Il Quaternario
Italian Journal of Quaternary Sciences
***21**(1B), 2008 - 267-278*

RECENT MORPHOLOGICAL CHANGES OF THE RIVER PANARO (NORTHERN ITALY)

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ABSTRACT: Castaldini D. & Ghinoi A., *Recent morphological changes of the River Panaro (Northern Italy)* (IT ISSN 0394-3356, 2008).
This paper describes the morphological changes of the River Panaro from the 19th century to date and provides the relationships between human activity and stream geomorphology. The studies were carried out using historical documents and maps, aerial and satellite imagery taken on various dates, digital treatment of maps and orthophotographs and field surveys.
The River Panaro has a catchment basin of 1,784 km^2 and collects waters from the central section of the Northern Apennines. It starts from the confluence of the Scoltenna and Leo torrents and flows down through Modena Apennines for some 63 km. It then makes its way across the Po Plain for 85 km until it joins the River Po. In the Po Plain it flows across two distinct sectors with different morphological characteristics: in the upper sector the river runs deep in the alluvial plain, whereas in the mid-lower part it is elevated above the level of the plain, contained within artificial embankments.
In the Panaro valley, from the 1930s to the 1950s, the river showed a braided pattern which occupied almost the entire flat valley floor. Important changes occurred later, due to the downcutting and narrowing of the active channel, which have continued until the present day.
In the upper part of the plain., the river occupied a large depression with a braided riverbed at the beginning of the 19th century. In the following periods there was an increase of human interventions along the river (construction of embankments, walls and groynes), in order to reclaim surrounding areas from flooding and turn highwater beds into farming land. This led to narrowing in several stretches of the riverbed, although it still maintained a braided pattern until the 1930s. Subsequently, after the 1950s, the braided pattern became canalised and deepened and the shape of the longitudinal profile changed from a hyperbola-type curve to a step-type one.
The channel changes in the Apennines and in the upper part of the plain were mainly due to gravel excavation along the riverbed. Quarrying activities stopped after a law was passed in the early 1980s and, at the same time, fluvial barrages were constructed. On the whole, these hydraulic works reduced the bed load, increasing water erosion power downstream. As a result, the deepening process has continued and a new terrace level has formed in the past 30 years. Channel adjustments have led to the change from a braided channel pattern to a transitional one.
In the mid-lower part of the plain, the river length has been reduced by 10-11 km (which corresponds to about 13% of its length in this plain sector) by artificial meander cut-offs carried out since the 19th century to reduce flood hazard. In this way, along long stretches of its course, the River Panaro has assumed the aspect of an artificial watercourse. Since the cut-offs did not adequately reduce flood hazard, "flow regulation systems" were constructed in the area east of Modena.
It can therefore be stated that the morphology and evolution trend of the River Panaro have been conditioned by direct and indirect human activities over the past two centuries, especially after the 1950s, and that its evolution is similar to what has been recorded in other Italian rivers

RIASSUNTO: Castaldini D. & Ghinoi A., Recenti cambiamenti morfologici del Fiume Panaro (Italia settentrionale) *(IT ISSN 0394-3356, 2008).*
Il presente articolo descrive i cambiamenti morfologici del Fiume Panaro a partire dal 19° secolo e illustra le relazioni tra l'attività antropica e la morfologia fluviale. Lo studio è stato realizzato analizzando documenti storici, carte, fotoaeree e immagini satellitari di vari periodi, tramite GIS, ed eseguendo rilevamenti sul terreno.
Il F. Panaro, che ha un bacino di 1.784 km^2, raccoglie le acque dal settore centrale dell'Appennino Settentrionale e le convoglia nel F. Po dopo aver attraversato l'Appennino Modenese, dove nasce dalla confluenza dei torrenti Leo e Scoltenna, per 63 km e la Pianura Padana per 85 km. Nella Pianura Padana il F. Panaro si sviluppa in due settori con diverse caratteristiche morfologiche: nel settore di alta pianura scorre incassato mentre nel settore di media-bassa pianura scorre pensile tra argini artificiali.
Nel tratto vallivo, dagli anni '30 agli anni '50 del secolo scorso, il fiume denotava un alveo a canali intrecciati che occupava quasi l'intero fondovalle. Importanti cambiamenti sono intervenuti successivamente in seguito a processi di approfondimento e restringimento dell'alveo che sono continuati sino ad oggi. Nel settore di alta pianura, all'inizio del 19° secolo, il fiume occupava una larga depressione con un tracciato a canali anastomizzati. A partire dalla fine di questo secolo, l'aumento degli interventi antropici lungo il fiume (costruzione di argini, muri e pennelli) realizzati per proteggere il territorio dalle esondazioni ed acquisire terreni per l'agricoltura, ha condotto ad un restringimento dell'alveo sebbene abbia mantenuto un tracciato a canali intrecciati sino agli anni '30. Successivamente agli anni '50 l'alveo si è approfondito e canalizzato; il profilo longitudinale è passato dalla classica curva a forma di iperbole a quella a gradini.
I cambiamenti morfologici dell'alveo del F. Panaro sia nel tratto vallivo sia nel tratto di alta pianura sono dovuti principalmente all'attività estrattiva lungo l'alveo, cessata per legge a partire dai primi anni '80, e alla relativa costruzione di briglie. Le briglie hanno ridotto il trasporto solido incrementando in tal modo l'energia della corrente nei tratti a valle di queste strutture. Il risultato è stato che il processo di approfondimento d'alveo è continuato e un nuovo terrazzo si è formato nell'ultima trentina d'anni. L'evoluzione del fiume ha portato ad un cambiamento d'alveo da una morfologia a canali intrecciati ad una transizionale.
Nel settore di media e bassa pianura, la lunghezza del fiume è stata ridotta di circa 10-11 km (che corrispondono a circa il 13% del percorso in questo settore) in seguito a tagli di meandri realizzati sin dal 19° secolo per ridurre il pericolo di esondazioni; in questo modo il F. Panaro ha assunto in lunghi tratti l'aspetto di corso d'acqua artificiale. Poiché i tagli di meandro non hanno ridotto tale pericolo, come testimoniato dalle alluvioni verificatesi dopo la loro realizzazione, ad Est di Modena sono state costruite delle casse di espansione.
In definitiva si può affermare che la morfologia del F. Panaro e la sua evoluzione sono stati condizionati direttamente ed indirettamente da interventi antropici succedutisi negli ultimi secoli, ed in particolare a partire dagli anni '50, e che la sua evoluzione è simile a quella riscontrata in altri fiumi italiani.

Keywords: Morphological changes, anthropogenic interventions, River Panaro, Northern Apennines, Po Plain.

Parole chiave: Cambiamenti morfologici, interventi antropici, Fiume Panaro, Appennino settentrionale, Pianura Padana.

1. INTRODUCTION

It is well known from many studies that in the past few centuries human activity has influenced channel changes and stream morphology all over the world (see LEOPOLD, 1973; PETTS, 1979; HICKIN, 1983; GREGORY, 1987; LAJCZAK, 1995; LÓCZY, 1997; LIEBAULT & PIEGAY, 2002; HERGET *et al*. 2007).

As regards Italy, channel changes along the River Po (the longest watercourse in Italy, 652 km), occurring during the 20th century, are, at least in part, a consequence of river engineering (see GOVI & TURITTO, 1993; CASTALDINI & PIACENTE, 1995). The same can be said for the streams Enza (PEREGO, 1988), Tidone (FARAVELLI & MESSINA, 1997), Trebbia and Vara (RINALDI *et al*., 2005) in the Northern Apennines and rivers Dora Riparia (FRANCESCHETTI *et al*., 1990), Piave and Brenta (SURIAN, 1999; SURIAN *et al*., 2005) in the Alps.

A general outline of the main channel adjustments that have occurred in 27 Italian rivers during the past 100 years was given by SURIAN & RINALDI (2003).

This paper illustrates the morphological changes of the River Panaro (Fig. 1) from the 19th century to date and discusses the relationships between human activity and stream morphology. As regards the evolution of the river in previous centuries, see PELLEGRINI M. (1969) and CASTALDINI (1989).

Studies concerning the recent evolution of the R. Panaro go back to 30-40 years ago. In detail, PELLEGRINI & ROSSI (1967) notice that after a period of flooding or equilibrium, the stretch of the R. Panaro, from the lower mountain area as far as the city of Modena, has undergone an erosional phase, starting around 1950, which has caused a lowering of the riverbed. Quarrying activities within the riverbed have been identified as the main cause of this process, since the authors have noted how the location of quarries correspond to the river stretches subject to erosion; the onset of this process also coincides with gravel and sand extraction on a wider scale. In addition, PELLEGRINI M. (1969) notices that some morphological features of the R. Panaro, as well as of the nearby R. Secchia, tend to have changed: riverbed narrowing, stretching up of the river courses and rejuvenation of the equilibrium profile. These changes are mainly ascribed to artificial causes, such as meander cutoffs and excavation of building materials from riverbeds.

PELLEGRINI M. *et al*. (1979) describe the evolution which has taken place in the past decades in the tributaries of the River Po in the Emilia Region. These authors show that the R. Panaro is certainly one of the rivers which have undergone major changes due to anthropogenic activities: intense gravel excavation from the riverbed up to the mid-mountain area, subtraction of vast highwater areas for farming practices, construction of embankments in the upper plain area etc.

After these studies, though, no significant investigations have been carried out on the evolution of the R. Panaro.

Yet, the simple comparison between the actual morphological situation and the Regional Technical Map (CTR) of the Emilia-Romagna Region, at a 1:10,000 scale (which is commonly used a as topographic basis for territorial studies) clearly shows that hydrography has undergone remarkable changes also in the past 30 years. In fact, the general representation of morphology, hydrography and vegetation in the CTR second edition corresponds to the situation between 1973 and 1979.

Therefore, on the one hand this paper aims to be an updating of previous investigations and, on the other hand, it reconstructs the morphological changes of the R. Panaro by means of a detailed examination of cartographic and remote sensing documents introduced into a GIS.

In addition, this research may be considered as a contribution to the outline of channel adjustments in Italian rivers, since the River Panaro was not considered in the list by SURIAN & RINALDI (2003).

2. GEOGRAPHICAL, GEOMORPHOLOGICAL AND GEOLOGICAL SETTING

The River Panaro has a catchment basin of 1,784 km^2 and collects waters from the central section of the Northern Apennines. It originates in the mid-Modena Apennines, at the confluence of the streams Scoltenna and Leo (altitude of about 320 m a.s.l.) and flows down through Modena Apennines for some 63 km (Fig. 1). After flowing along a flat-bottomed valley, it reaches the Po Plain at the foot of the Apennine chain near Vignola (altitude of 110 to 100 m a.s.l.). In the plain, the River Panaro flows across two distinct sectors with different morphological characteristics: in the upper sector of the plain, upstream of Modena, the river runs deep in the alluvial plain, whereas in the mid-lower part of the plain, it flows elevated over the plain, contained within artificial embankments, as far as the confluence with the River Po (altitude of about 10 m a.s.l.).

The study area is situated in a temperate climatic zone (Type "Cfa" of Köppen's classification). From the pluviometric viewpoint, it has annual average precipitation ranging from about 1200 mm in the mountain sector to some 700 mm in the plain sector, with seasonal peaks concentrated in autumn and spring, and minimum values in summer (BOCCOLARI *et al*., 1998). Therefore, the hydrological regime of the R. Panaro is characterised by two very similar peaks in the spring (March-April) and autumn (November), and a minimum in summer (August).

The main geological units forming the Modena Apennines are as follows (BETTELLI *et al*. 1989):

1) Tuscan Units, made up of Tertiary deep-water turbidites, continuously cropping out along the Apennine chain axis.
2) Ligurian Units made up of deep-sea sediments including Jurassic Ophiolites followed by thick sequences of Cretaceous to Eocene calcareous or terrigenous turbidites.
3) The mainly terrigenous epi-Ligurian sequences of the Middle Eocene to the Late Messinian, unconformably resting on the previously deformed Ligurian Units. The epi-Ligurian sequences and the Ligurian Units are exposed in the mid-Apennines.
4) The belt of Plio-Quaternary marine terrigenous deposits unconformably overlying the Ligurian Units and the epi-Ligurian sequences cropping out at the Apennine margin and dipping under the alluvial deposits of the Po Plain.

The Modena plain lies at the foot of the Apennine chain which is still in full evolution. At the Apennine margin the streams reaching the plain have built up alluvial fans which extend to the north. Since they overlap each other, they can be regarded as part of a continuous belt of coarse alluvial deposits spreading all along the Apennine foot. Remains of old fans appear at the foot of the Apennine chain, and are characterised by paleosols and Pleistocene aeolian covers (loess), terraced upstream and buried downstream by the Holocene alluvia. Many ridges formed by the local evolution of ancient streams depart from the foot of the fans, their patterns revealing the recent migration of these rivers. North of the city of Modena, depressed areas are located in between the fluvial ridges. The superficial alluvial deposits in the study area were mainly formed during the Holocene; their particle-size distribution ranges from gravel to clay (Gasperi *et al*., 1989; Castiglioni *et al*., 1997; Castiglioni & Pellegrini G.B., 2001).

The plain/Apennine boundary is purely morphological as the Apennine structures continue towards NNE as far as the River Po, buried under the Quaternary continental sediments. Fault or fold displacements have also involved these deposits (Pieri & Groppi, 1981; Di Dio, 1998).

3. METHODS AND DATA SOURCES

The study was carried out according to the traditional methods used in geomorphology (bibliographic research; research on historical documents and maps, morphological analysis by means of interpretation of aerial photographs and satellite imagery taken in various periods, morphological field-survey of the present-day river course) as well as methods concerning the digital treatment carried out on maps, aerial photographs and satellite images.

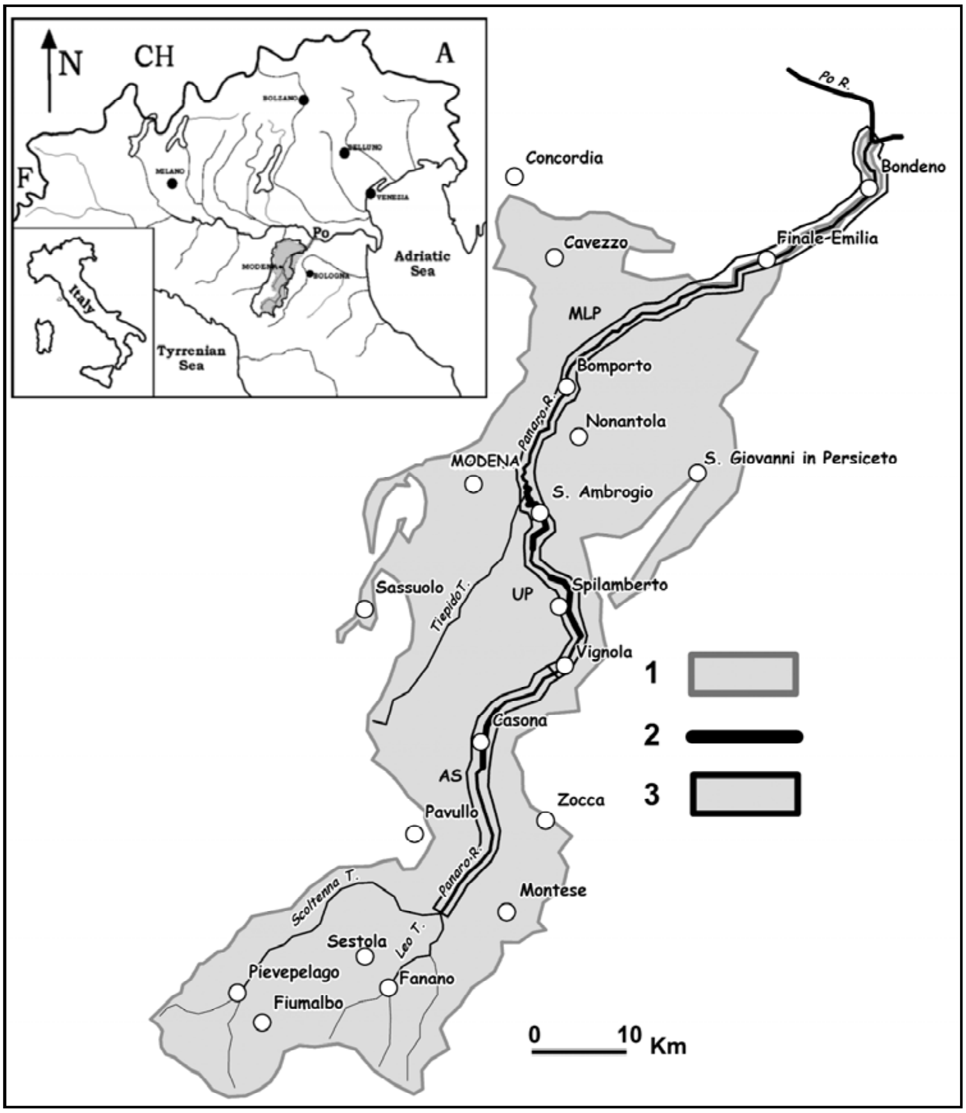


Fig. 1 - Location of the study area. Legend: 1) basin of the River Panaro; 2) stretches of the River Panaro shown as examples near Casona, Spilamberto and S. Ambrogio; 3) Sectors of the River Panaro (AS: Apennine sector; UP: upper part of the plain; MLP: mid-lower part of the plain).

Ubicazione dell'area di studio. Legenda: 1) bacino idrografico del Fiume Panaro; 2) tratti del F. Panaro illustrati come esempi presso Casona, Spilamberto e S. Ambrogio; 3) Settori del F. Panaro (AS: Settore Apenninico; UP: alta pianura ; MLP: medio-bassa pianura).

The use of digitisers and image processing in geomorphology and especially in fluvial process mapping has been illustrated in several works (see Leys & Werritty, 1999; Westaway *et al*., 2000; Wright *et al*., 2000).

The technique consists in the elaboration of maps of fluvial features (morphological maps), starting from topographic maps, aerial photographs and satellite images.

As the River Panaro course has been shown accurately on maps only since the 19th century, this study has focused on the evolution of the last two centuries. The documents listed in Tab. 1 have been considered.

The topographic maps of the study area, corresponding to different years, have been rasterised in the first phase. Due to their early date of publication, some maps did not present a georeferenced base; it has therefore not been possible to introduce them into a GIS.

Subsequently, they were scanned and georeferenced within the ArcGis GIS. In this way it was possible to measure, with acceptable approximation, the changes taking place in the riverbeds.

As regards aerial photographs and satellite images, the method used consisted in interpretation and digital treatment using photogrammetry techniques, which afterwards allowed the georeference of geomorphological information.

A field-survey of the present-day course has been carried out in order to update the features of the stream through geomorphological mapping.

Table 1 - Documents considered in this study. IGM: Italian Military Geographic Institute; GAI: Aerial Italian Group; CTR: Regional Technical Maps (CTR) of Emilia-Romagna Region; RER: Emilia-Romagna Region;

Documenti utilizzati nel presente studio: IGM: Istituto Geografico Militare Italiano; GAI: Gruppo Aereo Italiano; CTR: Carta Tecnica della Regione Emilia -Romagna; RER: Regione Emilia - Romagna.

Type of document	Age	Scale/Resolution	Note
Carandini maps	1821 - 1828	1:50,000	Colour
IGM maps	1881 - 1894	1:25,000	Black & White
IGM maps	1911 - 1914	1:25,000	Black & White
IGM maps	1933 - 1935	1:25,000	Black & White
GAI aerial photographs	1954 - 1955	1:33,000	Black & White
RER aerial photographs	1973	1:15,000	Black & White
CTR maps	1973 - 1978	1:10,000	Black & White
RER aerial photographs	1978	1:20,000	Colour
CTR maps	1985 - 1986	1:10,000	Black & White
Volo Italia aerial photographs	1988 - 1989	1:70,000	Black & White
Volo Italia 2000 orthophotographs	2000	1 m	Colour
Quick Bird satellite orthophotographs	2003	0.6 m	Black & White

4. MORPHOLOGICAL CHANGES OF THE RIVER PANARO SINCE THE 19TH CENTURY

In this part the morphological changes of the River Panaro since the 19th century to date are illustrated in detail. They were reconstructed on the basis of the documents listed in table 1.

This research and its conclusions were supported by analyses carried out on the entire course of the River Panaro. The description will be made in chronological sequence, making a division between three sectors: Apennine sector (AS); upper part of the plain (UP); mid-lower part of the plain (MLP). In particular, this paper will focus on the illustration of the channel changes occurring on the most significant partial stretches: Casona in the AS sector, Spilamberto in the UP sector and St. Ambrogio in the MLP sector (Fig. 1).

4.1 Channel changes in the Apennine sector

In the Apennine sector the comparison between topographic maps, aerial and satellite imagery and topographic elements currently visible in the field has highlighted substantial changes along the River Panaro valley from the first half of the 20th century (the oldest map examined for this sector are the 1933-35 IGM maps).

In particular, in the 1930s the River Panaro bed showed a braided pattern which occupied almost the entire flat valley bottom; terraces (of small extent) were present only locally, and no significant human dwellings existed (Fig. 2A). A very similar situation can be found in the 1954-1955 aerial photographs. Important changes are evident in more recent documents. In fact, in the 1970s the river abandons its braided pattern and the river channel gets deeper and narrower, as testified by the formation of side-valley terraces used for farming and human settlements (Fig. 2B). Some check dams can be found along the river course.

The downcutting and narrowing of the active channel has continued until the present day. In detail, besides considerable growth of human activities on the river terraces, the river has undercut its bed forming a new terrace (Fig. 2C). This is about 1 m higher than the riverbed and reaches several meters at the Apennine margin, just downstream of check dams where the bedrock crops out. This terrace, characterized by dense vegetation, is already visible and developed in the 1988/89 aerial photographs, while it is not present in those of the 1970s. Therefore, its formation is likely to date back to the end of the seventies and the beginning of the 1980s.

4.2 Upper part of the plain

In the first half of the 19th century the R. Panaro occupied a depression in the alluvial plain with a vast extension of deposits and showed a braided pattern (Fig. 3A). It is not possible to evaluate the depth between the alluvial plain and the river channels because of lack of information on altimetry in the Carandini (1821-1828) maps. The first modest excavations of gravel from the riverbed go back to that period (Lombardini, 1865).

At the end of the 19th century (Fig. 3B), the river flowed within a depression which, as assessed on the basis of the few altitude points shown, was around 1-2 m lower than the surrounding ground surface. The watercourse still showed braided channels. Of course, the trend of the low-water channels had undergone changes compared with the previous period. In this period, the first systematic human interventions along the river (embankments, walls and groynes) were carried out in order to reclaim the surrounding areas from flooding and turn highwater beds into farming land.

Significant channel changes were recorded in the first half of the 20th century (Fig. 3C and 3D), caused by further construction of walls and embankments. This had two consequences: the first was a narrowing of the riverbed (Fig. 3D); the second was a result of the first and consisted in a huge aggradation process in the active channel (Fig. 4A). Nevertheless, the R. Panaro maintained its braided pattern. Other important human works carried out in this period were the excavation of small gravel pits at the sides of the river.

The analysis of the channel changes for the second half of the 20th century is much better docu-

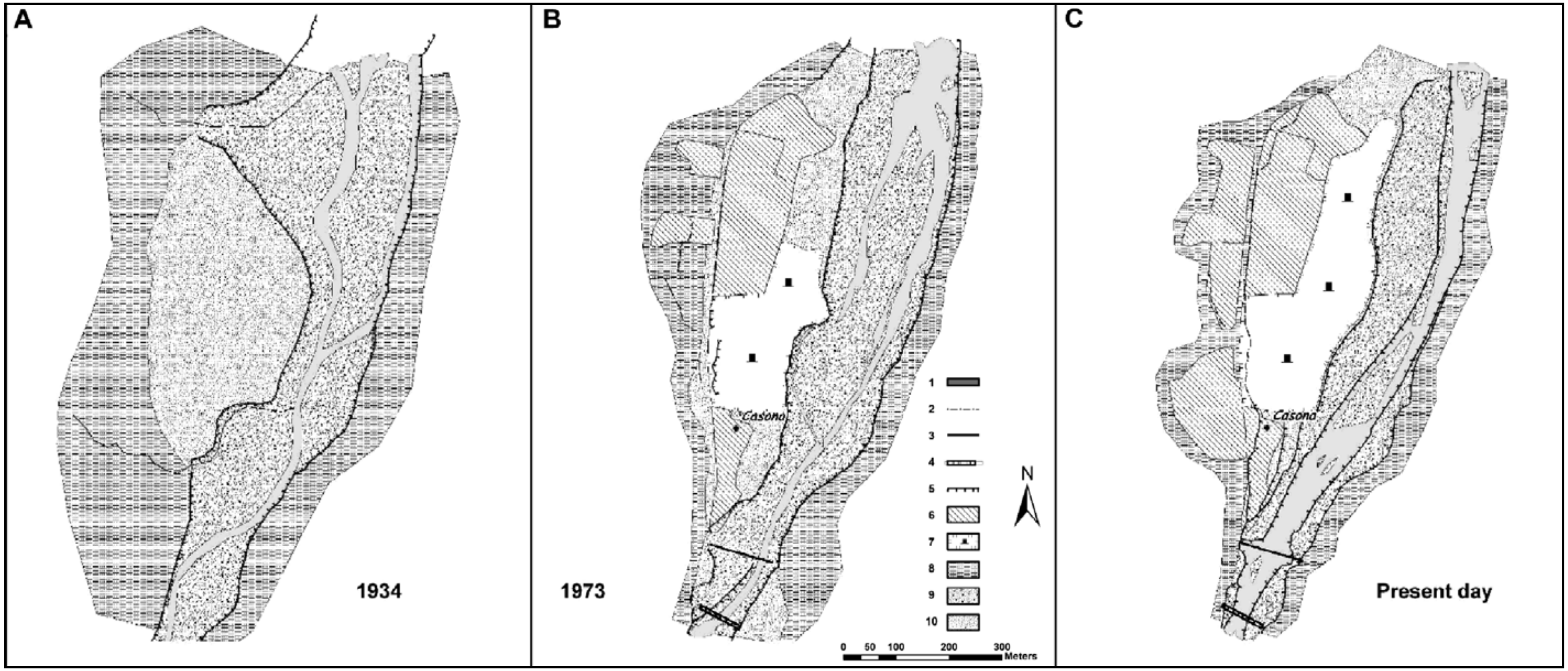


Fig. 2 - Geomorphological sketch of the R. Panaro in its flat valley floor, near Casona (Apennine sector) in the 1930s (elaborated from the 1934 IGM map), in the1970s (elaborated from the 1978 CTR map and aerial photographs) and at present (elaborated from the 2003 Quick-Bird satellite imagery and field survey). Legend: 1) River Panaro; 2) artificial scarp; 3) check dam; 4) bridge; 5) fluvial scarp; 6) built-up area; 7) quarrying activity area; 8) valley slope; 9) active alluvial deposits; 10) dormant/inactive alluvial deposits.

Carta geomorfologica schematica del fondovalle del F. Panaro presso Casona (settore appenninico) negli anni '30 (elaborata sulla base della cartografia IGM del 1934), negli anni '70 (elaborata sulla base della CTR e delle fotografie aeree del 1978) e nel presente (elaborata sulla base delle immagini del satellite Quick Bird del 2003 e di rilevamenti sul terreno). Legenda: 1) F. Panaro; 2) scarpata artificiale; 3) briglia; 4) ponte; 5) scarpata fluviale; 6) area antropizzata; 7) area interessata da attività estrattiva; 8) versanti ; 9) depositi alluvionali attivi; 10) depositi alluvionali quiescenti/inattivi.

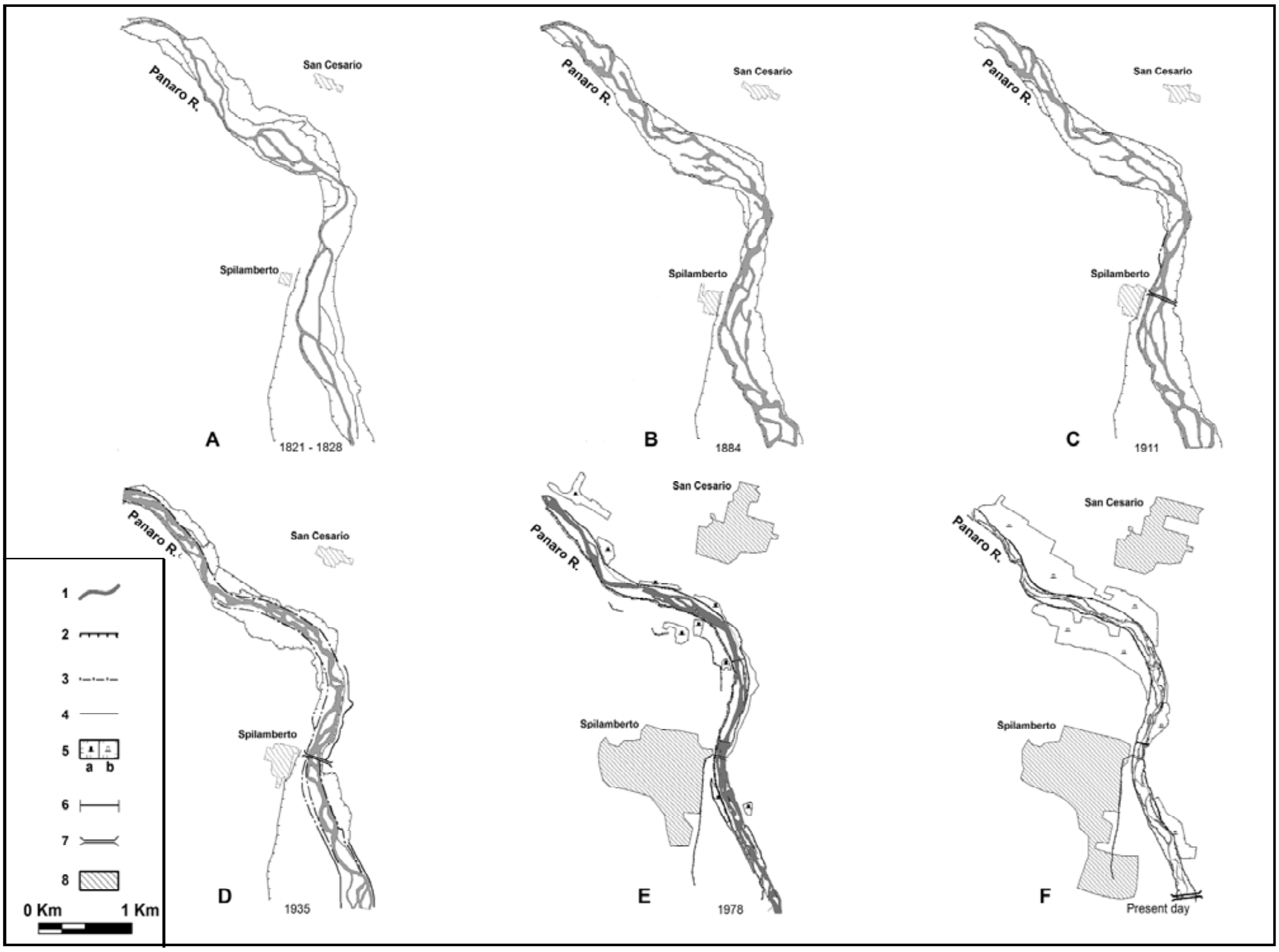


Fig. 3 - Morphological sketch of the R. Panaro in the upper part of the plain near Spilamberto. Legend: A) first half of 19th century (elaborated from Carandini, 1821-28 maps); B) second half of 19th century (from the 1884 IGM map); C) 1911 and D) 1935 (from the 1911 and 1935 IGM maps); E) second half of 20th century (from the 1978 CTR maps and aerial photographs); F) present situation (from the 2003 Quick-Bird satellite imagery and field surveys); 1) River channel; 2) fluvial scarp; 3) artificial scarp; 4) artificial embankment; 5) quarrying area (a: active; b: abandoned); 6) check dam; 7) bridge; 8) built-up area.

Carta geomorfologica schematica del F. Panaro nell'alta pianura presso Spilamberto. Legenda: A) prima metà del 19° secolo (elaborata sulla base della cartografia Carandini, 1821-28; B) seconda metà del 19° secolo (dalla cartografia IGM del 1884; C) 1911 e D)1935 (dalla relativa cartografia IGM); E) prima metà del 20° secolo (dalla CTR e da fotoaeree del 1978); F) attuale (dalle immagini del satellite Quick-Bird del 2003 e da rilevamenti sul terreno); 1) alveo fluviale; 2) scarpata fluviale; 3) scarpata artificiale; 4) argine artificiale; 5) area di cava (a: attiva; b: abbandonata); 6) briglia; 7) ponte; 8) area antropizzata.

mented thanks to CTR Maps, new IGM maps, aerial photographs, satellite imagery and field surveys. They show important human interventions along the river which have influenced stream morphology (Fig. 3E).

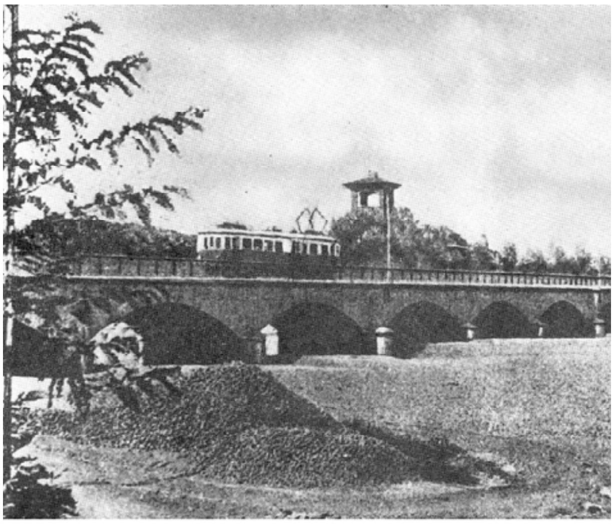
In this period, quarrying activities and fluvial barrages influenced channel changes. These factors produced the same effects on the river: deepening and canalisation of the riverbed.

After the 1950s, the considerable expansion of urban and industrial areas required an increase of building materials and therefore of quarrying activities; these activities were concentrated inside and in proximity of the riverbed. The first effect of excavations inside the riverbed was the removal of the superficial coarse alluvial deposits which brought to the surface alluvial material of different particle size that was easily eroded by the stream.

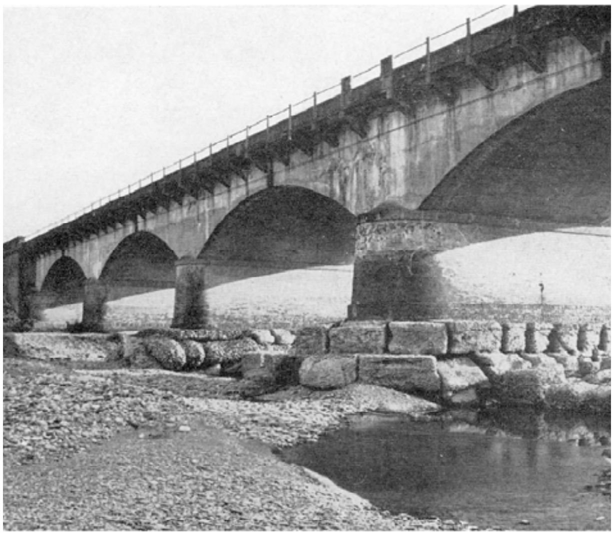
This resulted in increased deepening of the riverbeds and a new channel morphology, which undermined or damaged bridge piers at Marano, Vignola, Spilamberto and S. Donnino (motorway bridge). Deepening of over 6 m was recorded near Spilamberto bridge (Fig. 4B).

In order to overcome these unforeseen problems, various check dams were constructed. However, these hydraulic structures have stopped riverbed deepening only locally. In fact, acting as local base levels, these barrages have favoured aggradation processes and the re-deposition of the alluvial cover only in the upstream tracts (Fig. 4C). On the whole, check dams have reduced bed load, thus increasing water erosion power downstream. The result was that deepening processes have continued in the stretches downstream of the barrages.

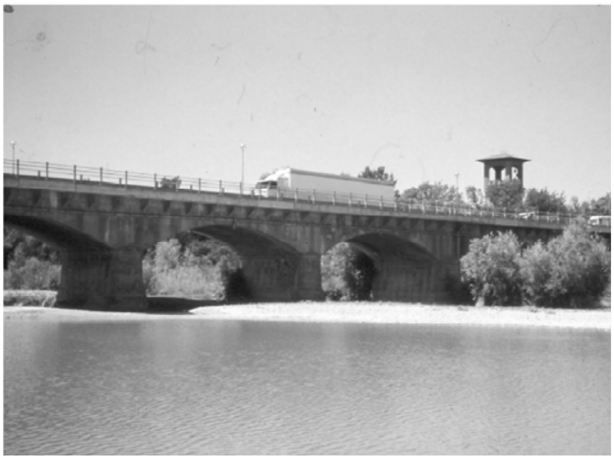
Riverbed deepening also introduced an important modification. In fact, the reduction of lateral movements caused by downcutting produced a change in morphology from a braided to a wandering pattern. The deepe-



A) 1930



B) 1967



C) 2004

Fig. 4 - The R. Panaro channel at the bridge of Spilamberto: A) in the 1930 circa (by PELLEGRINI M. *et al*., 1979); B) in the 1967 (by PELLEGRINI M. & ROSSI, 1967); C) in the 2004 (photo by D. Castaldini).

L'alveo del F. Panaro presso il ponte di Spilamberto. A) nel 1930 circa (da PELLEGRINI M. et al. *1979); B) nel 1967 (cfr. by PELLEGRINII M. & ROSSI, 1967); C) nel 2004 (foto D. Castaldini).*

ning process was particularly marked in the 1970s. Since the 1980s the river has been flowing within a single riverbed (or with very few channels) and the process of downcutting has continued accompanied by a marked narrowing of the active channel (Fig. 3F). The deepening, together with the construction of check dams, has also modified the longitudinal profile of the riverbed from a hyperbola-type curve to a step-type one (Fig. 5).

Quarrying activities, located at the sides of the river, have irreversibly altered the natural morphological features of the depression and have dismembered or destroyed the hydraulic defence works constructed since the end of the 19th century. In this way the boundary depression has changed from a "natural" type to an "artificial" type. In the present day, the R. Panaro shows a transitional pattern, mainly confined within a single flow channel still characterised by intense downcutting.

In order to solve the impacts of quarrying activities on the landscape, some measures have been taken by the province administration board in recent decades. Within the framework of a strategy for environmental protection and improvement, local administrations have concentrated their efforts on reclaiming quarrying areas. In this way many of them have become Nature protection areas where industrial activities are no longer permitted (PROVINCIA DI MODENA, 2003).

In short, especially after the 1950s, the River Panaro switched from a braided riverbed to a canalised course subject to considerable deepening and narrowing. This trend has lasted up to the present. For instance, near Spilamberto, a deepening of 8-9 m and a narrowing of about 390 m (56%) of channel width has been recorded in the past 120 years (Fig. 6).

4.3 Mid-lower part of the plain

In this part of the plain, in the first half of the 19th century, the R. Panaro showed several, well developed meanders, with a bend radius of up to 200 m; it also showed alternate channel width: from 80 m (slightly winding stretches) up to 500 m wide (with large highwater beds). In this sector the river flowed within artificial embankments which were "uplifted and strengthened" during this period (LOMBARDINI, 1865); this means that floods were a hydrological hazard.

At the end of the 19th century, the R. Panaro still showed several meanders, even if it was shortened at the beginning of 1889 by about 5.5 km between Finale Emilia and Bondeno. Moreover, some meanders appear to have been straightened near its outlet, with a reduction of the watercourse length of about 2 km. In this way the R. Panaro was shortened by about 7-8 km.

The meander cutoffs were mainly carried out in order to reduce the highwater level along the straightened reach, where the sinuous course caused a slowdown of the flow, and therefore to mitigate flood hazard. In fact the River Panaro, in the 19th century, flooded several times (in 1812, 1813, 1842, 1852, 1862, 1868, 1872 and 1887) (CASTALDINI, 2006). These interventions proved ineffective, as shown by floods which later occurred: after the artificial cutoffs and before the end of the century, the R. Panaro flooded again in October 1889 and October 1897. Of course, meander cutoffs did not eliminate flood hazard but only transfer-

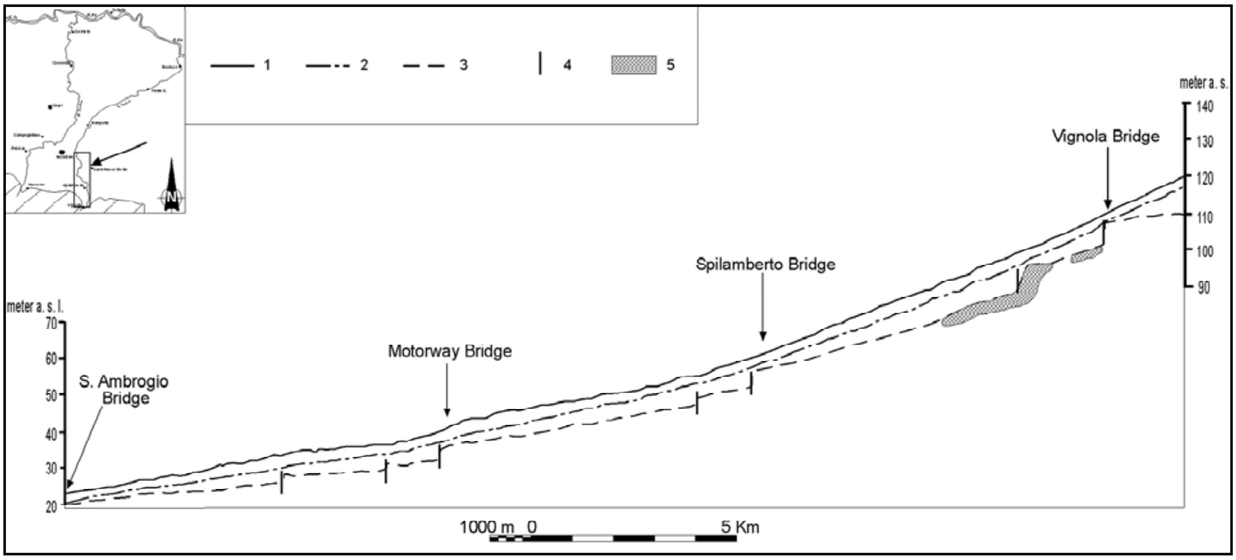


Fig. 5 - Modification of the longitudinal profile of the R. Panaro in the upper part of the plain (between the Vignola Bridge and S. Ambrogio Bridge). Legend: 1) Longitudinal profile of the plain level in 1973-1978 (elaborated from the CTR Maps at a 1:10,000 scale); 2) longitudinal profile of the R. Panaro channel in the 1960s (from Pellegrini M. & Rossi,I, 1967); 3) longitudinal profile of the R. Panaro channel in 1978 (elaborated from the CTR maps at 1:10,000 scale); 4) check dam: 5) bedrock outcrop. The vertical scale is exaggerated with respect to the longitudinal scale.

Modificazione del profilo longitudinale del fiume Panaro tra Vignola e il ponte di Sant'Ambrogio sulla Via Emilia. Legenda: 1) profilo longitudinale del livello della pianura nel 1973-1978 (elaborato dalle CTR a scala 1:10.000); 2) profilo longitudinale dell'alveo del Panaro negli anni '60 (da Pellegrini M. & Rossi,, 1967); 3) profilo longitudinale dell'alveo del Panaro nel 1973-1978 (elaborato dalle CTR a scala 1:10.000); 4) briglia: 5) affioramento del substrato. La scala delle altezze è esagerata rispetto a quella delle lunghezze.

red the problem to the river reach downstream of the cutoffs.

In the first half of the 20th century, the course of the R. Panaro remained practically identical to the course of the 19th century. In this century the R. Panaro flooded several times in the area of Modena: in 1928, 1939, 1949, 1951, 1952, 1956, 1960, 1964, 1966, 1969, 1972 and 1973 (Castaldini, 2006). In order to reduce flood hazard, the latest meanders cutoff was made in the early 1970s when the R. Panaro was shortened by four meanders (a length of about 3 km) near St. Ambrogio, east of Modena (Fig. 7 and 8). But also this work proved ineffective, as testified by the flood which struck the territory of Finale Emilia in November 1982.

Therefore, a “flow-regulation system” was planned and constructed to the East of Modena, at the boundary between the upper and middle sectors of the plain, adjacent to the river course, in order to better control hydrogeological hazard (Castaldini & Pellegrini M., 1989).

The flow regulation system is located where R. Panaro flows inside its natural depression, that is approximately 2 km wide, previously used as quarrying areas (Fig. 8). This structure, operating since 1985, consists principally of a regulating dam built across the riverbed and a storage basin (which allows the store of about 24 million m^3 of water) almost completely confined by embankments about 6 km long and 4 to 5 m high. During low-water periods, the water is discharged through mouths located in the regulating dam at the same level as the riverbed. During highwater events, no more than a limited amount could be discharged through the dam's mouths. Excess water is stored upstream of the regulating dam, producing an increase in water level and regulating the flow downstream. The flow regulation system was completed in November 1999. The most

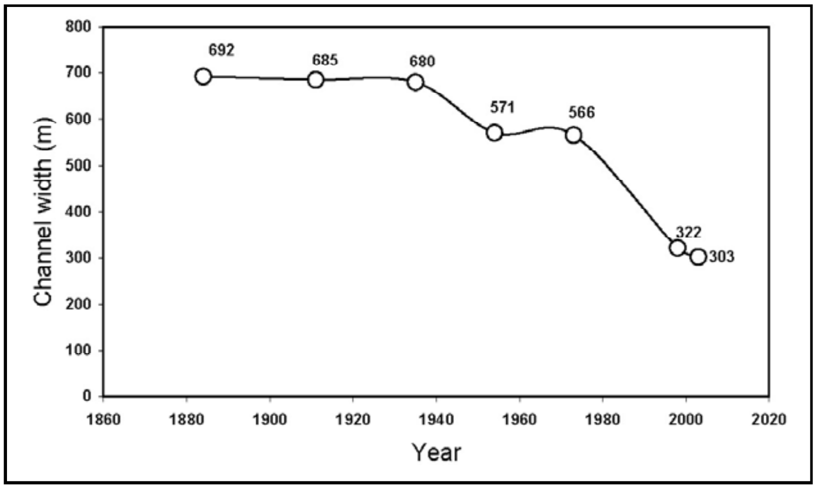


Fig. 6 - Trends of the channel width in the stretch of the R. Panaro in the upper part of the plain near Spilamberto since the end of 19th century (the stretch is about 4 km long). Channel width was measured on maps, aerial and satellite images as indicated in Tab. 1.

Variazioni della larghezza dell'alveo del F. Panaro nell'alta pianura presso Spilamberto dalla fine del 19° secolo (il tratto d'alveo è lungo circa 4 km). La larghezza è stata misurata su documenti cartografici, fotoaeree e immagini satellitari indicati in Tab. 1.

Fig. 7 - Aerial photograph of the R. Panaro near S. Ambrogio, east of Modena. It flows from the left (south) to the right (north); meander cut-offs carried out in the early 1970s are evident (photo by D. Castaldini).

Foto dall'aereo del F. Panaro presso S. Ambrogio, a est di Modena. Il fiume scorre da sinistra (Sud) verso destra (Nord); risultano evidenti I tagli di meandro effettuati agli inizi degli anni '70 (foto D. Castaldini).

important function of this large hydraulic work is to reduce flood peaks; that is, they intervene on a very limited water capacity but with a high hydrometric level. Similar structures were also built on other watercourses of the Emilia-Romagna Region, such as the Secchia River to the west of Modena.

The above mentioned deepening processes of the upper part of the plain have affected also the stretches north of Modena, where the R. Panaro flows as an elevated river within artificial embankments. Moreover fluvial erosion takes place in correspondence with concave banks, causing their undermining which in some places leads to bank retreat and soil slips. In order to curb bank erosion, rockfill protection structures have been set up along many reaches. In several reaches both the banks of the R. Panaro are covered by thick riverine vegetation which reduces the water flow section with an increase in hydraulic hazard.

5. CONCLUSIONS

The morphological changes of the R. Panaro from the 19th century to date were reconstructed on the basis of reliable and detailed maps, aerial and satellite imagery and field surveys. The morphological changes were examined in three distinct sectors, which are the flat bottom valley in the Apennine sector, the upper part of the plain, where the river cuts through the alluvial plain, and the mid-lower plain sector, where it flows as an elevated water course within artificial embankments.

In the 19th century all anthropogenic interventions described by CASTIGLIONI & PELLEGRINI G.B. (2001) are furthermore accentuated in the Po Plain. A new phenomenon, consisting of ever increasing highwater events takes place starting from 1705, as recorded by instrumental measurements: each highwater event tends to overcome the maximum hydrometric levels of the previous one (for R. Panaro, see LOMBARDINI, 1865). Floods are disastrous and the economies of pre-Unity Italian states and subsequently of the newly founded Kingdom of Italy were at the end of their resources. The establishment of land reclamation agencies in this country is the consequence of this situation.

Among the hydraulic engineers of that period a very heated discussion started about the causes of this phenomenon. According to LOMBARDINI (1865), the causes were to be found exclusively in deforestation. Other experts, though, noticed that also the riverbed bottom altitudes were progressively increasing.

All the rivers' alluvial deposits, which will be removed in the second half of the 20th century, can be ascribed to the end of 16th century-first half of 20th century period. The climatic meaning of this considerable depositional phase is probably related to the Little Ice Age (see FERRARI & PELLEGRINI M., 2007 and annexed bibliography).

Research aimed to show how the deepening process of the R. Panaro, which became very evident in the 1960s, is an alarming phenomenon which has undermined or damaged bridges, piers and weirs (PELLEGRINI M. & ROSSI, 1967; PELLEGRINI M., 1969; PELLEGRINI M. *et al*., 1979) and has continued up to recent decades. In fact, it has been demonstrated that a new terrace level was formed in the past 30 years, both in the Apennine sector and in the upper part of the plain.

PELLEGRINI M. & ROSSI (1967) believed that the tendency of watercourses to deepen their riverbeds might have a positive aspect since, by increasing the river section, it also reduced the dangers of flooding even in the stretch where the river is elevated over the surrounding plain. Subsequently, though, PELLEGRINI M. *et al*. (1979) showed that the new type of riverbed had caused a change in water runoff dynamics (decrease of highwater events with tendential increase of hydrometric levels but unchanged integral flow rate). According to these authors, this new hydraulic regime, which was a direct consequence of the altered morphological conditions of the river, should be considered the cause of the frequent inundations occurring in the 1960s and 1970s near Modena (1960, 1964, 1966, 1969, 1972 and 1973).

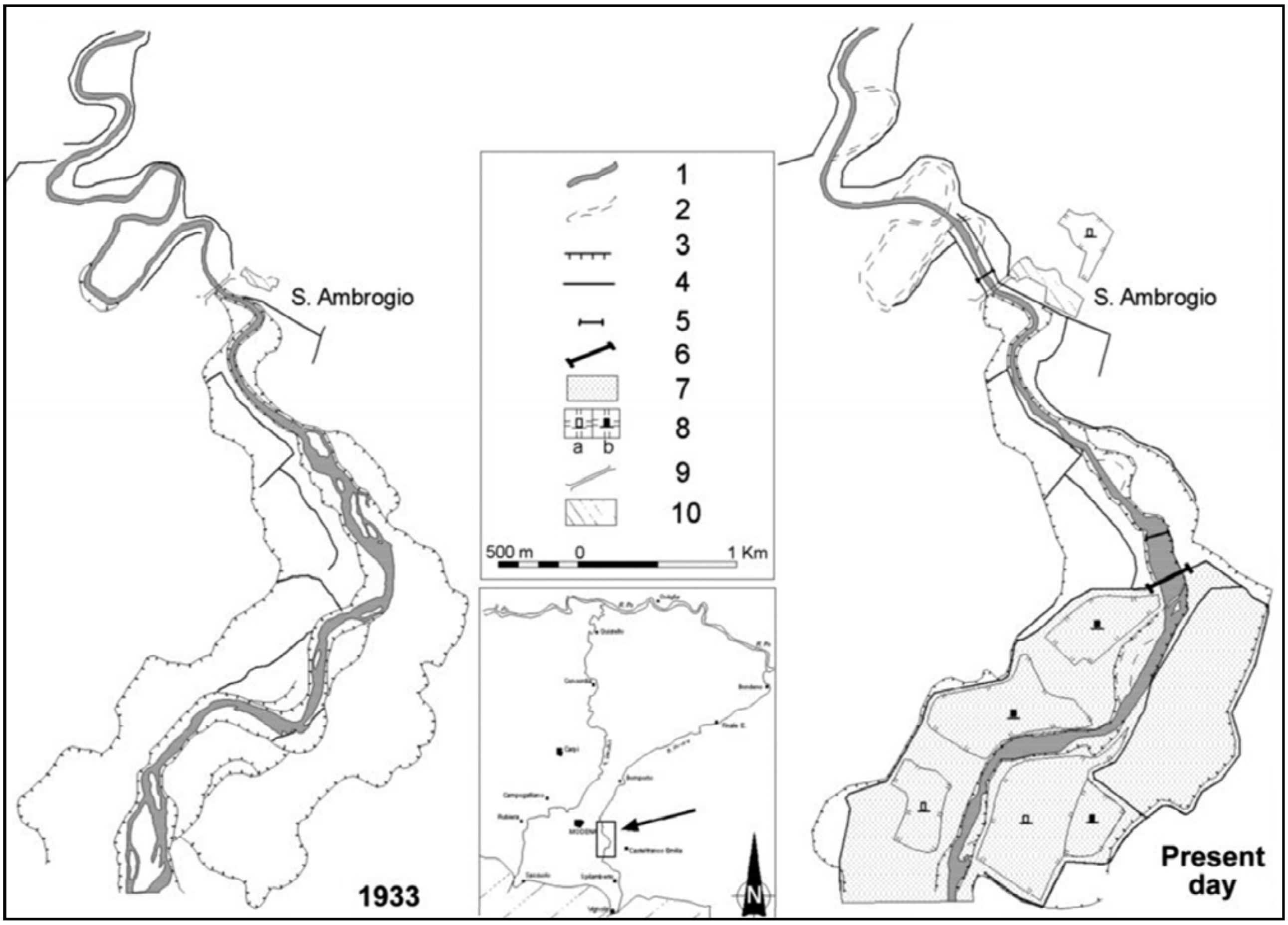


Fig. 8 - Morphological sketch of the R. Panaro near S. Ambrogio (east of Modena) in the 1930s (elaborated from the 1933 IGM map) and at present (elaborated from the 2003 Quick-Bird satellite image and field survey). To be noted: in the northern sector, the meander cut-offs carried out in the early 1970s and, in the southern sector, the flow regulation system. Legend: 1) River channel; 2) paleo-riverbed; 3) fluvial scarp (in some stretches remodelled by man's intervention); 4) artificial embankment; 5) check dam; 6) dam of the flow regulation system; 7) storage basin of the flow regulation system; 8) depleted quarry area (a: dry floor; b: flooded floor); 9) bridge; 10) built-up area.

Carta geomorfologica schematica del F. Panaro presso S. Ambrogio, (est di Modena) negli anni '30 (elaborata sulla base della cartografia IGM del 1934) e nel presente (elaborata sulla base delle immagini del satellite Quick Bird del 2003 e di rilevamenti sul terreno). Legenda: 1) alveo fluviale; 2) Paleoalveo; 3) scarpata fluviale (in qualche tratto rimodellata dall'antropizzazione) ; 4) argine; 5) briglia; 6) manufatto regolatore della cassa di espansione; 7) bacino d'esondazione della cassa di espansione; 8) area di cava abbandonata (a: a fondo asciutto; b: a fondo allagato); 9) Ponte; 10) area antropizzata.

In order to overcome the downcutting process, various check dams were constructed along the river, but this solution proved ineffective as witnessed by the fact that this phenomenon has continued also in the last three decades.

At present new types of barrages allowing the passage of bed load are being designed. They are equipped with small hydroelectric plants located along the sides of the river in order to exploit the morphological step of these check dams for the activation of water turbines.

In general, channel adjustments since the 19^{th} century have led to a change in the channel pattern from braided to transitional. This evolution is similar to what has been recorded by SURIAN & RINALDI (2003; 2004) in other Italian rivers.

As for the causes of these modifications - mainly limited to the past 50 years - we fully agree with the remarks of the previously mentioned authors and the early authors who studied the River Panaro. According to their views, the effects of natural causes (such as uplift of the Apennine chain, subsidence of the alluvial plain, climate changes) seem to have played a minimal role, since they have had only gradual repercussions on the evolution of watercourses. On the contrary, emphasis is given to anthropogenic activities affecting the riverbeds (such as quarrying and construction of check dams).

Nevertheless, other causes for changes are:

i) hydraulic non-equilibrium between new flow rates (concentration and increase of Qmax) and canalised riverbed;
ii) along long stretches water stream erodes weaker bedrock formations with lower roughness index (marine clays of the Plio-Pleistocene cycle, alluvial marine clays, previously underlying or juxtaposed to gravel deposits; highly weathered gravels with matrix of Pleistocene deposits; see GASPERI *et al*., 1989).
iii) absence of bed load for the hydraulic arrangement of the basin in the 1950 - to date period.

In the mid-lower plain sector, the present course of the R. Panaro was conditioned by the meander cutoffs carried out in the late 19th century and at the beginning of the 1970s. In this study it was calculated that meander cutoffs reduced the length of the R. Panaro by about 10-11 km. These length reductions correspond to about 13% of its length in this plain sector before cutoffs (Tab. 2). Thus, like other rivers of the mid-lower plain south of the R. Po, R. Panaro has taken on the appearance of an artificial watercourse for long stretches, owing to a decrease of its width and length and the disappearance of its highwater beds. These morphological changes, combined with undercutting processes, which are active also in the mid-lower plain sector, have obviously caused variations of the river's hydrometric characteristics (runoff time, height and flow rate of highwater events).

Since the cutoffs did not reduce flood hazard adequately, which was the primary goal of these interventions, "flow regulation systems" were constructed in the area east of Modena along the river. Obviously, also the construction of the flow-regulation system has contributed to modifying both the natural morphology of the riverbeds and water runoff dynamics.

According to investigations carried out and data collected, it can be forecast that the R. Panaro riverbed will take some more decades before finding a new equilibrium following the changes that have affected it over 50 years; although the ever-present anthropogenic activities will probably never allow a new equilibrium to be fully attained.

It can be stated that the present morphology and evolution trend of the River Panaro have been conditioned by direct and indirect human intervention over the past centuries, especially since the 1950s. Therefore, human action as a morphogenetic agent has been once more confirmed.

Table 2 -Length reduction of the R. Panaro, following meander cut-offs, in the mid-lower sector of the plain where it flows elevated over the plain within artificial embankments.

Riduzione in lunghezza del F. Panaro in seguito ai tagli di meandro nella media-bassa pianura dove il fiume scorre pensile tra argini artificiali.

Age of cutoffs	
19th century	*7.5 km*
20th century	*3 km*
Total reduction	*10.5 km*
Present-day length	*70 km*
Length before cutoffs	*80.5 km*
Reduction (%)	*13%*

ACKNOWLEDGMENT

Research was carried out in recent years in co-operation with the Land Reclamation Syndicate of Burana-Leo-Scoltenna-Panaro, and within the framework of CERG (Centre Européen sur les Risques Géomorphologiques, Strasbourg, France) research activities and FAR Project Research of the Earth Science Department. The Authors are grateful to N. Surian (Padova University), M. Rinaldi (Firenze University) and M. Pellegrini (Modena and Reggio Emilia University) for their critical review of this paper and to A.M. Lord and G. Tosatti (Modena and Reggio Emilia University) for the revision of the English text.

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Ms. ricevuto il 30 gennaio 2008
Testo definitivo ricevuto il 5 maggio 2008

Ms. received: January 30, 2008
Final text received: May 5, 2008