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SCIENCE DIRECT
Geomorphology 50 (2003) 307–326
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Morphological response to river engineering and management in alluvial channels in Italy

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Received 2 February 2002; received in revised form 19 July 2002; accepted 21 July 2002

Abstract

In response to various types of human disturbance, most Italian rivers have experienced considerable channel adjustment during the last centuries and in particular in the last decades. This paper reviews all existing published studies and available data, and aims to reconstruct a general outline of the main channel adjustments that have occurred in Italian rivers during the past 100 years.

Two main types of channel adjustment have been recognized: (a) incision, which is commonly on the order of 3–4 m, but in some cases is even more than 10 m; (b) narrowing, with channel width reduction up to 50% or more. In some reaches, these adjustments have led to changes in channel pattern in particular from braided to wandering.

Such channel adjustments are due to several types of human intervention, particularly sediment extraction, dams and channelization. A strong temporal relationship (specifically, short reaction times) between human disturbance and channel adjustment can be inferred, but trends of adjustment are available for only a few rivers (e.g. the Po, the Arno and the Piave Rivers). These trends show that incision and/or narrowing are more intense immediately after the disturbance and then slow and become asymptotic; the same trends also suggest that larger rivers could have longer relaxation times.

The results of this study are synthesised in a general classification scheme that summarises the main styles of adjustment observed in Italian rivers. According to the scheme, braided rivers adjust through prevalent narrowing with varying rates of incision, whereas single-thread rivers adjust mainly through a more pronounced incision accompanied by various amounts of narrowing. The scheme, representing initial and final (present) morphologies and not including intermediate stages of channel adjustment, will need to be tested on the basis of more detailed data to have a wider application both to the Italian context and to fluvial systems elsewhere, affected by similar types of human disturbance causing a reduction of sediment supply.

Keywords: Channel incision; Channel narrowing; Human disturbances; Channel adjustment; Italian rivers

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doi:10.1016/S0169-555X(02)00219-2

1. Introduction

During the past tens or hundreds of years, in many fluvial systems, river dynamics have been significantly affected by human disturbances such as land use changes, urbanization, channelization, dams, diversions, gravel and sand mining. Since these disturbances cause substantial changes to the flow and sediment regimes, at present few rivers are in a natural or semi-natural condition. For instance, in the Alps less than 10% of the total length of the rivers is in a semi-natural condition (Ward et al., 1999). Several studies have analysed the response of rivers to human impact, showing that remarkable channel changes generally take place, such as vertical adjustment, changes in channel width and pattern (e.g. Leopold, 1973; Gregory and Park, 1974; Williams, 1978; Petts, 1979; Williams and Wolman, 1984; Andrews, 1986; Knighton, 1991; Collier et al., 1996; Petit et al., 1996; Kondolf, 1997). These changes are generally much larger than those that could be expected from natural channel evolution, although in some cases also natural phenomena, such as large floods, fires and volcanic eruptions, or short-term climatic fluctuations (e.g. Rumsby and Macklin, 1994; Macklin et al., 1998) may have an important role in controlling channel instability and changes.

Since channel incision and narrowing can produce a range of environmental and social effects, such as undermining of structures, loss of groundwater storage, loss of habitat diversity (Bravard et al., 1999), a better understanding of channel adjustments is essential for preventing their consequences, and predicting future channel evolution. River management and water resource strategies should take into account the styles and magnitude of channel changes, to avoid or mitigate their adverse effects to present and future human activities.

Italian rivers have been subjected to human disturbance and modification for a long time, some of them (for instance the Po, the Arno and the Tevere Rivers), since Roman times. Up to the 19th century, the most common human modifications were channelization and diversion, to provide flood protection and to increase the productivity of agricultural land, respectively. In addition, during the 20th century and particularly during the last decades, two other types of intervention have been widely carried out, namely the construction of dams, and sediment mining. Within this context, an exception is represented by the Tagliamento River (Eastern Alps) that can be considered the last large river in the Alps essentially retaining pristine morphological and ecological characters (Ward et al., 1999; Gurnell et al., 2001).

In response to these various types of human disturbance, most of the Italian rivers have experienced drastic channel adjustments during the last centuries. Although studies have focused on responses of Italian rivers to human impact, a general review of the available data and a reconstruction of types and amount of channel adjustments is still lacking.

In this paper, published studies and existing data on recent channel adjustments of rivers in Italy are reviewed and discussed. Our aims are to: (a) reconstruct a general outline of river channel adjustments and their causes in the recent past (generally the last 100 years); (b) define the general temporal trends of channel changes and the different styles of adjustment; (c) compare the morphological changes with those observed in fluvial systems outside Italy.

2. General setting

The Italian territory has an area of 301 280 km^2, and covers more than 10° of latitude (from 37° lat. N to 47° lat. N). A large part of the country is made of mountains (51%) and hills (29%), while only 20% is occupied by plains. The Alps and the Apennines represent the main physiographic features, while the Po Plain in northern Italy is the only large plain in the country, with minor plains in central and southern Italy. The geology varies widely: there are different kinds of sedimentary, igneous and metamorphic rocks, while Quaternary deposits (mainly fluvial, glacial and slope deposits) cover large areas. Most of the territory is tectonically active.

Climate and precipitation reflect the morphological heterogeneity of the country. Climate is mainly "temperate", but it varies from "cool temperate" to "subtropical temperate" (according to Köppen classification) and in the Alps it is also "cold" (type E). Precipitation ranges from more than 3000 mm/year (3310 mm at Musi in the Isonzo basin) to less than 500 mm/year (426 mm/year at Manfredonia in the Salso basin), the average being 990 mm/year (Rusconi, 1994).

The hydrologic and physiographic characteristics of the main Italian rivers (most of which are considered in this paper) are summarised in Table 1 (see Fig. 1 for location). Commonly, the areas of drainage basin range between 1000 and 10 000 km^2 and only three drainage basins (Po, Adige and Tevere) have an area larger than 10 000 km^2. All these rivers exceed 100 km in length (the longest is the Po River at 651 km). Basin relief is relatively high, and generally higher in Alpine rivers (in some basins, it is more than 4000 m) than in Apennine rivers (in the latter, it is commonly 1500–2500 m). As mentioned above, precipitation varies widely within the country: the river basins in the north present the highest values (2150 mm/year, Tagliamento basin), whereas those in the south and in the two main islands (Sicily and Sardinia) have the lowest values (547 mm/year, Salso basin). Also the runoff ratio varies significantly, from 68% in the northern part of the country to 45% in the central and southern parts of the country, and 30% on the two main islands. The highest and lowest runoff ratio values are 103% (Brenta River) and 13% (Bradano River), respectively. Floods are relatively flashy due to basin characteristics (e.g. relief), but also to the fact that they result mainly from rainfall runoff rather than snowmelt.

Notwithstanding the high human impact general to most of the Italian alluvial plains, it is still possible to recognise a range of channel morphologies, related mainly to the variability of physiographic conditions. In the Alpine valleys and piedmont alluvial fans of the northern side of the Po Plain, as well as in the

Table 1
Hydrologic and drainage basin characteristics of the main Italian rivers (from Morandini, 1957; Ministero dei Lavori Pubblici—Servizio Idrografico, 1980; Cati, 1981; Tonini, 1983)

River	Drainage basin area (km^2)	Length (km)	Basin relief (m)	Precipitation (mm yr^{-1})	Mean annual discharge (m^3 s^{-1})	Runoff (%)	Flood peak discharge (m^3 s^{-1})
Po	70 091	651	4799	1106	1470	60	11 800
Dora Baltea	3313	160	4544	949	96	97	–
Tanaro	7985	276	3218	997	127	50	3170
Ticino	6599	284	4443	1695	292	82	5000
Adda	7775 (4572)	313	–	1315	157	82	740
Oglio	5682 (1842)	280	–	1232	59	81	410
Adige	11 954	410	3890	933	220	62	4000
Brenta	1787 (1567)	160	3079	1386	71	103	2810
Piave	3899	222	3162	1330	132	78	4250
Tagliamento	2580	172	2696	2150	109	73	4000
Reno	3410	211	1942	979	42	39	1000
Secchia	2174 (341)	172	2055	1170	12	47	–
Arno	8830 (8186)	241	1650	1038	99	37	2290
Ombrone	3480 (2657)	161	1679	924	27	35	3120
Tevere	17 556 (16 545)	396	2486	1044	236	43	2800
Liri-Garigliano	6500 (1410)	168	2105	1183	29	55	450
Volturno	5558	175	2238	1173	103	50	1800
Pescara	3190 (3125)	152	2790	896	53	60	380
Trigno	1200 (544)	120	–	1020	7	41	–
Sangro	1515 (762)	117	2531	1206	3	–	420
Ofanto	2760 (2716)	134	1461	724	15	24	930
Bradano	2743	116	1218	672	7	13	1030
Basento	1405	149	1815	796	12	34	990
Simeto	(1832)	116	3257	747	18	41	1460
Salso	2120 (1782)	144	1856	547	5	15	260
Flumendosa	1780 (1011)	122	1752	965	11	35	1970
Tirso	3375 (587)	150	1077	816	4	29	1100

The drainage basin areas between parentheses are those upstream of the gauging stations where mean annual and flood peak discharges were estimated.

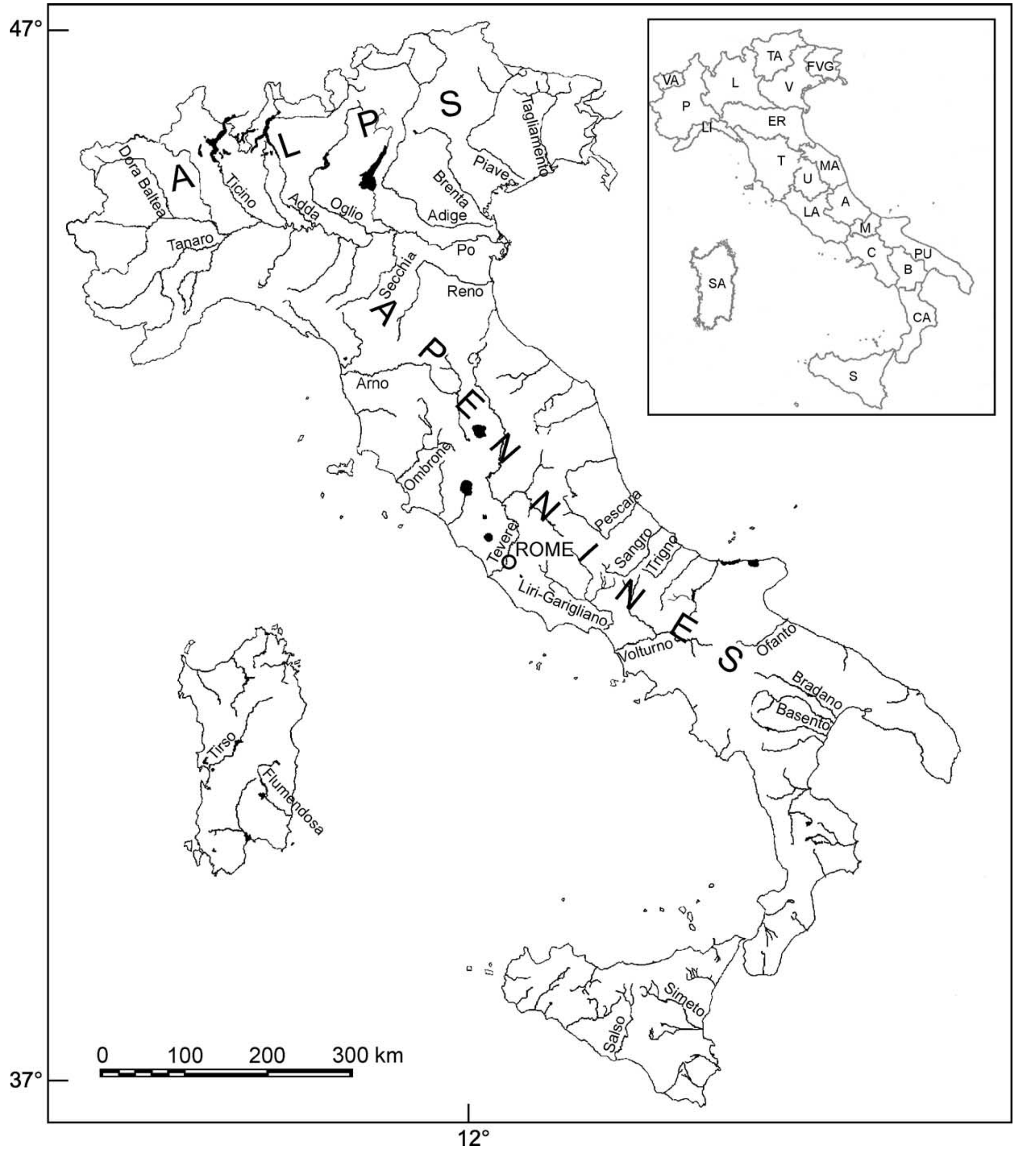

Fig. 1. Location map to show the main Italian rivers (see Table 1 for their hydrologic and drainage basin characteristics). Inset: Regions of Italy. Valle d'Aosta (VA), Piedmont (P), Lombardy (L), Trentino Alto Adige (TA), Venetia (V), Friuli Venezia Giulia (FVG), Liguria (LI), Emilia Romagna (ER), Tuscany (T), Umbria (U), Marche (MA), Latium (LA), Abruzzo (A), Molise (M), Campania (C), Apulia (PU), Basilicata (B), Calabria (CA), Sicily (S), Sardinia (SA).

Venetia–Friuli plains and along the Apennines tributaries of the Po River, multithread braided and transitional patterns, between braided and single thread (wandering), are common. For most of its course, the Po River is a typical meandering river, with large point bars and chute channels. Due to structural control, northern and central Apennines on the Tyrrhenian side are characterised by an alternation of alluvial channels, crossing intermountain basins, and semi-confined channels crossing bedrock gorges (e.g. the Arno and the Tevere Rivers). Conversely, rivers on the Adriatic side of the Apennines are characterised by relatively short courses, laid out approximately orthogonal to the Apennine chain. In both cases, the present channel morphologies are mostly single thread, ranging from sinuous with alternate bars (in some cases locally braided), along the upper valleys, to meandering along the coastal plains. The rivers of Calabria and eastern Sicily are generally characterised by multithread braided channels, short courses and relatively high channel slopes (those rivers are termed "fiumare"), having an ephemeral hydrological regime associated with a semi-arid climate.

3. Channel changes and human impact in Italian rivers

A systematic review of the studies regarding morphological changes in Italian rivers has been carried out (Table 2). Some of these studies deal with channel dynamics during the last few centuries. However, the data discussed here are restricted to the last century, and more specifically to the last few decades. Besides the type and magnitude of morphological changes, this review is focused on: (a) causes of change, and (b) effects of changes on human structures and environment. The information is not homogeneous nor complete for all the rivers.

3.1. Morphological changes

The most common morphological changes in Italian rivers turn out to be bed-level lowering, channel narrowing and changes in channel pattern. Channel aggradation and widening are mentioned in few studies and considered as secondary processes compared to those cited above. Bed incision of 3–4 m is very common, and in some cases (e.g. some rivers of the Emilia Romagna, Marche, Abruzzo and Calabria Regions) incision of 10 m, or even more, was observed. For example, the Arno River (Tuscany) has been subjected to widespread channel incision, with a maximum total bed-level lowering higher than 6 m in the Lower Valdarno reach on average (Fig. 2). Narrowing of the active channel has been observed in many streams (Fig. 3), but only in few studies the magnitude of this process has been evaluated. In several rivers of the Piedmont and Tuscany Regions and in the Piave River, channel width reduction has been up to 50% or more. Finally, changes in planform configuration have been pointed out in some cases, in particular from braided to wandering (e.g. several rivers in the Piedmont Region, the Piave River and the Trigno River; see also Fig. 3). The latter term, increasingly used in literature, indicates rivers with braided-anastomosed or braided-meandering transitional characters (Neill, 1973; Church, 1983; Ferguson and Werritty, 1983; Knighton and Nanson, 1993).

As regards location and time of morphological changes, information is not homogeneous and complete for all the rivers. Morphological changes were commonly observed in piedmont and alluvial plain reaches and seem to take place simultaneously along the rivers without migration of processes. This could be due to the fact that human intervention is often widespread along the rivers and in the drainage basins. With respect to time of morphological changes, most of the studies document that the main phase of channel adjustment started in the 1950s to 1960s (Table 2), although a complete analysis of temporal trends of channel adjustment is possible in only few cases (see Discussion).

3.2. River engineering and management

Several human interventions (dams, gravel and sand mining, channelization, land-use changes) have been indicated as the causes of those changes in river morphology since they alter flow regime, channel boundary characteristics, and especially sediment supply (Table 2). Sediment mining has occurred in many rivers and, in several cases (e.g. rivers in the Emilia Romagna Region or the Brenta River), this has represented the main or the only cause of river system alteration. Generally this practice was very intense in

Table 2
Recent channel adjustments in Italian rivers and relative causes and effects

River	Morphological changes	Location and time of morphological changes	Causes	Location and time of human intervention	Effects on structures and environment	Reference
Po	Channel shifting		Neotectonics, embankments			Braga and Gervasoni (1989)
	Channel narrowing; reduction of sinuosity		River engineering (at least in part)	1930s up to the present		Castaldini and Piacente (1995)
	Incision (1–6 m); reduction of channel length; reduction of sinuosity; meander cutoff; channel narrowing; changes in channel pattern	1920s to 1950s, 1960s up to the present	Changes in flood regime; gravel and sand mining; channelization; intervention at basin level	Since the Roman times, but particularly intense from 1950s up to the present	Undermining of bank-protection structures and bridges; loss of groundwater resources; loss of agricultural land; increase of flow velocity	Maraga and Mortara (1981), Tacconi and Billi (1990), Govi and Turitto (1993), Lamberti (1993), Dutto and Maraga (1994), Lamberti and Schippa (1994), Maraga (1999), Marchetti (2002)
Rivers of the Piedmont Region (High Po Plain)	Channel narrowing (in several cases more than 50%); incision (up to 5–8 m); decrease of braiding index; changes in channel pattern (from braided to wandering)	Piedmont and alluvial plain reaches; 1950s to 1980s	Gravel mining; channelization	1950s to ?	Loss of groundwater resources	Maraga and Mortara (1981), Maraga (1989, 1992), Dutto and Maraga (1994)
Brenta	Incision (up to 7–8 m)	Alluvial plain reach; 1960s to 1970s	Gravel mining; dams	Alluvial plain reach; 1960s to 1970s	Failure of bridges; loss of groundwater resources	Castiglioni and Pellegrini (1981a,b)
Piave	Channel narrowing (more than 50%); decrease of braiding index; incision (up to 2–3 m); changes in channel pattern (from braided to wandering)	Mountain and alluvial plain reaches; 1900s up to the present	Dams; diversions; gravel mining; channelization	Mountain and alluvial plain reaches; 1930s up to the present	Loss of groundwater resources	Surian (1999, in press)

Rivers of the Emilia Romagna Region	Incision (3–4 m on average, up to 12–13 m); channel narrowing, changes in channel pattern (from braided to meandering)	Piedmont and alluvial plain reaches: 1950s to 1980s (particularly intense in 1970s)	Gravel mining, dams, construction of weirs	Piedmont reach; 1950s to 1980s	Failure and damage to bridges and protection structures; loss of groundwater resources; increase of flow velocity; reduction of sediment supply to the beaches	Pellegrini et al. (1979a,b), Perego (1994), Castaldini et al. (1999)
Arno	Incision (2–5 m on average, up to 9 m)	Alluvial and coastal plain reaches; two phases of incision: minor phase from the beginning of 1900; second phase from 1945–60 to 1990s	Interventions at basin level (construction of weirs, reforestation)	Mountain areas, from the end of 1800 and first decades of 1900	Damage to bridges, bank protections and levees; upstream migration on tributaries; riverbanks instability; loss of groundwater resources; reduction of sediment supply to the beaches	Natoni (1944), Becchi and Paris (1989), Canuti et al. (1994), Billi and Rinaldi (1997), Rinaldi et al. (1997), Agnelli et al. (1998), Rinaldi and Simon (1998)
			Intense gravel-mining;	Alluvial reaches: 1950s to 1980s		
			Dams	1957		
Rivers of the Tuscany Region	Incision (usually 0.5–2 m; more than 2 m in some cases); channel narrowing (in several reaches more than 50%); changes in channel pattern	Alluvial plain reaches: 1950s to 1990s	Interventions at basin level (construction of weirs, reforestation)	Mountain areas, from the end of 1800 and first decades of 1900	Damage to bridges, bank protections and levees; riverbanks instability; loss of groundwater resources; reduction of sediment supply to the beaches	Billi et al. (1994), Rinaldi (1995, in press), Rinaldi and Rodolfi (1995)
			Gravel mining	Alluvial reaches: 1950s to 1980s		
Tevere (Upper reach)	Channel narrowing and reduction of bars	Alluvial plain reach: from 1825 to present	Embankments	Alluvial reach: from 1800 to present	Damage to bridges, adjacent roads, bank protections; upstream migration on tributaries; riverbanks instability	Cencetti et al. (1992), Canuti et al. (1992)
	Incision (on average more than 2 m, up to 3.5 m)	1960s to 1980s	Gravel mining; dam and weirs	1960s to 1990s		
Volturno (Lower reach)	Incision (2 m on average, up to 5 m)	Coastal plain reach: 1960s to 1990s	Sediment mining; hydraulic structures	Coastal plain and upstream alluvial reaches: 1950s to 1980s	Coast retreat	Biggiero et al. (1994, 1996)

(continued on next page)

Table 2 (*continued*)

River	Morphological changes	Location and time of morphological changes	Causes	Location and time of human intervention	Effects on structures and environment	Reference
Rivers of the Marche Region	Incision (2–5 m on average, up to 10 m); channel narrowing	Alluvial plain and coastal reaches: 1960–1980	Reforestation Channelization Gravel mining	Upland areas: 1920–1930 Alluvial reaches: 1930s to 1950s Alluvial reaches: 1950s to 1980s	Damage to bridges; loss of groundwater resources; reduction of sediment supply to the beaches; coast retreat	Tazioli (1982), Aquater (1982), Conti et al. (1983), Gentili and Pambianchi (1987), Coltorti et al. (1991)
Rivers of the Abruzzo Region	Incision (up to 10 m); channel narrowing; change in channel pattern from multithread to single thread	Alluvial plain reach: 1970s to 1990s	Gravel mining; dams and weirs	Alluvial plain and upstream reaches: 1960s to 1980s	Damage to bridges and protection structures; streambank instability; loss of groundwater resources	Adamoli and Bertini (1993)
Sangro	Incision (up to 4 m); channel narrowing; changes in channel pattern	1980s to 1990s	Dams; channelization; gravel mining	Upland and alluvial reaches 1950s to 1990s	Damage to protection structures; loss and pollution of groundwater resources	Capelli et al. (1997, 1998)
Trigno	Channel pattern change from braided to single thread and channel narrowing; incision (2–4 m and locally up to 8 m)	Alluvial plain reaches: 1950s to 1990s	Reforestation and measures for reduction of soil erosion Gravel mining	Mountain areas: 1930s to 1970s Alluvial reaches: 1960s to 1970s	Regressive erosion on tributaries; damage to weirs; undermining and failure of embankments	Aucelli and Rosskopf (2000)
Rivers of the Calabria Region	Incision (several meters); channel narrowing	Piedmont: 1950s to 1980s	Embankments, groynes, weirs Gravel mining	1930s to 1960s 1950s to 1970s	Damage to bridges and other structures; coast retreat	Sabato (1994, 1999)

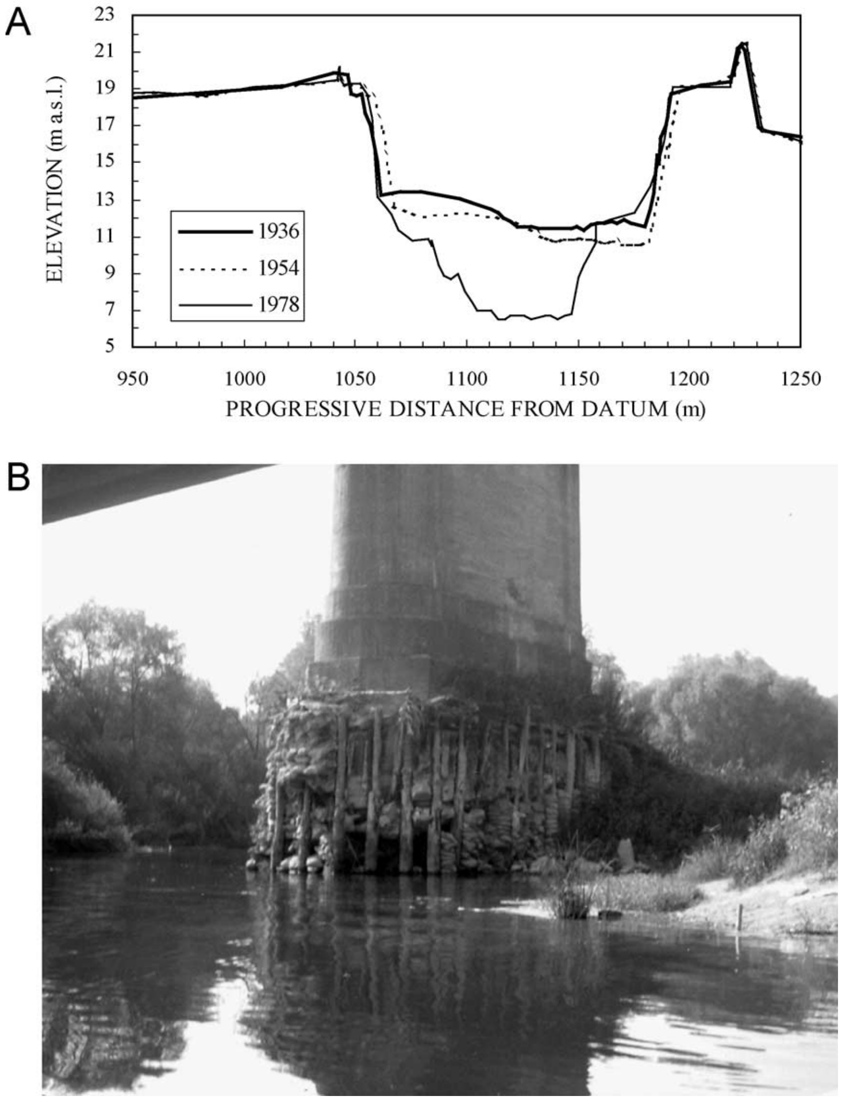

Fig. 2. Channel incision along the Arno River in the Lower Valdarno–Pisa Plain reach. (A) Example of typical change in cross section, with limited bed lowering from 1936 to 1954, and intense incision from 1954 to 1978. Total bed level lowering from 1844 to 1978 was 6.3 m. (B) Bridge 2 km upstream of the previous section, with exposed piles due to the incision.

the period between the 1950s and the 1970s, but it is still going on nowadays, although with a lower intensity. For instance in the Po basin, instream mining increased from about 3 million m^3/year to about 12 million m^3/year during the period 1960–1980, and then it decreased back to about 4 million m^3/year, with the highest value (12 million m^3/year) approximately equal to the estimated average annual production of sediment in the basin (Lamberti, 1993).

In Italy there are 729 large dams (dams higher than 10 m or with a reservoir capacity>10^5 m^3) and 8000–9000 smaller dams (Rusconi, 1994). These dams affect both the river flow and the sediment regime. With respect to the river flow, dams generally cause a decrease of the lowest discharges but not necessarily of the channel-forming discharges (e.g. Surian, in press). On the other hand, dams significantly affect the supply and transport of sediments in river chan-

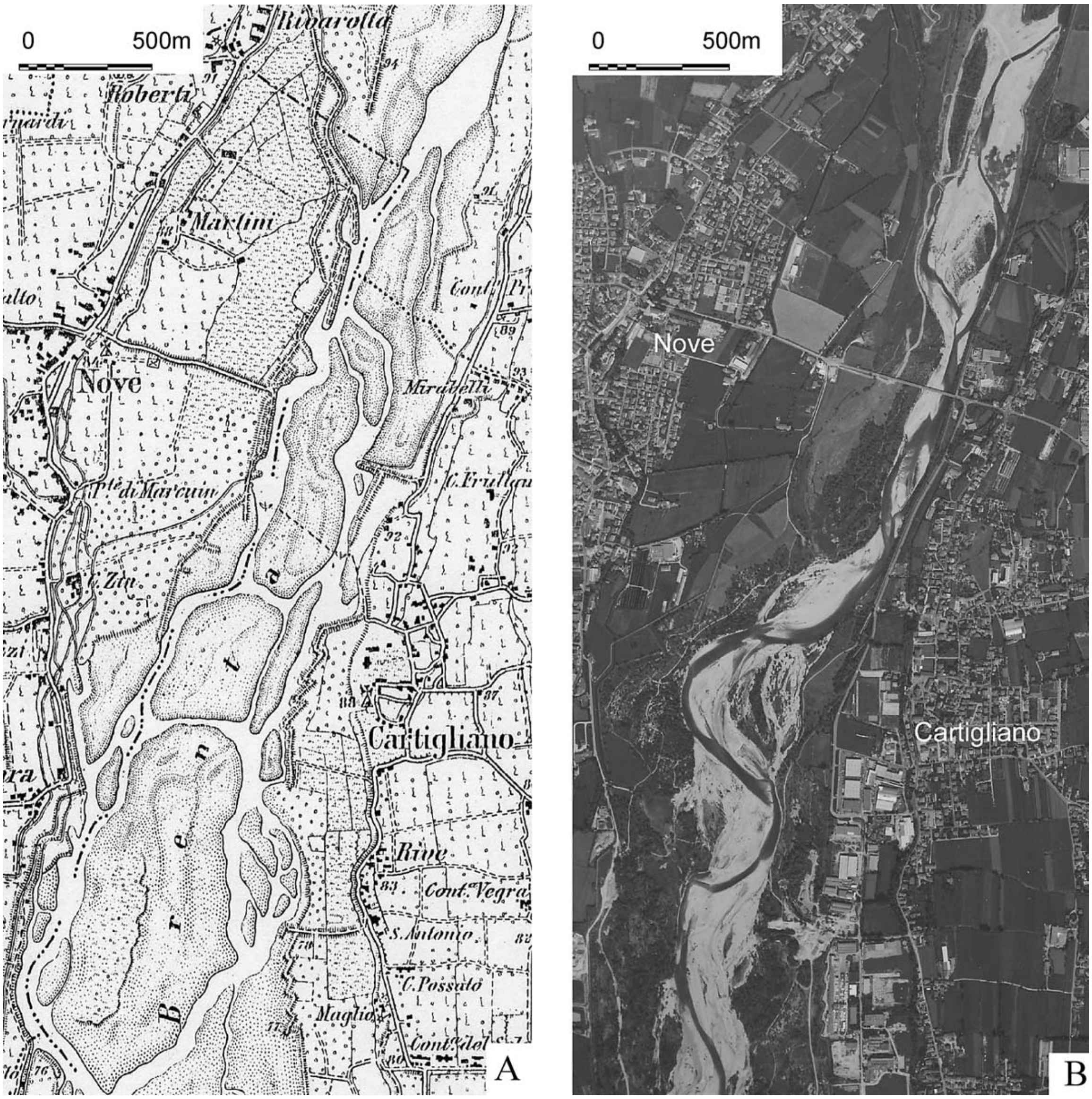

Fig. 3. Channel narrowing along the Brenta River: (A) topographic map (I.G.M.) of 1887; (B) aerial photograph of 1999. Besides narrowing, decrease in intensity of braiding, increase in channel sinuosity and change in channel pattern (from braided to wandering) have taken place during the last century.

nels: in the case of the Piave River, for instance, dams trap the sediment yield from more than 50% of the drainage basin (Surian, 1999).

Therefore sediment mining and dams, plus in some cases land-use changes (e.g. reforestation), have produced a remarkable decrease in sediment supply to river channels. This decrease was recorded in several rivers during the second half of the 20th century, for instance in the Po River (a decrease of 38%), in the Adige River (23%) and in the Brenta River (68%) (Bondesan, 2001).

A direct effect on river morphology (particularly on channel width, but also on channel pattern and bed-level stability) has resulted from streambank protection structures. In some reaches, structures such as groynes and levees constrain the river to maintain a narrower channel, reducing bank erosion and giving opportunity for agricultural uses while in other cases, the river has been completely fixed and channelized by continuous structures.

3.3. Effects on structures and environment

Morphological changes of river channels may have several effects on hydraulic structures, infrastructures, and environment (Table 2). Bed-level lowering has caused undermining and damage to protection structures and bridges. Where incision has been particularly severe, failure of these structures has occurred (e.g. two bridges along the Brenta River; Castiglioni and Pellegrini, 1981b). Among all the effects on the environment, two were more commonly recognised: loss of groundwater resources and reduction of sediment supply to beaches. The effects on the ecosystems along the riparian corridors are not mentioned in the studies reviewed: this is due to the ‘‘physical’’ approach of those studies and not to the absence of such kind of effects, which undoubtedly exist.

4. Discussion

4.1. Magnitude of channel adjustments

In Italian rivers, recent channel adjustments have been considerable, since processes of such magnitude (bed-level lowering of 10 m, channel narrowing to 50% or more, and changes in channel pattern) generally require much longer time (10^2–10^3 years) under natural conditions. The types and magnitude of the channel adjustments observed raise the question whether they represent a peculiarity of Italian rivers or whether similar situations occur along rivers throughout the world. Studies that analyse incision and narrowing in different countries and physiographic environments were reviewed to answer this question (Table 3). In the case of channel incision, in Europe, USA and China, several rivers have been subjected to bed-level lowering of some metres in the time of few years or decades. The maximum values of incision documented are: 10 m in France, 9 m in England, and 7.5 m in the USA (Table 3). Also channel narrowing was observed in many cases: in the North Platte and Platte Rivers (Nebraska, USA), this process caused a decrease in channel width up to 80–90%. Finally, dramatic changes in channel pattern, generally from braided to single thread, have been documented in UK, France and China. All these data show that generally channel adjustments in Italian rivers are similar in magnitude to those which have occurred in other countries. Notwithstanding this, it must be pointed out that channel incision in Italy has been particularly intense, considering that in several rivers, incision is 10 m or even more (up to 13 m), whereas incision has reached such values less frequently in other countries.

4.2. Temporal trends of channel adjustments

In addition to analysing the magnitude of channel adjustments, it is also worthwhile considering their temporal trends. Even though such an analysis is possible for just a few rivers, it reveals exactly when channel adjustments (i.e. incision, narrowing) started, identifies whether they are still going on, and indicates future evolution that can be expected in these rivers.

Numerous examples in the literature report how bed-level changes at a site are best described mathematically by non-linear functions, where adjustments occur rapidly, immediately after the disturbance, and then slow and become asymptotic (Graf, 1977; Williams and Wolman, 1984; Simon and Hupp, 1986). Few examples of bed-level adjustments at a site are available for Italian rivers. However, the two cases reported in Fig. 4 are particularly significant, and show similar trends for two of the main Italian rivers (Po and Arno). Data sources are different for the two cases: for the Arno River, the bed elevation obtained from available longitudinal profiles and cross sections is plotted, while for the Po River, the minimum annual river stage at a gauging station is used as indicator of bed adjustments (Lamberti and Schippa, 1994).

In the case of the Arno River, the trend reported here is representative of the general adjustments observed in many other cross sections along the two main alluvial reaches (Lower and Upper Valdarno) of the river (Rinaldi and Simon, 1998). Two main phases of incision have been identified, with the first starting around the beginning of the past century and related to changes in land-use and land-management practices. The second phase, triggered in the period 1945–1960,

Table 3
Channel incision, narrowing and change in channel pattern due to human activities: case studies from different countries and environments

Region	Channel adjustments	Causes	Reference
United States			
Mississippi	Incision (1–5 m); widening; secondary aggradation	Channelization; flood control reservoirs	Schumm et al. (1984), Thorne (1999)
Tennessee	Incision (generally 3–4 m, up to 6.1 m); widening (up to 59 m); secondary aggradation (about 1 m)	Dredging and straightening	Simon and Hupp (1986), Simon (1989)
Iowa, Nebraska, Missouri	Incision (up to 7.5 m); widening (up to 34 m)	Dredging and straightening	Piest et al. (1977), Simon and Rinaldi (2000)
Nebraska	Narrowing (width decreased by 80–90%, between 1865 and 1969); reduction in braiding; increase in sinuosity	Dams; water regulation	Williams (1978)
Oklahoma, North and South Dakota, Montana	Incision (from negligible up to 5.1 m)	Dams	Williams and Wolman (1984)
California	Incision up to 5 m	Reservoirs construction; gravel mining	Kondolf (1995)
Colorado River	Incision downstream of dams (from 4.6 to 7.5 m)	Dams	Williams and Wolman (1984)
Green River	Narrowing (width decreased by 10–13%)	Dam	Andrews (1986)
United Kingdom			
Scotland	Incision, narrowing and change in channel pattern, from wide, braided channels to narrower single thread	Channel regulation, changes in flood frequency and magnitude, metal mining and gravel extraction	Lewin and Weir (1977), McEwen (1989), Winterbottom (2000)
England	Incision (2–3 m), contraction of braided reaches, reduction of active gravel bars and channel width	High magnitude floods; agricultural improvement; local flood embankment construction; gravel extraction	Passmore et al. (1993)
	Incision up to 9 m (Northeast England), changes in channel pattern from laterally active wandering gravel-bed river to single-thread, sinuous channel	Gravel mining	Sear and Archer (1998)
Western Europe			
France	Incision (from 1 up to 10 m) (French Alps); channel narrowing and cases of pattern change, from braided to single thread	Sediment delivery decrease induced by land-use changes (cessation of wood-cutting and grazing), climatic changes, reafforestation, shortening, construction of lateral embankments, reservoir construction, gravel mining	Marston et al. (1995), Liebault and Piegay (2001, 2002), Kondolf et al. (2002)
France (Rhone River)	Incision (up to 4.5 m, between 1847 and 1952)	Channelization	Petit et al. (1996)
Spain	Incision up to 2 m during the last 20 years along many Pyrenean rivers	Land management changes (abandonment of slopes, reafforestation)	Garcia-Ruiz et al. (1997)

Table 3 (*continued*)

Region	Channel adjustments	Causes	Reference
Eastern Europe			
Poland	Incision (from 1.5 to 3 m); channel narrowing by direct river regulation works and by intense sedimentation in the inter-embankment zones	Alterations in agricultural practices and regulation of mountain streams; river-control works; gravel extraction	Wyzga (1993), Lajczak (1995), Lach and Wyzga (2002)
China			
Yellow River, Laoha River, Hanjiang River	Incision (from 0.6 to 2 m); channel pattern (from braided to single thread)	Dams	Chien (1985), Xu Jiongxin (1997)

was characterised by more intense incision and was related to the effects of instream gravel mining and the construction of two dams. No data are available for the more recent channel changes (after 1978 in the example of Fig. 4, and after 1990 for other reaches), but the incision is likely to be exhausted (in some cases, an inversion of tendency is possible).

For the Po River, the temporal trend of bed-level adjustments in Fig. 4B is perfectly similar to that just described, with two distinct well-recognisable phases of incision, the first starting slightly before (around 1885) if compared to the Arno River. However, from the analysis at other sites (Lamberti and Schippa, 1994), the first phase of incision is not always clearly evident, while the second major incision is common to all the cross sections and always starts in the period 1950–1960. Sediment mining has been identified as the main cause of this second phase of incision. Numerical simulations of bed adjustments performed by Lamberti and Schippa (1994) have predicted that bed-level lowering at Cremona will continue during the period 1993–2023 even though sediment mining is no longer allowed, with an estimated total amount of about 1.6 m.

With respect to channel narrowing, a temporal trend may be analysed for the Piave River (Fig. 5). The trend, which refers to the average channel width of a reach 115 km long, shows a dramatic narrowing during the 20th century with intensification of the process since the 1960s. The first phase of narrowing, from the beginning of the 20th century up to the 1960s, corresponds with some human intervention in the river system (construction of dams, diversions, and bank protection structures), whereas the second phase is related to a major increase of those interventions coupled, since the 1950s, with gravel mining. The most recent changes in channel width, during the 1990s, point out that narrowing could now have ceased and there could be an inversion of tendency (Surian, in press).

The previous results point out that channel incision and narrowing followed very similar temporal trends, although cases showing both trends of channel adjustment are not available for the same river.

The examples described above show that there is a strong relationship between causes (human intervention) and effects (channel adjustments) and, in all these fluvial systems, reaction times are short. As for all those cases where temporal trends are not available, it is also possible to infer a strong relationship between human interventions and channel adjustments. Most studies report that the main phase of channel adjustment started in the 1950s or at the beginning of the 1960s and was due mainly to instream sediment mining and dam construction which were carried out mainly since the 1950s (Table 2).

4.3. Styles of channel adjustments

Since different kinds of adjustment have been recognised in Italian rivers, it is now worth analysing the style of river response (if incision and narrowing both occurred or if one process was largely dominant) for different types of channel. For this purpose, a schematic, qualitative model has been derived (Fig. 6), based on those cases studies with more information on channel adjustment (Table 4). A regional classification scheme, specific for the context of Tuscany, has been recently proposed by Rinaldi (in press), and the scheme proposed here represents an

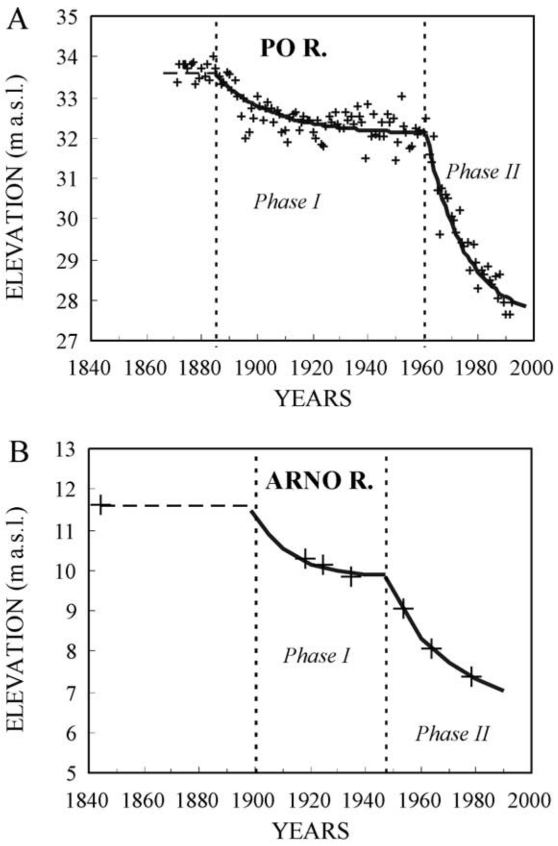

Fig. 4. Trends of bed-level adjustments. (A) Po River: minimum annual river stage at the gauging station of Cremona (modified from Lamberti and Schippa, 1994). (B) Arno River in the Lower Valdarno reach: changes in bed bottom elevation obtained from longitudinal profiles and cross sections of different years (modified from Rinaldi and Simon, 1998). Horizontal hatched line: trend of stable (dynamic equilibrium) conditions before incision; continuous curves: fitting exponential decay functions.

extension of that classification, including a wider range of cases observed in the entire Italian context. The scheme, representing initial and final (present) morphologies and not including intermediate stages of channel adjustment, groups the observed channel changes into a series of main categories of adjustment. Therefore, it should be seen as a classification scheme based on types of morphological change, such as that proposed by Downs (1995), rather than a conceptual channel evolution model.

Three initial channel morphologies have been considered, single thread (A), including both straight and sinuous-meandering channels, braided (C), and transitional morphologies (B), the latter ranging from sinuous channels with alternate bars, locally braided, to wandering (Fig. 6).

Braided rivers (case C) have adjusted predominantly through channel narrowing, with a slight or moderate incision (cases G and F), or through narrowing combined with a more significant incision (case H; e.g. several tributaries of the Po River in Piedmont, rivers in Emilia Romagna, and the Brenta River) (Table 4). In some cases, the braided morphology has been retained, but with a decrease in braiding intensity (case G; Surian, 1999), whereas in others, a dramatic change in channel morphology has taken place, from braided to wandering (cases F and H; e.g. Dutto and Maraga, 1994; Surian, 1999; Aucelli and Rosskopf, 2000).

Few examples of channel adjustments from initial transitional morphologies (case B) are available (Table 4). Some cases observed in Tuscany indicate that these channel types have adjusted through a slight or moderate incision combined with channel narrowing (case E), in some cases with a passage to a single-thread configuration (case D).

In single-thread channels (case A), the dominant adjustment has been incision, which can be moderate (i.e. up to 3 m, case D), but also very severe and greater than in braided rivers (case I; e.g. some reaches of the Po River and the Arno River in the Lower Valdarno) (Table 4). Generally, some degree of channel narrowing is associated with incision, varying from a small width reduction to a more significant one, accompanied by a drastic reduction or, in extreme case, a complete disappearance of active bars.

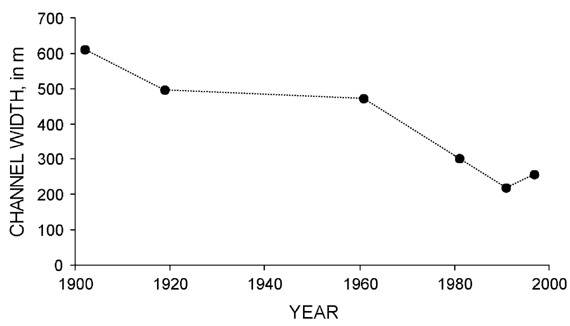

Fig. 5. Trends of average channel width in the braided reach of the Piave River (the reach is 115 km long). Channel width was measured along 94 transects on historical maps and aerial photographs (modified from Surian, in press).

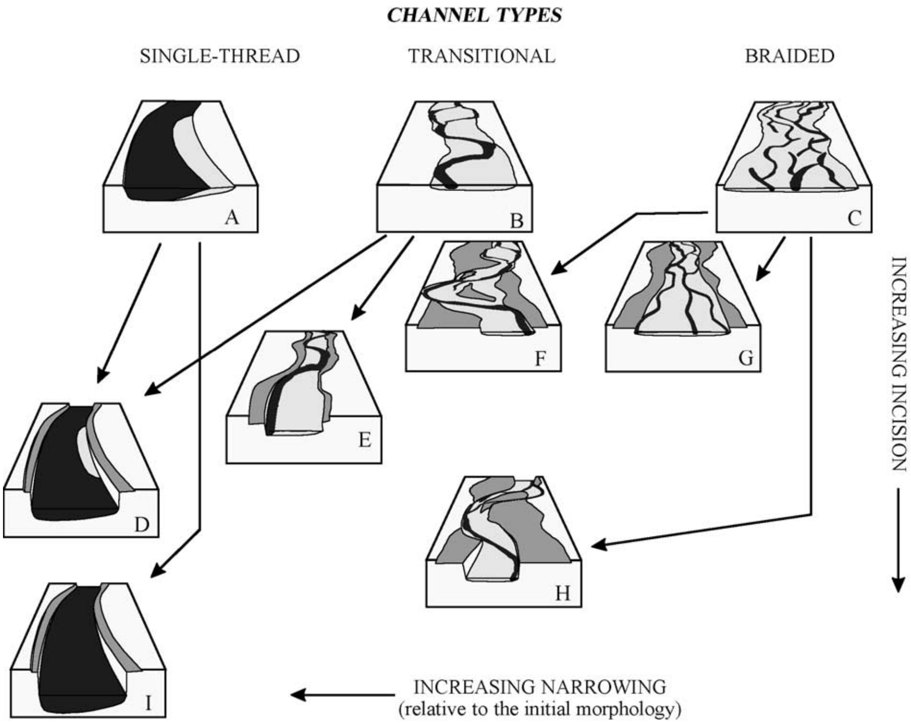

Fig. 6. Classification scheme of channel adjustments for Italian rivers. Starting from three initial morphologies (A, B and C), different channel adjustments take place due to variable degrees of incision and narrowing.

In any case, in single-thread channels, narrowing is never so intense as in braided channels.

It is worth noting that the final morphologies of this scheme (Fig. 6) do not necessarily represent the last stage of channel evolution. In fact, recent evidence in some rivers (Piave, Brenta and Taro Rivers) seems to suggest that other kinds of adjustment, such as widening and aggradation, could follow the main phase of adjustment characterised by incision and narrowing.

The scheme of dominant channel adjustment described above can be seen as an application of existing qualitative models of channel adjustments induced by changing discharge and sediment load (e.g. Schumm, 1977; Petts, 1979) to Italian rivers, considering not only the direction of channel changes induced by a disturbance but also, though still in qualitative terms, the rate of change and channel pattern adjustment. It is consistent with the model proposed by Schumm (1977), since in the case of a decrease in sediment supply, that model predicts a decrease of channel width, an increase of channel depth, a decrease of gradient, an increase of sinuosity and a decrease of meander wavelength. Future research on Italian rivers should test this scheme but also, to obtain a conceptual model that could include different stages of channel evolution, significantly increase the amount of data which are essential to define intermediate stages and other kinds of possible adjustment (e.g. widening and aggradation).

Channel evolution models (CEMs) proposed for incised rivers in loess-derived alluvium in southeastern USA (Schumm et al., 1984; Simon and Hupp, 1986) seem to have some limitations when applied to Italian rivers. In fact, CEMs do not consider possible narrowing, which is an important component of channel evolution of many Italian rivers, and predict channel widening and aggradation following a phase of incision, for which, so far, there is little evidence in Italian rivers. The main reasons for the limited applicability of existing CEMs to the Italian context appear to be: (a) different channel morphologies and bed materials (CEMs have been proposed for single-thread rivers predominantly composed of fine material, while the scheme proposed in this study is

Table 4
Channel adjustments in Italy: selected rivers used to develop the classification scheme of Fig. 6

River	Reach	Initial morphology	Incision	Narrowing	Pattern change	Type of adjustment (referring to Fig. 6)
Arno	Medium	Single thread	1–2 m	29–47%	No	From A to D
Po	Medium and lower	Single thread	1–3 m	slight–moderate	No	
Volturno	Lower	Single thread	2 m	slight–moderate	No	
Arno	Lower	Single thread	2–5 m, up to 9 m	9–20%	No	From A to I
Po	Medium and lower	Single thread	3–6 m	slight–moderate	No	
Brenta	Medium	Single thread	up to 7–8 m	slight–moderate	No	
Era, Cecina, Cornia, Orcia and Albegna (Tuscany Region)	Medium	Transitional (sinuous with alternate bars)	1–2 m	10–80%	No	From B to E
Sieve and Ombrone	Medium	Transitional (sinuous with alternate bars)	1–3 m	50–60%	From transitional to single thread	From B to D
Piave	Upper and medium	Braided	1–2 m	58–70%	No	From C to G
Several rivers in Piedmont Region (e.g. Ticino, Scrivia)	Medium	Braided	slight–moderate	10–30%	No	
Po	Upper	Braided	slight–moderate	56%	No	
Piave	Upper and medium	Braided	1–2 m	58–70%	From braided to transitional	From C to F
Orcia and Albegna (Tuscany Region)	Medium	Braided	0–2 m	60–80%	From braided to transitional	
Sesia, Cervo, Orco, Stura L. (Piedmont Region)	Medium	Braided	slight–moderate	up to 70–90%	From braided to transitional	
Sesia, Cervo, Orco, Stura L. (Piedmont Region)	Medium	Braided	locally up to 5–8 m	up to 70–90%	From braided to transitional	From C to H
Piave	Medium	Braided	2–3 m	69%	From braided to transitional	
Trigno	Upper to Lower	Braided	2–4 m	50–65%	From braided to transitional	

Table 4 (*continued*)

River	Reach	Initial morphology	Incision	Narrowing	Pattern change	Type of adjustment (referring to Fig. 6)
Secchia, Taro and other rivers in Emilia Romagna Region	Medium	Braided	3–4 m (locally up to 12 m)	moderate–severe	From braided to transitional	
Brenta	Medium	Braided	4–5 m	moderate–severe	From braided to transitional	

referred to predominantly gravel-bed rivers with initial channel morphologies also including braided rivers); (b) differences in the type of human disturbance (CEMs are referred to rivers disturbed mainly by channelization resulting in changes in channel gradient, while Italian rivers are disturbed mainly by dams and sediment mining, causing a drastic reduction of in channel sediment supply).

5. Summary and conclusions

(1) In the last century, and particularly since the 1950s to 1960s, most of the Italian rivers have experienced considerable morphological change. Two types of channel adjustment have been recognised: incision, which is commonly of the order of 3–4 m, but in some cases even more than 10 m; narrowing of the active channel, in some cases up to 50% (or even more). In some rivers, these channel adjustments, which frequently occur together, have led to changes in channel pattern from braided to wandering.

(2) The causes of these channel adjustments are represented by various types of human intervention, such as land-use changes, channelization, construction of dams, and sediment mining all of which, have been particularly severe since the 1950s. The main effect of these interventions on fluvial processes has been a dramatic reduction in sediment supply.

(3) A strong temporal relationship between human disturbance and channel adjustment exists; all these river systems exhibit short reaction time. The few rivers for which temporal trends of channel adjustment are available suggest that the adjustments (incision and/or narrowing) are more intense at the beginning (just after the disturbance), and then slow and become asymptotic.

(4) Referring to the three main types of channel morphologies (braided, transitional and single thread), a general classification scheme of channel evolution of Italian rivers has been developed. The scheme highlights both the reciprocal role of incision and narrowing and the changes in channel pattern, and their relationship with the initial channel morphology. Braided rivers adjusted predominantly through narrowing, while incision occurred but, generally, was never very severe. On the other hand, single-thread rivers adjusted mainly through bed-level lowering accompanied to a greater or less degree by narrowing. Transitional morphologies (wandering and sinuous channels with alternate bars) adjusted through a moderate incision combined with channel narrowing. Future research should be addressed to test this general scheme and to significantly increase the amount of data on morphological changes in Italian rivers. A wider database is essential for identification of other possible kinds of adjustments (e.g. widening and aggradation) and for developing the scheme proposed here in a conceptual model that could include different stages of channel evolution.

Acknowledgements

We wish to thank A. Marcus and an anonymous referee for their helpful reviews and Marisa Spagnuolo for improving our English.

References

Adamoli, L., Bertini, T., 1993. Evoluzione geomorfologica recente e processi erosivi in atto nell'alveo del F. Vomano. Proceedings of the 4° Geological Day, L'impatto degli interventi antropici sulla dinamica fluviale e possibilità di recupero ambientale. Ordine

Regionale dei Geologi dell'Abruzzo, SIGEA. Edilgrafital, S. Atto di Teramo.

Agnelli, A., Billi, P., Canuti, P., Rinaldi, M., 1998. Dinamica evolutiva recente dell'alveo del Fiume Arno. Monografia CNR-GNDCI, Pubblicazione no. 1739. Pacini Editore, Pisa, 191 pp.

Andrews, E.D., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. Geological Society of America Bulletin 97, 1012–1023.

Aquater, 1982. Regione Abruzzo. Studio generale per la difesa della costa: prima fase. Rapporto interno, S. Lorenzo in Campo.

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

Becchi, I., Paris, E., 1989. Il corso dell'Arno e la sua evoluzione storica. Acqua Aria 6, 645–652.

Biggiero, V., Fiorentino, M., Pianese, D., 1994. Evoluzione d'alveo del Fiume Volturno. XXIV Convegno di Idraulica e Costruzioni Idrauliche, vol. II. Bios, Cosenza, pp. T4-233–T4-246.

Biggiero, V., Cargnelutti, M., Fiorentino, M., Olesen, K.W., 1996. Indagini sperimentali sull'evoluzione dell'alveo del Volturno. Proceedings of the XXV Convegno di Idraulica e Costruzioni Idrauliche, vol. II. Edizioni MAF Servizi, Torino, pp. 158–169.

Billi, P., Rinaldi, M., 1997. Human impact on sediment yield and channel dynamics in the Arno River basin (central Italy). In: Walling, D.E., Probst, J.L. (Eds.), Human Impact on Erosion and Sedimentation, Proceedings of Rabat Symposium. IAHS, pp. 301–311. Publication no. 245.

Billi, P., Chiaverini, I., Ostuni, D., 1994. Studi preliminari su degradazione fisica e stabilità dell'alveo del F. Cecina. Il Quaternario 7 (1), 311–316.

Bondesan, M., with a contribution by Castaldini, D., 2001. Hydrography. In: Castiglioni, G.B., Pellegrini, G.B. (Eds.), Illustrative Notes of the Geomorphological Map of Po Plain (Italy), Suppl. Geogr. Fis. Dinam. Quat. IV, pp. 33–44.

Braga, G., Gervasoni, S., 1989. Evolution of the Po River: an example of the application of historic maps. In: Petts, G.E., Moller, H., Roux, A.L. (Eds.), Historical Change of Large Alluvial Rivers: Western Europe. Wiley, Chichester, pp. 113–126.

Bravard, J.P., Kondolf, G.M., Piegay, H., 1999. Environmental and societal effects of channel incision and remedial strategies. In: Darby, S.E., Simon, A. (Eds.), Incised River Channels: Processes, Forms, Engineering and Management. Wiley, Chichester, pp. 303–341.

Canuti, P., Cencetti, C., Conversini, P., Rinaldi, M., Tacconi, P., 1992. Dinamica fluviale recente di alcuni tratti dei fiumi Arno e Tevere. Proceedings of the Conference "Fenomeni di erosione e alluvionamenti degli alvei fluviali", University of Ancona, 14–15 October 1991, 21–35.

Canuti, P., Cencetti, C., Rinaldi, M., Tacconi, P., 1994. The fluvial dynamics of the Arno River: 2. Historical evolution of the Arno River bed. Memorie Società Geologica Italiana 48, 851–864.

Capelli, G., Miccadei, E., Raffi, R., 1997. Fluvial dynamics in the Castel di Sangro plain: morphological changes and human impact from 1875 to 1992. Catena 30, 295–309.

Capelli, G., Mazza, R., Raffi, R., Agostini, S., Di Benedetto, A., 1998. Rischio di piena e dinamica fluviale nella piana di Castel di Sangro (Appennino centrale–Abruzzo). Memorie Società Geologica Italiana 53, 585–607.

Castaldini, D., Piacente, S., 1995. Channel changes on the Po River, Mantova Province, Northern Italy. In: Hickin, E.J. (Ed.), River Geomorphology. Wiley, Chichester, pp. 193–207.

Castaldini, D., Piacente, S., Malmusi, S., 1999. Evoluzione del F. Secchia in pianura nel XIX e nel XX secolo (Province di Reggio Emilia, Modena e Mantova, Italia settentrionale). In: Orombelli, G. (Ed.), Studi geografici e geologici in onore di Severino Belloni. Glauco Brigati, Genova, pp. 169–187.

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

Castiglioni, G.B., Pellegrini, G.B., 1981b. Geomorfologia dell'alveo del Brenta nella pianura tra Bassano e Padova. In: Zunica, M. (Ed.), Il territorio della Brenta. Amm. Prov. di Padova–Università di Padova, Padova, pp. 12–32.

Cati, L., 1981. Idrografia e idrologia del Po. Pubblicazione n. 19 dell'Ufficio Idrografico del Po, 310 pp.

Cencetti, C., Conversini, P., Martani, C., Nejad Massoum, M., 1992. Considerazioni sulla dinamica fluviale del F. Tevere nel tratto Tosco-Umbro compreso tra l'invaso di Montedoglio e S. Lucia. In: Cancelli, A. (Ed.), Proceedings I Convegno Nazionale dei Giovani Ricercatori in Geologia Applicata. Ricerco Scientifica ed Educazione Permanente, CUEM, Milano, pp. 527–536. Supplemento 93.

Chien, N., 1985. Changes in river regime after construction of upstream reservoirs. Earth Surface Processes and Landforms 10, 143–159.

Church, M., 1983. Pattern of instability in a wandering gravel bed channel. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. IAS University Press, Cambridge, pp. 169–180. Special Publication no. 6.

Collier, M., Webb, R.H., Schmidt, J.C., 1996. Dams and rivers. A primer on the downstream effects of dams. U.S. Geological Survey Circular 1126 (94 pp.).

Coltorti, M., Nanni, T., Vivalda, P., 1991. La bassa valle del Fiume Musone (Marche): geomorfologia e fattori antropici nell'evoluzione della pianura alluvionale. Geografia Fisica e Dinamica Quaternaria 14, 101–111.

Conti, A., Di Eusebio, L., Dramis, F., Gentili, B., 1983. Evoluzione geomorfologica recente e processi in atto nell'alveo del Tenna (Marche Meridionali). Proceedings XXIII Congr. Geogr. It., Catania, vols. II, III, pp. 53–66.

Downs, P., 1995. Estimating the probability of river channel adjustment. Earth Surface Processes and Landforms 20, 687–705.

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

Ferguson, R.I., Werritty, A., 1983. Bar development and channel changes in the gravely River Feshie, Scotland. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. IAS University Press, Cambridge, pp. 181–193. Special Publication no. 6.

Garcia-Ruiz, J.M., White, S.M., Lasanta, T., Marti, C., Gonzalez, C., Errea, M.P., Valero, B., Ortigosa, L., 1997. Assessing the effects of land-use changes on sediment yield and channel dynamics in the central Spanish Pyrenees. In: Walling, D.E., Prost, J.L. (Eds.), Human Impact on Erosion and Sedimentation. Proceedings of Rabat Symposium S6. IAHS Press, Institute of Hydrology, Wallingford, pp. 151–158. Publication no. 245.

Gentili, B., Pambianchi, G., 1987. Morfogenesi fluviale ed attività antropica nelle Marche centro-meridionali. Geografia Fisica e Dinamica Quaternaria 10, 204–217.

Govi, M., Turitto, O., 1993. Processi di dinamica fluviale lungo l'asta del Po. Acqua Aria 6, 575–588.

Graf, W.L., 1977. The rate law in fluvial geomorphology. American Journal of Science 277, 178–191.

Gregory, K.J., Park, C., 1974. Adjustment of river channel capacity downstream from a reservoir. Water Resources Research 10, 870–873.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms 26, 31–62.

Knighton, A.D., 1991. Channel bed adjustment along mine-affected rivers of northeast Tasmania. Geomorphology 4, 205–219.

Knighton, A.D., Nanson, G.C., 1993. Anastomosis and continuum of channel pattern. Earth Surface Processes and Landforms 18, 613–625.

Kondolf, M.G., 1995. Managing bedload sediment in regulated rivers: examples from California, USA. In: Costa, J.E., Miller, A.J., Potter, K.W., Wilcock, P. (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology. Geophysical Monograph, vol. 89. American Geophysical Union, pp. 165–176.

Kondolf, M.G., 1997. Hungry water: effects of dams and gravel mining on river channels. Environmental Management 21 (4), 533–551.

Kondolf, G.M., Piegay, H., Landon, N., 2002. Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. Geomorphology 45, 35–51.

Lach, J., Wyzga, B., 2002. Channel incision and flow increase of the upper Wisloka River, southern Poland, subsequent to the reafforestation of its catchment. Earth Surface Processes and Landforms 27, 445–462.

Lajczak, A., 1995. The impact of river regulation, 1850–1990, on the channel and floodplain of the Upper Vistula River, Southern Polonia. In: Hickin, E.J. (Ed.), River Geomorphology. Wiley, Chichester, pp. 209–233.

Lamberti, A., 1993. Le modificazioni recenti verificatesi nell'asta principale del Po e problemi connessi. Acqua Aria 6, 589–592.

Lamberti, A., Schippa, L., 1994. Studio dell'abbassamento dell'alveo del Fiume Po: previsioni trentennali di abbassamento a Cremona. Navigazione Interna (Suppl. of nos. 3–4, 23 pp.).

Leopold, L.B., 1973. River channel change with time: an example. Geological Society of America Bulletin 84, 1845–1860.

Lewin, J., Weir, M.J.C., 1977. Morphology and recent history of the lower Spey. Scottish Geographical Magazine 93, 45–51.

Liebault, F., Piegay, H., 2001. Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France. Geomorphology 36, 167–186.

Liebault, F., Piegay, H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surface Processes and Landforms 27, 425–444.

Macklin, M.G., Passmore, D.G., 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., Komar, P.D. (Eds.), Gravel Bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, CO, pp. 257–278.

Maraga, F., 1989. Ambiente fluviale in trasformazione: l'alveo-tipo pluricursale verso un nuovo modellamento nell'alta pianura padana. Proceedings of the International Congress on Geoengineering "Suolosottosuolo", Torino, 27–30 September 1989, 119–128.

Maraga, F., 1992. Riduzione del campo di attività fluviale e disponibilità di sedimento nei tratti d'alveo pluricursali: casi di studio nella Pianura Padana. Proceedings of the Conference "Fenomeni di erosione e alluvionamenti degli alvei fluviali", University of Ancona, 14–15 October 1991, 51–62.

Maraga, F., 1999. Tagli di meandro sul Fiume Po. Geologia dell'Ambiente 7 (1), 3–7.

Maraga, F., Mortara, G., 1981. Le cave per inerti lungo i corsi d'acqua: rapporti con la dinamica fluviale. Bollettino Associazione Mineraria Subalpina 18 (3–4), 385–395.

Marchetti, M., 2002. Environmental changes in the central Po Plain (northern Italy) due to fluvial modifications and anthropogenic activities. Geomorphology 44, 361–373.

Marston, R.A., Girel, J., Pautou, G., Piegay, H., Bravard, J.P., Arneson, C., 1995. Channel metamorphosis, floodplain disturbance and vegetation development: Ain River, France. Geomorphology 13, 121–131.

McEwen, L.J., 1989. River channel changes in response to flooding in the Upper River Dee catchment, Aberdeenshire, over the last 200 years. In: Beven, K., Carling, P.A. (Eds.), Floods: Hydrological, Sedimentological and Geomorphological Implications. Wiley, Chichester, pp. 219–237.

Ministero dei Lavori Pubblici—Servizio Idrografico, 1980. Dati caratteristici dei corsi d'acqua italiani. Istituto Poligrafico dello Stato, Roma. Pubblicazione no. 17.

Morandini, G., 1957. Idrografia d'Italia. L'Italia Fisica. Touring Club Italiano, Milano, pp. 271–283.

Natoni, E., 1944. Le piene dell'Arno e i provvedimenti di difesa Felice Le Monnier, Firenze.

Neill, C.R., 1973. Hydraulic and morphologic characteristics of Athabasca River near Fort Assinboine. Alberta Research Council, Edmonton, Hway River Engng. Div. Rep. REH/73/3, 23 pp.

Passmore, D.G., Macklin, M.G., Brewer, P.A., Lewin, J., Rumsby, T., Newson, M.D., 1993. Variability of late Holocene braiding in Britain. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geological Society, London, pp. 205–229. Special Publication no. 75.

Pellegrini, M., Perego, S., Tagliavini, S., 1979a. La situazione morfologica degli alvei degli affluenti emiliani del Po. Convegno di Idraulica Padana, Parma, 19–20 October 1979. 9 pp.

Pellegrini, M., Perego, S., Tagliavini, S., Toni, G., 1979b. La situazione morfologica degli alvei dei corsi d'acqua emiliano-romagnoli: stato di fatto, cause ed effetti. Proceedings of the Conference "La programmazione per la difesa attiva del suolo

e la tutela delle sue risorse: i piani di bacino idrografico", Modena, 28–29 June 1979, 169–195.
Perego, S., with collaboration of Tellini, C., 1994. Evoluzione naturale e antropica del medio e basso corso del F. Taro (Prov. di Parma). Acta Naturalia de L'Ateneo Parmense 30, pp. 5–27.
Petit, F., Poinsart, D., Bravard, J.P., 1996. Channel incision, gravel mining and bedload transport in the Rhone river upstream of Lyon, France (canal de Miribel). Catena 26, 209–226.
Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Progress in Physical Geography 3, 329–362.
Piest, R.F., Elliott, L.S., Spomer, R.G., 1977. Erosion of the Tarkio drainage system, 1845–1976. Transactions, American Society of Agricultural Engineers 20, 485–488.
Rinaldi, M., 1995. Dinamica di un alveo fluviale antropizzato: il Fiume Sieve (Toscana). Unpublished PhD Thesis, University of Perugia, 223 pp.
Rinaldi, M., 2002. Recent channel adjustments in alluvial rivers of Tuscany, Central Italy. Earth Surface Processes and Landforms (in press).
Rinaldi, M., Rodolfi, G., 1995. Evoluzione olocenica della pianura alluvionale e dell'alveo del Fiume Sieve nel Mugello (Toscana). Geografia Fisica e Dinamica Quaternaria 18, 57–75.
Rinaldi, M., Simon, A., 1998. Bed-level adjustments in the Arno River, Central Italy. Geomorphology 22, 57–71.
Rinaldi, M., Simon, A., Billi, P., 1997. Disturbance and adjustment of the Arno River, Central Italy: II. Quantitative analysis of the last 150 years. In: Wang, S.S.Y., Langendoen, E.J., Shields, F.D. (Eds.), Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation, Restoration. Center for the Computational Hydroscience and Engineering, University of Mississippi, Oxford, MS, pp. 601–606.
Rumsby, B.T., Macklin, M.G., 1994. Channel and floodplain response to recent abrupt climate change, the Tyne basin, northern England. Earth Surface Processes and Landforms 19, 499–515.
Rusconi, A., 1994. Acqua. Conoscenze su risorsa e utilizzo. Editoriale Verde Ambiente, Roma 303 pp.
Sabato, L., 1994. Human impact on alluvial environments in Calabria (southern Italy). Memorie Società Geologica Italiana 48, 935–941.
Sabato, L., 1999. Le fiumare: corsi d'acqua ad alto rischio ambientale. Geologia dell'Ambiente 1, 8–13.
Schumm, S.A., 1977. The Fluvial System. Wiley, New York 338 pp.
Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. Incised Channels: Initiation, Evolution, Dynamics, and Control Water Resources Publication, Littleton, CO 200 pp.
Sear, D.A., Archer, D., 1998. Effects of gravel extraction on stability of gravel-bed rivers: the Wooler Water, Nothumberland, UK. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B. (Eds.), Gravel-Bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, CO, pp. 415–432.
Simon, A., 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14, 11–26.
Simon, A., Hupp, C.R., 1986. Channel widening characteristics and bank slope development along a reach of Cane Creek, West Tennessee. In: Subitzsky, S. (Ed.), Selected Papers in Hydrologic Sciences. U.S. Geological Survey Water-Supply Paper, vol. 2290, pp. 113–126.
Simon, A., Rinaldi, M., 2000. Channel instability in the loess area of the Midwestern United States. Journal of American Water Resources Association 36 (1), 133–150.
Surian, N., 1999. Channel changes due to river regulation: the case of the Piave River, Italy. Earth Surface Processes and Landforms 24, 1135–1151.
Surian, N., 2002. Impatto antropico sulla dinamica recente del Fiume Piave (Alpi orientali). Geografia Fisica e Dinamica Quaternaria (in press).
Tacconi, P., Billi, P., 1990. Indagine sull'abbassamento del fiume Po. Analisi morfometrica dello stato attuale e tendenza evolutiva dell'alveo. Po AcquAgricolturAmbiente, vol. II: L'alveo e il delta. Società Editrice Il Mulino, Bologna, pp. 15–111.
Tazioli, G.S., 1982. Trasporto solido e fenomeni erosivi. Proceedings Convegno Conclusivo P.F. Conservazione del Suolo. CNR, Roma, pp. 129–134.
Thorne, C.R., 1999. Bank processes and channel evolution in the incised rivers of North-Central Mississippi. In: Darby, S.E., Simon, A. (Eds.), Incised River Channels: Processes, Forms, Engineering and Management. Wiley, Chichester, pp. 97–121.
Tonini, D., 1983. Elementi di idrografia ed idrologia Edizioni Libreria Cortina, Padova.
Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., Bretschko, G., Gurnell, A.M., Petts, G.E., Rossaro, B., 1999. A reference river system for the Alps: the "Fiume Tagliamento". Regulated Rivers: Research and Management 15, 63–75.
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 pp.).
Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286 (83 pp.).
Winterbottom, S.J., 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. Geomorphology 34, 195–208.
Wyzga, B., 1993. River response to channel regulation: case study of the Raba River, Carpathians, Poland. Earth Surface Processes and Landforms 18, 541–556.
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 22, 953–965.