A.	N.A.	–62	–39	–0.9	–55	–34	–1.4	–117	–72

N.A.—not available; n.c.—no change; the width change is lower than the measurement error.
*(%)—calculated referring to the original width in the early nineteenth century or in the 1880s.
†($m\ yr^{-1}$)—average rate of change estimated over the different time periods, considering initial and final channel widths.

exhibit a distinct morphology (i.e., braided, wandering, or single-thread). Then, in order to compare such sub-reaches, whose average width ranges from 31 m (Cecina in 2004) to 1975 m (Tagliamento in 1833), a dimensionless width, "W/W_{max}," was defined, where W is the width measured on the different dates, and W_{max} is the maximum width for each sub-reach for the study period. The data from the 27 sub-reaches clearly show that channel narrowing has been the dominant process, but also that changes have occurred at similar times because data are not randomly distributed (Fig. 3). Such a data distribution suggests that intervals characterized by different width changes can be defined. In taking the overall set of data, but also considering width change of the single sub-reaches, four intervals were defined.

During the first period, corresponding approximately to the nineteenth century, narrowing occurred in 6 sub-reaches out of 12 (for that period only a smaller data set was available), varying from 9% (upper reach of the Orco) to 17% (middle reach of the Orco); 4 sub-reaches underwent some widening, varying from 7% (mountain reach of the Piave and lower reach of the Tagliamento) to 28% (middle reach of the Tagliamento); and 2 sub-reaches show no change (Table 4). According to the limited data set, that period was characterized by small width changes in terms of magnitude and by the absence of a dominant process (i.e., channel widening or narrowing). Narrowing became the dominant process in the following two phases. In the second period, from the end of the nineteenth century to the 1950s (first phase of adjustment in Fig. 3), narrowing occurred in 26 sub-reaches out of 27, the average being 29%, varying from 6% (Cellina) to 55% (lower reach of the Vara). In the third period, from the 1950s to the 1980s–1990s (second phase of adjustment), 26 sub-reaches underwent narrowing, and 1 sub-reach had no change. Narrowing varied from 11% (upper reach of the Orco) to 65% (lower reach of the Trebbia), the average being 37%. Narrowing was more intense in the third period than in the second, as evidenced by the rate of narrowing, which was 5.5 $m\ yr^{-1}$ and 2.0 $m\ yr^{-1}$ on average, respectively, in the two periods (Table 4). Maximum width reduction was reached in the 1980s–1990s in several of the selected rivers. At that time, width reduction was 65% on average, varying from 43% (middle reach of the Orco) to 81% (middle reach of the Magra). As for the most recent period, about the last 15–20 yr, a different phase of evolution is clearly shown by the data set (Table 5), but in contrast with the two previous phases when all the rivers showed a similar behavior, significant differences existed among the selected rivers. In fact, widening (varying from 1% to 91%) has occurred in 18 out of 27 sub-reaches, and narrowing in 6 sub-reaches (varying from 2% to 26%), whereas 3 sub-reaches show no change.

TABLE 5. WIDTH CHANGES DURING THE THIRD PHASE OF CHANNEL ADJUSTMENTS

River	Reach	Time period	Width change in the 3rd phase (1980s/1990s–2000/2007)			
			(m)	(%)*	(%)†	(myr^{-1})
Stura di Lanzo		1975–2003	104	37	108	3.7
Orco	Upper	1989–2003	94	41	75	6.7
	Middle	1989–2003	201	91	160	14.3
	Lower	1975–2003	145	39	124	5.2
Brenta	Upper	1981–2003	90	20	49	4.1
	Lower	1999–2003	32	8	25	8.0
Piave	Mountain	1990–2003	111	18	51	8.5
	Plain	1991–2003	153	16	59	12.7
Cellina		1997–2002	39	5	11	7.8
Tagliamento	Upper	1993–2007	26	1	3	1.9
	Middle	1988–2007	96	10	19	5.0
	Lower	1997–2007	n.c.			
Torre		1999–2004	–22	–4	–14	–4.3
Trebbia	Upper	1990–2006	34	12	22	2.1
	Middle	1990–2006	79	9	34	5.0
	Lower	1990–2006	33	6	23	2.1
Panaro	Upper	1997–2000	n.c.			
	Middle	1997–2007	–8	–2	–8	–0.8
	Lower	1997–2000	n.c.			
Magra	Upper	1995–2006	37	12	38	3.4
	Middle	1995–2006	15	3	12	1.4
	Lower	1995–2006	–41	–6	–21	–3.7
Vara	Upper	1995–2004	13	6	20	1.5
	Lower	1995–2004	9	2	9	1.0
Cecina	Upper	1994–2004	–45	–26	–50	–4.5
	Middle	1994–2004	–18	–13	–27	–1.8
	Lower	1994–2004	–14	–9	–31	–1.4

Note: n.c.—no change; the width change is lower than the measurement error.
*(%)—calculated referring to the original width in the early 19th century or in the 1880s.
†(%)—calculated referring to the width at the beginning of the 3rd phase of adjustment.

Bed-Level Changes

In terms of bed-level changes, the available topographic data and the geomorphological surveys have allowed (1) a definition of the magnitude of changes over the medium term, (2) a qualitative assessment of short-term trends, and (3) a few detailed temporal reconstructions (Table 6; Fig. 4). Incision has been the dominant process in the medium term (about the past 100 yr), even if a few short sub-reaches (e.g., in the Stura di Lanzo, Brenta, and Torre) can be considered in equilibrium during that period. Bed-level lowering has been commonly moderate (1–2 m) or intense (2–4 m) in the upper reaches, and even very intense—that is, up to 8–10 m (e.g., in the Brenta, Panaro, and Magra)—in the downstream and middle reaches, which are characterized by single-thread morphology (Table 6). For the short term (about the last 10–15 yr), very few reaches in the selected streams have incised, and most of the reaches exhibit equilibrium or sedimentation. Temporal changes of bed level could be reconstructed for the Brenta, Magra, and Tagliamento. The representative bed-level trends reported in Figure 4 show that initially a more or less intense phase of incision took place, and that recently some reaches are in or are getting close to a state of equilibrium (e.g., upper reach of the Brenta; middle reach of the Tagliamento), whereas in others some sedimentation has occurred (e.g., lower reach of the Brenta or middle reach of the Magra).

Some Examples of Channel Adjustments: Brenta, Orco, and Cecina Rivers

Three rivers were selected to add some details to the overall channel evolution described above. The Brenta River was selected because it is representative of many other rivers in terms of both channel adjustments and human impact. In contrast, channel adjustments in the Orco and Cecina Rivers differ in some way from the most common evolutionary trends.

The Brenta River, which drains from the Eastern Alps, shows a typical evolution in terms of channel-width changes; that is, a major phase of narrowing was followed by a recent channel widening (Fig. 5). It is worth noting that the widening did not occur simultaneously along the study reach but took place first in the upper sub-reach and later in the lower sub-reach. Similar bed-level changes were consistent in the medium term but differed in the short term. Incision has been intense, up to 8.5 m, in the medium term, whereas bed level has been relatively stable and aggrading in the upper and lower sub-reaches during the last phase of the adjustment (Figs. 4, 5). The construction

TABLE 6. BED-LEVEL CHANGES IN THE MEDIUM AND SHORT TERM

River	Reach	Changes in the medium term (about last 100 yr)* (m)	Changes in the short term (about last 10–15 yr)†
Stura di Lanzo		–5 to 0	E and I
Orco		–3 to –1	E/S
Brenta	Upper	–5 to 0	E
	Lower	–8 to –4	S
Piave	Upper	–2 to –1	E/S
	Lower	–3 to –1	E/S
Cellina		N.A.§	N.A.
Tagliamento	Upper	N.A.	E
	Middle	–2 to –1	E
	Lower	–4 to –2	E
Torre		–5 to 0	I
Trebbia		–4 to –2	S
Panaro	Upper	–6 to –4	E
	Middle	–10 to –6	E
	Lower	–6 to –4	E
Magra	Upper	–4 to –2	E/S
	Lower	–8 to –5	E/S
Vara	Upper	–3 to –1	E/S
	Lower	–4 to –2	E/S
Cecina	Upper	–2 to –1	E
	Lower	–3 to –2	E

*A range of values is indicated for each river reach; for instance, "–3 to –1" (Orco River) means that incision varies from 3 m to 1 m within the reach.
†I—incision; E—equilibrium; E/S—equilibrium/sedimentation; S—sedimentation.
§N.A.—not available.

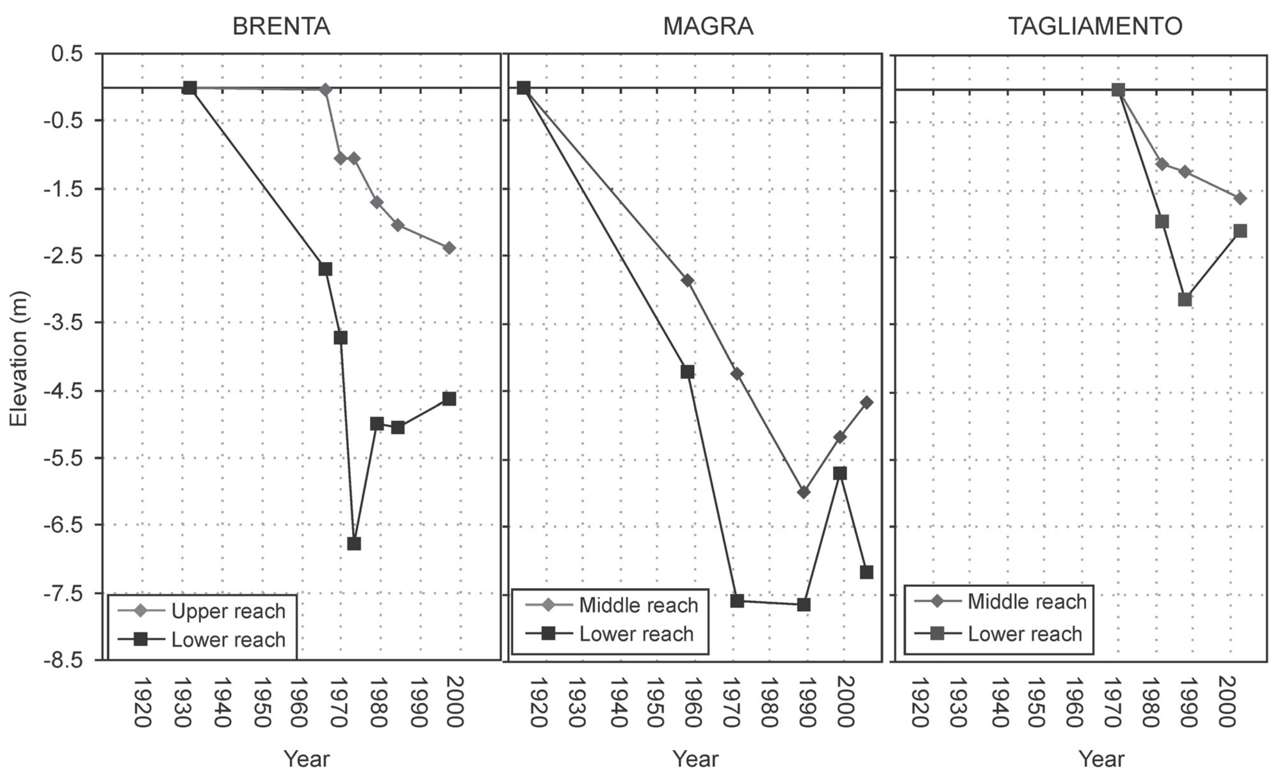

Figure 4. Temporal trends of bed-level changes in the Brenta, Magra, and Tagliamento Rivers. For each river, two typical trends are shown, e.g., one trend for the upper reach, and another for the lower reach in the case of the Brenta River.

of a sediment budget for the more recent period (1984–1997) points out that the sediments are supplied mainly by bank erosion and that little is supplied from upstream (Surian and Cisotto, 2007). This suggests that in the near future, once channel widening slows or ceases, bed-load supply could be very low, possibly causing a new phase of incision.

The evolution of the Orco River is unique, because after considerable channel narrowing from the 1950s to the 1980s, similar to that of most of the other rivers, intense widening occurred in the period 1989–2003 (Fig. 6). The channel widening has been so intense that in 2003 the width was larger than at the beginning of the nineteenth century (326 m and 221 m, respectively). The reasons for such recent widening are likely (1) the occurrence of a very large flood (the largest recorded in the twentieth century) in October 2000, and (2) the cessation of gravel mining since the end of the 1980s, implying higher in-channel sediment supply.

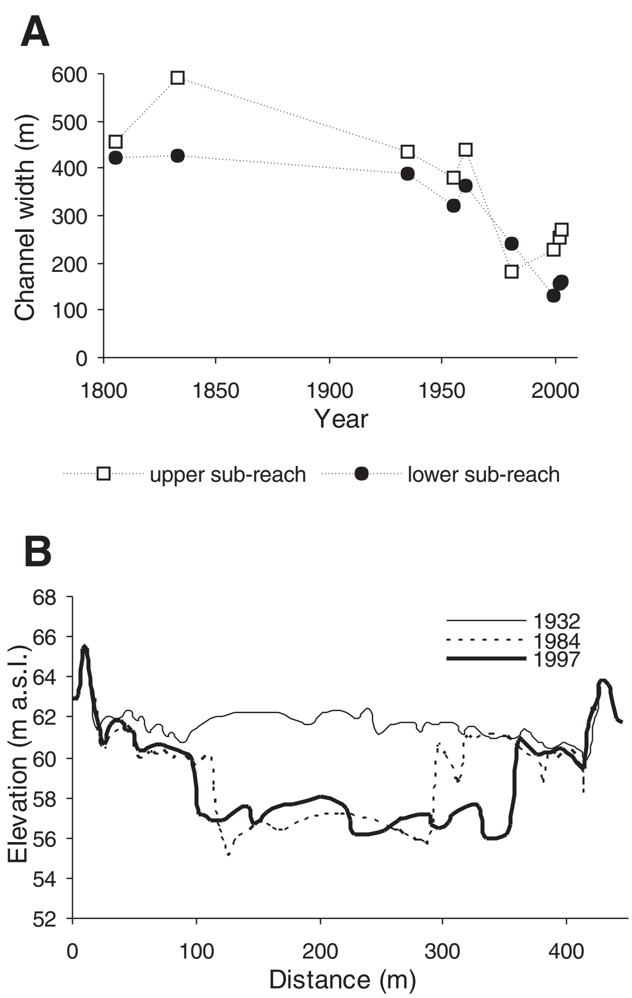

Figure 5. Channel adjustments in the Brenta River; a.s.l.—above sea level. (A) Temporal trends of channel width in the upper and lower sub-reaches. (B) Comparison of monumented cross sections, showing the major phase of incision and the recent phase of widening and sedimentation.

The Cecina River has been selected here because it is the smallest in size among the study cases, and it is representative of a geomorphological and climatic context distinct from the other cases, as it flows in the Apennines, with relatively low relief, and within an area of Mediterranean climate. In addition, there has been less human impact here than in other Italian rivers. Bed-level lowering has been generally moderate (1–3 m) during about the past 100 yr, whereas field evidence suggests that at present the dominant situation is of bed stability or, in some cases, of limited aggradation. The channel morphology of the Cecina in the 1950s can be described as wandering (locally braided), whereas in the following decades a significant narrowing occurred (Fig. 7), with a change in morphology to a sinuous, single-thread channel with alternate bars. A significant increase in sinuosity is observed, associated with channel narrowing, particularly during the last two decades (Fig. 7). The evolution of the Cecina River is, therefore, peculiar in some aspects and distinct from most of the other study cases, because (1) narrowing during the second phase of adjustment was less than in other rivers (Table 4), (2) narrowing is still going on (Table 5), and (3) increase in sinuosity appears to be an additional type of adjustment, with a partial shifting toward a single-thread, meandering morphology with gravel point bars.

DISCUSSION

The selected rivers underwent widespread channel adjustments over the past 100 yr. The dominant processes that have been observed are narrowing and incision: respectively the magnitude of such processes has been a decrease of as much as 81% in width (Magra River) and as much as 8–10 m of channel incision (Brenta, Panaro, and Magra Rivers). Narrowing and incision led to dramatic changes in channel configuration, becoming wandering or single-thread in several reaches that originally displayed a braided morphology. Subsequently, channel widening and sedimentation, or bed-level stabilization, have become dominant in most of the selected rivers over the last 15–20 yr, but the magnitude of such processes has generally been much lower in comparison with those of narrowing and incision. In fact, except for the Orco and Stura Rivers, which have undergone remarkable widening (up to 91% in the Orco River; see also Fig. 6), channel widening has been no more than 20%, and sedimentation on the order of 1–2 m (Fig. 4). It is worth noting that there are several examples outside of Italy where similar channel adjustments have been observed (e.g., in France, UK, USA, and China). Changes in channel width were often found to be comparable, whereas bed-level adjustments were generally less intense than in Italian rivers (e.g., Williams, 1978; Williams and Wolman, 1984; Simon, 1989; Xu Jiongxin, 1997; Sear and Archer, 1998; Winterbottom, 2000).

Although the same type of adjustments occurred in alluvial rivers of northern and central Italy, it is worth comparing the 27 sub-reaches in terms of both magnitude and time of channel adjustment. The fact that significant statistics ($R^2 = 0.47$ and P-values much lower than 0.05) exist for the first and second phase of adjustment is notable (Fig. 3), because it implies that

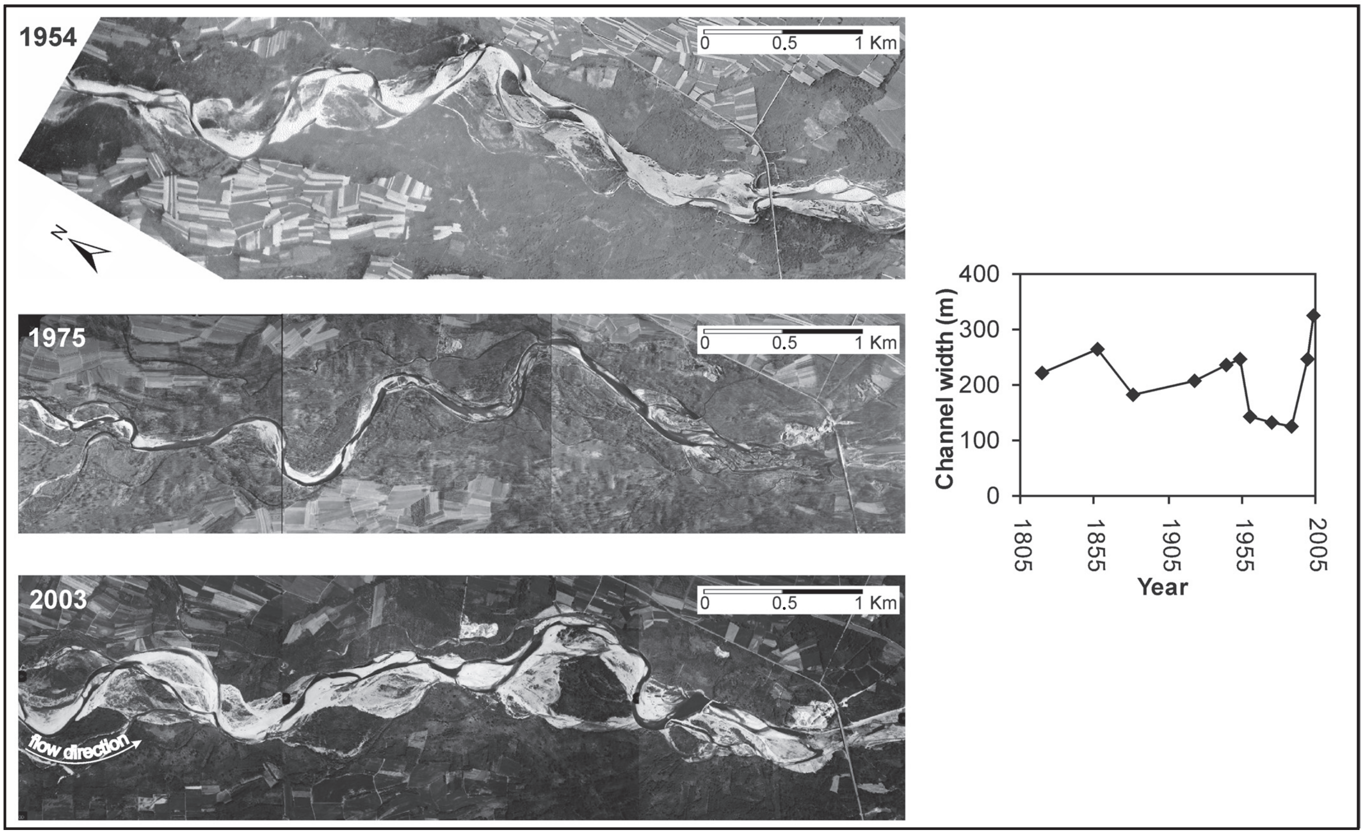

Figure 6. Channel changes in the Orco River: Aerial photographs of 1954 and 1975 document the narrowing phase from human impact, in particular gravel mining, whereas the 1975 and 2003 photographs show the remarkable widening that occurred in response to a number of floods, in particular the extreme flood of October 2000.

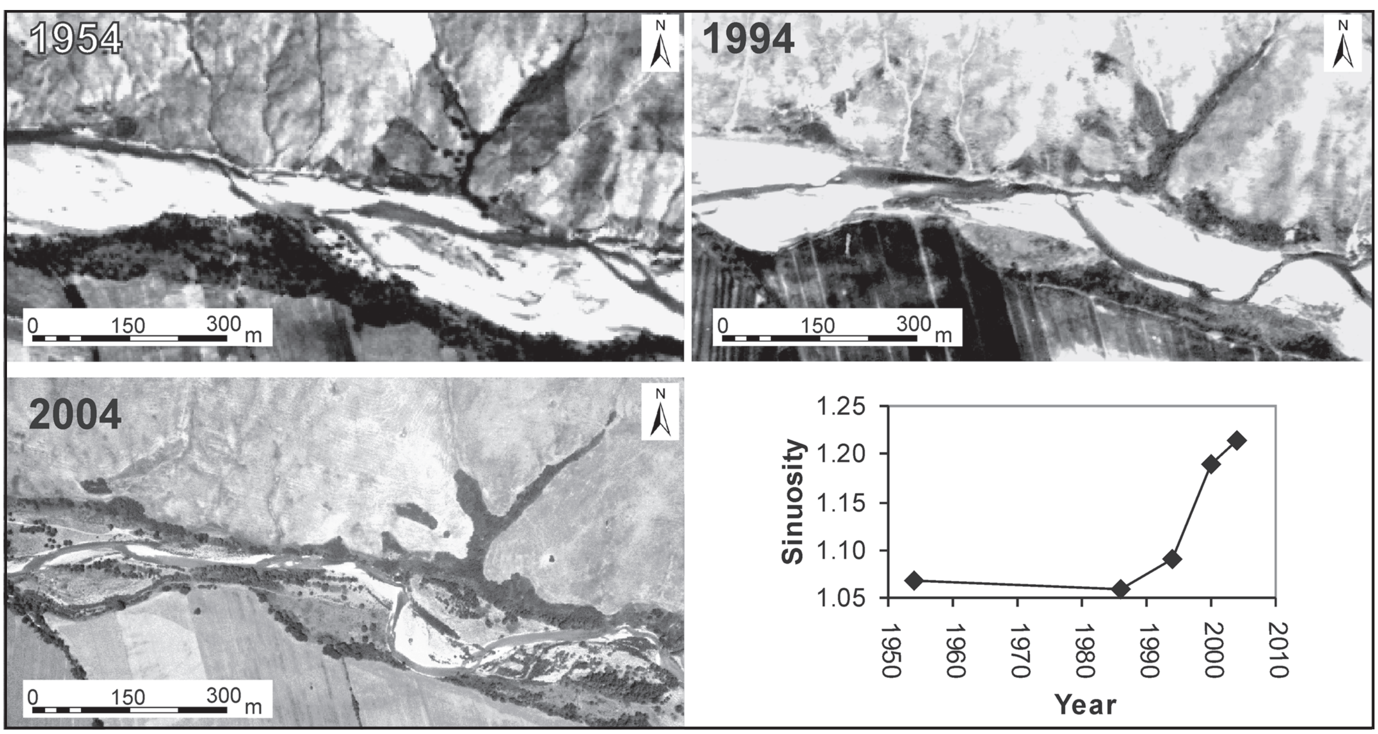

Figure 7. Channel adjustments in the Cecina River. This reach of the Cecina shows that channel narrowing instead of widening, as in most of the other rivers, has taken place from 1994 to 2004. A significant increase in sinuosity is observed, associated with channel narrowing.

those reaches not only underwent similar width changes but also that such changes took place at the same times. On the other hand, it is not surprising that the statistics are not significant for the third phase of adjustment ($R^2 = 0.03$, and $P = 0.42$). In fact, channel widening occurred only in 18 out of 27 sub-reaches, and four sub-reaches, those of the Stura and Orco, underwent an intense widening comparable to that of the other sub-reaches (Table 5). These results confirm that the existing models of channel evolution (Rinaldi, 2003; Surian and Rinaldi, 2003, 2004) are essentially correct, but they also give the opportunity for further development of such models. In particular, we improved the documentation of third phase of adjustment (the last 15–20 yr). This phase shows that channel widening and sedimentation, or bed-level stabilization, frequently occurred after narrowing and incision, but it also shows that the magnitude of processes can vary widely (see the case of the Orco). Besides, the fact that narrowing is still ongoing in some reaches will give the opportunity for investigating the reason why some reaches behave differently for certain periods of time.

The type, intensity, and chronology of various human actions described in a previous section suggest that the cause of channel adjustment is anthropogenic. That said, it is worth considering other possible causes, for instance, climate variability. Brunetti et al. (2006) found that precipitation in Italy over the past 200 yr has decreased (trends of total annual precipitation), but the decrease has been small and rarely significant. Similarly, no significant change of total annual precipitation was found for the Piave River (Surian, 1999). Though precipitation trends are not available for all the selected rivers, the data presented suggest that precipitation variability cannot be included among the major causes of channel adjustment. It is therefore reasonable to focus our attention on human actions. Besides the direct effect of channelization on channel morphology, what was the effect of human actions on flow and sediment regimes? Flow regulation has seldom affected maximum annual discharges (see Fig. 2), and consequently channel-forming discharges, whereas most human interventions (sediment mining, dams, reforestation, and torrent control works) have caused a dramatic alteration of sediment regime. Mining, usually intense between the 1950s and the 1980s, was likely the major cause of alteration because the extracted volumes largely exceeded replenishment rates. Gravel mining is not only a driving factor during the second phase of adjustment, but also during the most recent phase, which is characterized by widening and sedimentation, or bed-level stability, in several reaches. In fact, during this latter phase a significant reduction of mining has occurred, causing an increase of sediment availability. The effects of reforestation, torrent control, and dams on the sediment regime have been less intense than sediment mining but will be likely to persist for a longer period. Last, but not least, it is worth mentioning the role of large floods. It is well documented by the evolution of the Orco and Stura that large floods may have been the driving factor during the most recent phase of adjustment (Fig. 6). On the contrary, large floods seemed to have had less effectiveness during the second phase of adjustment, as a very large flood that occurred in November 1966 (with a recurrence interval of 100 yr or more) had minor effects on the trends of channel evolution.

Knowledge of channel adjustments and their causes has important implications in river management and restoration (Downs and Gregory, 2004; Habersack and Piégay, 2008). First of all it is worth recognizing that most of the Italian rivers—those analyzed in this study as well as many others (Surian and Rinaldi, 2003)—have been strongly altered by human actions and at present are very far from their pristine condition. River management and restoration should take into account that several conditions, in particular sediment fluxes, have changed significantly in the fluvial systems. This implies that the state of rivers before major human disturbances and channel adjustments can rarely be taken as a reference.

A second important issue raised by this study is the key role of sediments in channel evolution. This is why sustainable management and restoration strategies should aim at promoting sediment supply in order to mitigate situations where bed-load deficit and incision have occurred with severe effects on hydraulic, ecological, environmental, and societal aspects (Bravard et al., 1999). Sustainable strategies may include both promotion of sediment input from tributaries and hillslopes and bank-erosion preservation or promotion (Piégay et al., 2005; Habersack and Piégay, 2008).

CONCLUSIONS

Alluvial rivers in northern and central Italy underwent similar channel adjustments over the past 200 yr: (1) narrowing and incision occurred in all 12 selected rivers from the end of the nineteenth century to the 1980s–1990s, and were intense from the 1950s to the 1980s–1990s; (2) widening and sedimentation, or bed-level stabilization, were the dominant processes in the last 15–20 yr, although channel narrowing is still ongoing in some reaches.

Channel adjustments were driven mainly by human actions, but the role of large floods was also notable in some cases. Besides the direct effect of channelization on channel morphology, the major effect of human actions was on sediment regime. A significant decrease of in-channel sediment supply was determined by gravel mining. On the other hand, channel-forming discharges did not undergo significant changes in most of the study streams.

Management and restoration should take into account the fact that these rivers are far from their pristine condition and that severe effects on hydraulic, ecological, and environmental aspects were caused by channel adjustments. Sustainable strategies should pay close attention to sediment fluxes, in particular to gravel transport, which were dramatically altered in the last decades.

ACKNOWLEDGMENTS

This research was supported by funds from MiUR (Ministero dell'Istruzione dell' Università e della Ricerca) PRIN 2005 Project "Present and recent dynamics of river channels in Northern and Central Italy: evolutionary trends, causes and management implications”). We thank the two anonymous reviewers for their helpful comments.

REFERENCES CITED

Aucelli, P.P.C., and Rosskopf, C., 2000, Last century valley floor modifications of the Trigno River (Southern Italy): A preliminary report: Geografia Fisica e Dinamica Quaternaria, v. 23, p. 105–115.

Billi, P., and Rinaldi, M., 1997, Human impact on sediment yield and channel dynamics in the Arno River basin (central Italy), *in* Walling, D.E., and Probst, J.L., eds., Human Impact on Erosion and Sedimentation: Rabat, Morocco, Proceedings of Rabat Symposium, IAHS Special Publication 245, p. 301–311.

Bravard, J.P., Kondolf, G.M., and Piegay, H., 1999, Environmental and societal effects of channel incision and remedial strategies, *in* Darby, S.E., and Simon, A., eds., Incised River Channels: Processes, Forms, Engineering and Management: New York, Wiley & Sons, p. 303–341.

Brunetti, M., Maugeri, M., Monti, F., and Nanni, T., 2006, Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series: International Journal of Climatology, v. 26, p. 345–381, doi: 10.1002/joc.1251.

Capelli, G., Miccadei, E., and Raffi, R., 1997, Fluvial dynamics in the Castel di Sangro plain: Morphological changes and human impact from 1875 to 1992: Catena, v. 30, p. 295–309, doi: 10.1016/S0341-8162(97)00008-8.

Castaldini, D., and Piacente, S., 1995, Channel changes on the Po River, Mantova Province, Northern Italy, *in* Hickin, E.J., ed., River Geomorphology: Chichester, New York, Wiley & Sons, p. 193–207.

Castiglioni, G.B., and Pellegrini, G.B., 1981, Two maps on the dynamics of a river bed: Erosion and sediment transport measurement: Florence, Proceedings of IAHS Symposium, v. 22–26, p. 223–228.

Downs, P.W., and Gregory, K.J., 2004, River Channel Management: Towards Sustainable Catchment Hydrosystems: London, Edward Arnold, 395 p.

Dutto, F., and Maraga, F., 1994, Variazioni idrografiche e condizionamento antropico. Esempi in pianura padana: Il Quaternario, v. 7, p. 381–390.

Gregory, K.J., 2006, The human role in changing river channels: Geomorphology, v. 79, p. 172–191, doi: 10.1016/j.geomorph.2006.06.018.

Gurnell, A.M., 1997, Channel change of the river Dee meanders, 1946–1992, from the analysis of air photographs: Regulated Rivers: Research and Management, v. 13, p. 13–26, doi: 10.1002/(SICI)1099-1646(199701)13:1<13::AID-RRR420>3.0.CO;2-W.

Habersack, H., and Piégay, H., 2008, River restoration in the Alps and their surroundings: Past experience and future challenges, *in* Habersack, H., Piégay, H., and Rinaldi, M., eds., Gravel-Bed Rivers VI—From Process Understanding to River Restoration, Developments in Earth Surface Processes: New York, Elsevier, p. 703–738.

Hughes, M.L., McDowell, P.F., and Marcus, W.A., 2006, Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS: Geomorphology, v. 74, p. 1–16, doi: 10.1016/j.geomorph.2005.07.001.

Knighton, A.D., 1991, Channel bed adjustment along mine-affected rivers of northeast Tasmania: Geomorphology, v. 4, p. 205–219, doi: 10.1016/0169-555X(91)90004-T.

Kondolf, M.G., 1997, Hungry water: Effects of dams and gravel mining on river channels: Environmental Management, v. 21, p. 533–551, doi: 10.1007/s002679900048.

Lamedica, S., Dalla Valle, E., Pilli, R., and Anfodillo, T., 2007, Variazioni di superficie e fissazione di carbonio in foresta nel territorio montano della Regione Veneto in riferimento all’applicazione del Protocollo di Kyoto: Forest@, v. 4, p. 283–297, doi: 10.3832/efor0472-0040283.

Leopold, L.B., 1973, River channel change with time: An example: Geological Society of America Bulletin, v. 84, p. 1845–1860, doi: 10.1130/0016-7606(1973)84<1845:RCCWTA>2.0.CO;2.

Liébault, F., and Piégay, H., 2001, Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France: Geomorphology, v. 36, p. 167–186, doi: 10.1016/S0169-555X(00)00044-1.

Macklin, M.G., Passmore, D.G., and Newson, M.D., 1998, Controls of short and long term river instability: Processes and patterns in gravel-bed rivers, the Tyne basin, Northern England, *in* Klingemann, P.E., Beschta, R.L., Bradley, J., and Komar, P.D., eds., Gravel Bed Rivers in the Environment: Highlands Ranch, Colorado, Water Resources Publications, p. 257–278.

Maraga, F., 1983, Morphologie fluviale et migration des cours d’eau dans la haute plaine du Po (Italie, partie nord-ouest): Geologisches Jahrbuch, v. 71, p. 219–236.

Marston, R.A., Bravard, J.P., and Green, T., 2003, Impacts of reforestation and gravel mining on the Malnant River, Haute-Savoie, French Alps: Geomorphology, v. 55, p. 65–74, doi: 10.1016/S0169-555X(03)00132-6.

Petts, G.E., 1979, Complex response of river channel morphology subsequent to reservoir construction: Progress in Physical Geography, v. 3, p. 329–362, doi: 10.1177/030913337900300302.

Piégay, H., Darby, S., Mosselman, E., and Surian, N., 2005, A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion: River Research and Applications, v. 21, p. 773–789, doi: 10.1002/rra.881.

Rinaldi, M., 2003, Recent channel adjustments in alluvial rivers of Tuscany, Central Italy: Earth Surface Processes and Landforms, v. 28, p. 587–608, doi: 10.1002/esp.464.

Rinaldi, M., 2007, Geomorphological field survey for interpretation and classification of river channels adjustments: Epitome, v. 2, p. 362.

Rinaldi, M., and Simon, A., 1998, Bed-level adjustments in the Arno River, Central Italy: Geomorphology, v. 22, p. 57–71, doi: 10.1016/S0169-555X(97)00054-8.

Roveri, E., 1965, Sul ciclo d’erosione rinnovatosi lungo i corsi d’acqua dell’Appennino emiliano: Bollettino Società Geologica Italiana, v. 84, p. 290–309.

Rumsby, B.T., and Macklin, M.G., 1994, Channel and floodplain response to recent abrupt climate change, the Tyne basin, northern England: Earth Surface Processes and Landforms, v. 19, p. 499–515, doi: 10.1002/esp.3290190603.

Sear, D.A., and Archer, D., 1998, Effects of gravel extraction on stability of gravel-bed rivers: The Wooler Water, Northumberland, UK, *in* Klingeman, P.C., Beschta, R.L., Komar, P.D., and Bradley, J.B., eds., Gravel-Bed Rivers in the Environment: Highlands Ranch, Colorado, Water Resources Publications, p. 415–432.

Simon, A., 1989, A model of channel response in disturbed alluvial channels: Earth Surface Processes and Landforms, v. 14, p. 11–26, doi: 10.1002/esp.3290140103.

Simon, A., 1992, Energy, time, and channel evolution in catastrophically disturbed fluvial systems: Geomorphology, v. 5, p. 345–372, doi: 10.1016/0169-555X(92)90013-E.

Surian, N., 1999, Channel changes due to river regulation: The case of the Piave River, Italy: Earth Surface Processes and Landforms, v. 24, p. 1135–1151, doi: 10.1002/(SICI)1096-9837(199911)24:12<1135::AID-ESP40>3.0.CO;2-F.

Surian, N., 2006, Effects of human impact on braided river morphology: Examples from Northern Italy, *in* Sambrook Smith, G.H., Best, J.L., Bristow, C., and Petts, G.E., eds., Braided Rivers: Cambridge, Massachusetts, Blackwell Science, IAS Special Publication 36, p. 327–338.

Surian, N., and Cisotto, A., 2007, Channel adjustments, bedload transport and sediment sources in a gravel-bed river, Brenta River, Italy: Earth Surface Processes and Landforms, v. 32, p. 1641–1656, doi: 10.1002/esp.1591.

Surian, N., and Rinaldi, M., 2003, Morphological response to river engineering and management in alluvial channels in Italy: Geomorphology, v. 50, p. 307–326, doi: 10.1016/S0169-555X(02)00219-2.

Surian, N., and Rinaldi, M., 2004, Channel adjustments in response to human alteration of sediment fluxes: Examples from Italian rivers, *in* Golosov, V., Belyaev, V., and Walling, D.E., eds., Sediment Transfer through the Fluvial System: IAHS Press, Wallingford, UK, IAHS Special Publication 288, p. 276–282.

Williams, G.P., 1978, The Case of the Shrinking Channels—The North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Circular 781, 48 p.

Williams, G.P., and Wolman, M.G., 1984, Downstream Effects of Dams on Alluvial Rivers: U.S. Geological Survey Professional Paper 1286, 83 p.

Winterbottom, S.J., 2000, Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland: Geomorphology, v. 34, p. 195–208, doi: 10.1016/S0169-555X(00)00007-6.

Wyzga, B., 1993, River response to channel regulation: Case study of the Raba River, Carpathians, Poland: Earth Surface Processes and Landforms, v. 18, p. 541–556, doi: 10.1002/esp.3290180607.

Xu Jiongxin, 1997, Evolution of mid-channel bars in a braided river and complex response to reservoir construction: An example from the middle Hanjiang River, China: Earth Surface Processes and Landforms, v. 22, p. 953–965, doi: 10.1002/(SICI)1096-9837(199710)22:10<953::AID-ESP789>3.0.CO;2-S.

Manuscript Accepted by the Society 15 September 2008

Printed in the USA