

How multiple anthropic pressures may lead to unplanned channel patterns: Insights from the evolutionary trajectory of the Po River (Italy)

A. Brenna^{*}, S. Bizzi, N. Surian

Department of Geosciences, University of Padova, Padova, Italy

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ABSTRACT

The aim of this work is to investigate how a sequence of anthropic pressures that occurred on a river sector can generate mutual feedback that determines unplanned channel configurations. We reconstructed the evolutionary trajectory and historical human impacts on a sector of the Po River (Italy). A training scheme was implemented from the 1930 s to the 1950 s along a multi-thread sector of the river to ensure its navigability by bent navigation structures. Other human activities were carried out from the 1960 s to the 1970 s for the exploitation of sediment and water resources, inducing a dramatic reduction in sediment availability along the Po River. Our results show an evolution from multi-thread configurations in the 1950 s to single-thread configurations at the beginning of the 21st century, accompanied by remarkable channel narrowing (-50 %). This evolution has been interpreted as follows: Riverbed lowering occurred exclusively in the main channel during the 1970 s, and the training works enhanced the disconnection and deactivation of the secondary channels that were located behind navigation structures. This localised incision of the active channel (-4 m) was determined by the sediment starvation. In the absence of navigation structures, it is likely that the channel adjustments would have been less profound. The current single thread sinuous pattern is the result of these two anthropic pressures, with the training works defined as an anthropic predisposing condition and the sediment starvation recognised as the triggering factor generating morphological modifications. The channel rearrangement that resulted from these processes can accordingly be defined as unplanned, that is, not designed but caused by diachronous impacts acting on the same river sector for different purposes. The lesson learned from the Po River suggests that anthropogenic, unplanned channel configurations can represent a common type of riverscape in densely inhabited areas significantly affecting recovery potential and future geomorphological trajectories.

1. Introduction

Fluvial systems in many regions of the Earth have been extensively affected by anthropic pressures carried out for a range of socioeconomic reasons over the last century (Jain et al., 2016; Wohl, 2020; Surian, 2022). Anthropic pressures on rivers can be classified into two categories. The first typology of anthropic pressures considered in this work is represented by the human activities carried out in a river channel or at the catchment scale, for the exploitation of natural resources, such as the construction of dams for energy production, in-channel sediment mining and land use changes. These activities can affect sediment supply and/or flow regimes, determining variations in sediment fluxes and, consequently, contributing to morphological adjustment of river channels (Kondolf, 1997). Several works analysed in detail the effect of modifications induced by dam closures (Petts and Gurnell, 2005), gravel

extraction (Kondolf, 1994) and land use changes (Scorpio and Piégay, 2021) on rivers, recognising the common occurrence of three main morphological effects on the dramatic reduction of sediment availability and fluxes that occurred during the Anthropocene (Syvitski and Kettner, 2011): bed-level lowering, active channel narrowing and reduction in planform morphological complexity.

The second group of anthropic pressures includes river training works, representing a range of measures used to control channel morphology and processes and regulate water flow (Blazewski et al., 1995). Training works involve direct design of a river course and its channel morphology, which are artificially modified through a series of engineering interventions, such as guide banks and embankments, the construction of groynes, bed dredging and artificial meander cutoffs (Surian, 2005; Wang et al., 2007). These works are aimed at inhibiting the vertical and lateral mobility of a channel to reduce flooding risk and

^{*} Corresponding author.

E-mail address: andrea.brenna@unipd.it (A. Brenna).

allow river navigation under low discharge conditions. Functioning of different training schemes were analysed by numerous engineering studies (Belz et al., 2001; Markovic, 2012; Kakati et al., 2022), and the geomorphological community investigated the hydromorphological effects of training works for different river types and physiographic contexts (Erskine, 1990; Surian, 2005; Wang et al., 2007; Mosselman, 2020). Although the river responses to these interventions are case-specific, the negative effects were revealed in numerous case studies (Erskine, 1992; Korpak, 2007; Kidová et al., 2021). These responses include loss of geomorphic diversity, reduction in lateral connectivity between active channels and floodplains and, in general terms, degradation of river morphodynamic conditions.

“Alluvial rivers formed in the sediments that they have transported and deposited” (Church, 2006) are systems particularly prone to changing their architecture in response to modifications in the balance between sediment supply and water flow energy (Lane, 1955; Grant et al., 2013). All the aforementioned anthropic pressures can induce modifications of fluvial dynamics spanning various spatial scales (from hydraulic to landscape units) and temporal scales (from a few years to centuries), which can mutually interact and overlap the climatic and geological factors that control the river evolution at longer intervals (Antoine et al., 2000). Several alluvial rivers flowing in densely inhabited areas worldwide have been affected by multiple anthropic pressures over the last century (Syvitski and Kettner, 2011; Best, 2019; Downs and Piégay, 2019), which caused a broad spectrum of modifications affecting channel morphology and, in general terms, riverscapes (Chin et al., 2014; Wohl, 2020; Surian, 2022).

Because of the aforementioned mutual interactions and overlaps between various factors and responses, the interpretation of cause (i.e., anthropic impacts)-and-effect (i.e., channel modifications) relationships in fluvial systems affected by multiple human pressures is often a challenging task (Downs et al., 2013; Downs and Piégay, 2019; Brenna et al., 2021). The aim of this work is to investigate how a sequence of diachronous river training works and multiple human activities carried out for the exploitation of sediment and water resources that acted – and interacted – over time on a single river sector can generate mutual feedbacks that determine unplanned anthropogenic channel patterns. Interestingly, such morphological configurations, in the absence of a deep understanding of their formative processes, may be misinterpreted as directly and exclusively caused by the training work interventions (i.e., designed river configurations) or even as natural occurrences. To address this topic, we analysed a long sector (123 km) of the Po River (Italy), where training works for navigation seem to control the sinuous channel configuration. By a detailed reconstruction of morphological changes and human activities during the last 100 years, we aim to obtain a better understanding of the driving factors and their role on the past and present morphodynamics of this fluvial system.

2. Po River case study

2.1. General setting

The Po River, with a total length of 651 km and a drainage area of 75,000 km², is the largest river in Italy. The average daily discharge at the catchment outlet is 1470 m³s⁻¹ (Zanchettin et al., 2008; Montanari, 2012), with maximum annual discharges recorded at the gauging station of Pontelagoscuro ranging from 2400 to 9520 m³s⁻¹ over the period 1940 – 2010 (Fig. 1). The course of the Po River is commonly divided into four parts (Marchi et al., 1995): the Upper Po (from its sources to the confluence of the Po River and Ticino River with a channel slope ranging between 0.150 % and 0.057 %), the Middle Po (between the confluence of the Ticino River and Secchia River with a channel slope ranging between 0.028 % and 0.011 %), the Lower Po (from the confluence of the Po River and Secchia River to the beginning of the delta with a channel slope ranging between 0.011 % and 0.004 %) and the Po delta (Fig. 1). The Po Plain, the largest plain in Italy, has been extremely attractive for

human settlement and experienced an intensive agricultural, industrial and urban development during the last few centuries, which reached its maximum intensity during the 20th century. In accordance with this finding, a long history of multiple anthropic pressures acted on the Po River and its catchment (Marchetti, 2002).

2.2. Human activities, river processes and channel adjustments

Human activities were carried out for the exploitation of natural resources in the Po River catchment during the 20th century (Parrinello et al., 2021). Intense in-channel mining of sand and gravel (1940 s–1990 s) was performed along both the Po River main stem (at a maximum rate of approximately 7 Mm³ yr⁻¹ during the 1970 s and 1980 s) and its tributaries (at a maximum rate during the 1960 s and 1970 s of approximately 11 Mm³ yr⁻¹) (Dal Cin, 1983; Marchetti, 2002; Surian and Rinaldi, 2003). Numerous dams were constructed for hydropower production on the Po River tributaries from the 1920 s to 1970 s (Surian et al., 2009; Parrinello et al., 2021) and the large Isola Serafini Dam (Fig. 1) was constructed in 1964 directly on the Po River (Lanzoni, 2012; Bizzi et al., 2015; Maselli et al., 2018). The catchment experienced significant land use changes with a remarkable increment of forest cover during the 20th century (Marchetti, 2002; Surian and Rinaldi, 2003; Falcucci et al., 2007; Parrinello et al., 2021). All these pressures caused a decrease in sediment availability along the main stem of the Po River, especially in the second half of the 20th century, leading to average decreases of 50 % and 20 % estimated for suspended load and bed material load, respectively (Billi and Spalevic, 2022; Brenna et al., 2022). From a morphological point of view, researchers (e.g., Colombo and Filippi, 2010; Lanzoni, 2012; Rinaldi, 2021) documented how the Po River has responded to human-induced sediment starvation, experiencing morphological changes at the highest rate from the 1960 s to 1990 s. Channel incision was comprehensively documented by previous works, which highlighted bed stability until the 1950 s, followed by a remarkable incision phase from the 1960 s to 1980 s, with average bed lowering of 2.5–3.5 m determined for segments of the Middle Po (Colombo and Filippi, 2010; Rinaldi, 2021). Moreover, channel width reduction (average narrowing of approximately 20 % and maximum narrowing of 50 %) and simplification of planform morphological configuration was extensively recognised from the 1960 s to 1990 s (Lanzoni, 2012; Bizzi et al., 2019; Rinaldi, 2021; Brenna et al., 2022).

Additional anthropic interventions on the Po River were funded by the government agencies for controlling the water dynamics at low discharge conditions. In the 1920 s and 1930 s, agencies designed a large-scale river training scheme, inspired by the interventions carried out in the Rhône River (France) (i.e., Casiers Girardon; Thorel et al., 2018), to ensure the permanent navigability of a sector of the Po River. The project was approved in 1931 and involved extensive engineering works on the river sector encompassed by the confluence of the Adda River and Secchia River (Fig. 1), where the navigation under low discharge conditions was not permitted due to the low water depth in the main channel (MC) (Galvani and Pellegrini, 2009). Notably, this river course was mostly characterised at the beginning of the 20th century by a dominant multi-thread configuration (Gorio, 1953; Lanzoni, 2012) with water that normally flowed into various wet channels (Fig. 2). The training scheme involved the construction of elongated bent structures composed by ground covered by cobbles and stone slabs, capable of concentrating the water flow into a single navigable channel with a sinuous geometry (Gorio, 1953). These structures (hereafter referred to as navigation structures) were placed on a floodplain (i.e., levee) on the channel bank (i.e., bank protection) or in an active channel (i.e., groyne) (Fig. 2), forming a total of 51 river bends along the engineered river sector. Groynes were originally designed with an elevation overflowable by discharge of approximately 1000 m³s⁻¹ (Lanzoni, 2012), i.e., a discharge that, in the Middle Po course, occurred for approximately 180 days per year (ARPAE, 2020), allowing the water to flow in the channels located behind the navigation structures under

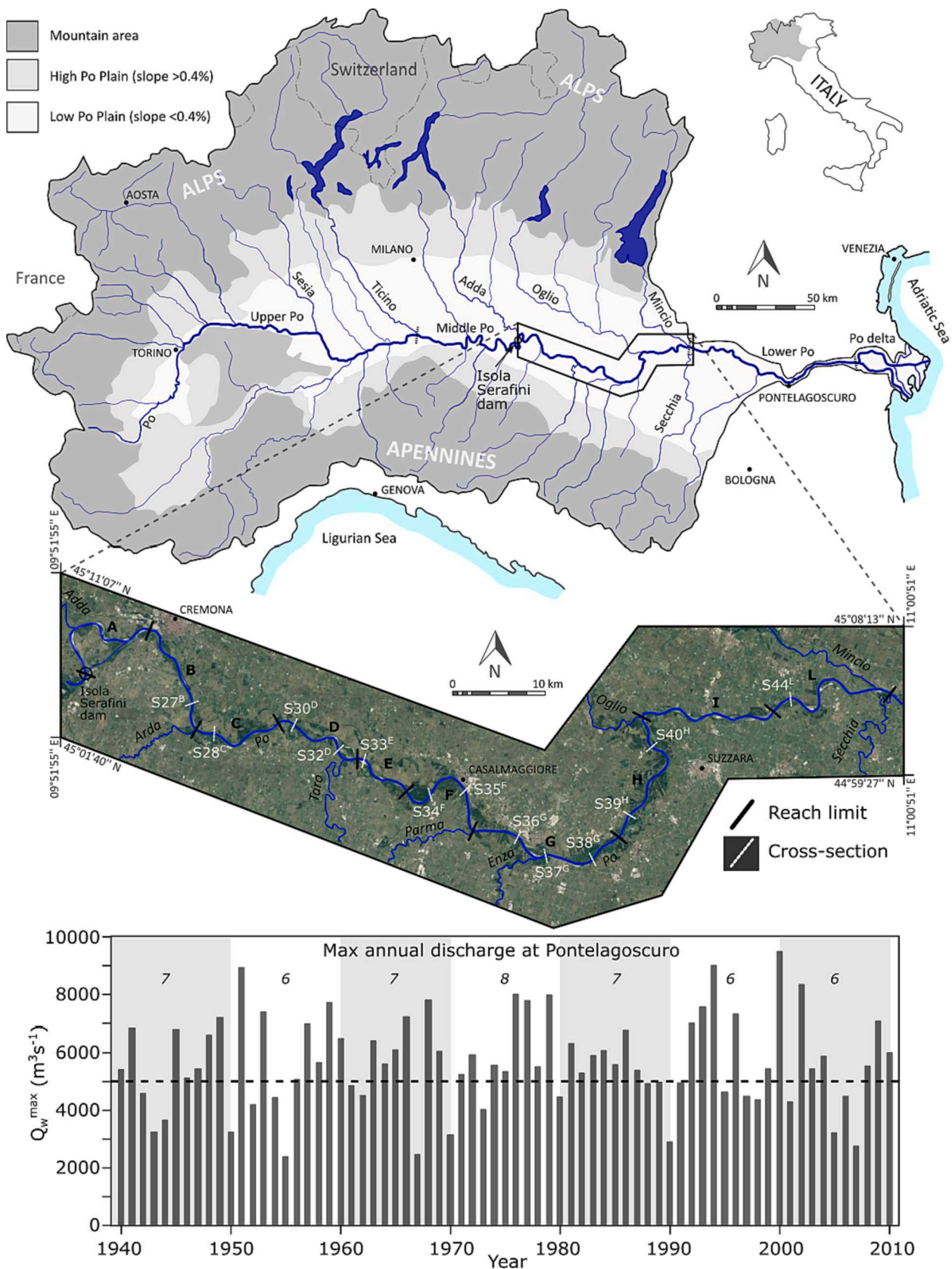


Fig. 1. The Po River catchment and the reaches defined along the study sector. The locations of the cross-sections considered in this work are reported in the lower panel. The superscript associated with the section number indicates the reach (A-L) in which the section is located. The maximum annual water discharges recorded at the gauging station of Pontelagoscuro over the period 1940 – 2010 are plotted in the lower panel. Numbers in italics refer to the number of floods in each decade that exceeded discharge values of $5000 m^3s^{-1}$ (i.e., a value selected to identify high-magnitude floods). The complete hydrograph is shown in Figure S1 of the Supporting Material.

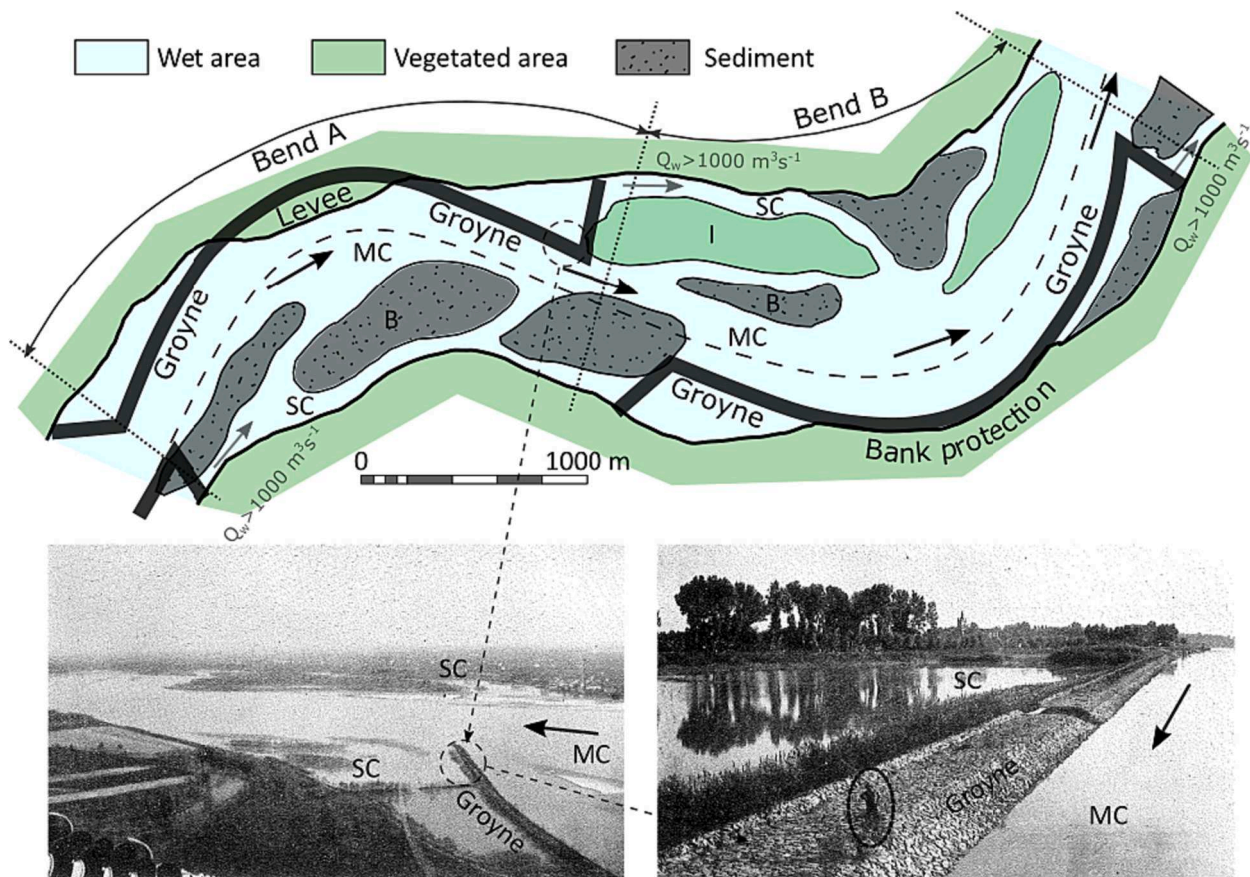


Fig. 2. Sketch of the navigation structures built in the Po River for the training works (B: sediment bar; I: island; MC: main channel; and SC: secondary channel). Historical photographs taken during the 1940 s are from Gorio (1953). The black arrows indicate flow direction.

moderate discharge conditions. Most of the works were performed during the 1930 s and 1940 s (Gorio, 1953), but the training scheme was completed in the 1950 s and 1960 s (Galvani and Pellegrini, 2009). The role played by these river training works on the morphological adjustments of the Po River is currently minimally investigated, even if Rinaldi (2021) recently hypothesised that “A major role for the onset of the phase of intense channel narrowing, more important than indicated in previous studies, may have been played by the construction of groynes ...”.

2.3. Study sector of the Po River

We focused on the downstream part of the Middle Po extending approximately 123 km between the confluence of the Adda River (near the Isola Serafini Dam) and Secchia River (Fig. 1), which was affected by the multiple anthropic pressures described in the previous section. This river sector has a channel slope ranging from 0.022 % to 0.010 % and is largely dominated by bed material falling in the class of medium sand (0.25 – 0.50 mm) with some fine gravel (AdBPO, 2006, 2008). Several analyses were conducted at the scale of channel sites having a length of hundreds of meters, but a segmentation procedure was adopted for defining homogeneous geomorphic reaches to effectively illustrate our analysis results. On the basis of current morphological characteristics of the river channel (i.e., width and planform pattern; see the next Section for the estimation methods) and the presence of tributaries representing major hydrological and sediment inputs, we divided the study sector into ten reaches with a length ranging from 7.6 km to 17.5 km (i.e., reaches from A to L; Table 1).

Table 1

Current characteristics of the reaches of the Po River defined in this study (see Fig. 1 for reach locations).

Reach	Length (km)	Average channel width (m)	Morphological configuration
A	9.1	764	Anabranching
B	12.2	307	Sinuuous
C	10.2	306	Sinuuous
D	9.1	368	Sinuuous
E	7.6	374	Sinuuous
F	13.2	319	Sinuuous
G	17.5	277	Sinuuous
H	15.3	378	Sinuuous
I	15.1	461	Wandering
L	13.9	384	Sinuuous

3. Materials and methods

3.1. Analysis of planform characteristics

An historical map (‘cartografia Brioschi’ of 1853), five sets of aerial photographs (‘volo GAI’ of 1954 and other four photographs with a spatial resolution in the range of 0.5 – 1.2 m/pixel) and one satellite image (spatial resolution of 0.6 m/pixel) (Table 2) were considered for analysing the channel planform characteristics of the study sector via a multitemporal GIS analysis. For four (i.e., 1853, 1954, 2006 and 2020) of the seven dates, the active channel, defined as the area occupied by low-flow channels and exposed sediment bars (Liébault and Piégay, 2002; Haschenburger and Cowie, 2009), where bed material load occurs (i.e., islands are excluded), was manually digitised in ArcMap 10.8 for defining the channel width and planform morphological configuration

Table 2

Planform and altimetry data employed in this work. Data source is reported (G AIPO: Geoportale of Agenzia Interregionale per il Fiume Po, <https://www.geoportale.agenziapo.it>; GL: Geoportale of Lombardia Region, <https://www.geoportale.regione.lombardia.it>; GN: Geoportale Nazionale of Italy, <https://www.pcn.minambiente.it>).

Planform data			Altimetry data		
Year	Data type	Data source	Year	Data type	Data source
1853	Historical map	G AIPO	1954	Topographic cross-section	G AIPO
1954	Aerial photographs	G L	1969	Topographic cross-section	G AIPO
1988	Aerial photographs	G N	1973	Topographic cross-section	G AIPO
1996	Aerial photographs	G N	1979	Topographic cross-section	G AIPO
1999	Aerial photographs	G N	1984	Topographic cross-section	G AIPO
2006	Aerial photographs	G N	1991	Topographic cross-section	G AIPO
2020	Satellite images	Google Earth	2000	Topographic cross-section	G AIPO
			2005	Topographic cross-section	G AIPO

(Fig. 3a).

The mean channel width of each reach in each year was calculated by dividing the polygonous area spanned by the active channel using the length of the reach. The channel planform configuration was defined for

the same dates determining the braiding (B_i), anabranching (A_i) and sinuosity (S_i) indexes (Thorne, 1997). B_i and A_i were determined at the reach scale using a channel count (Egozi and Ashmore, 2008). For each reach, a number of cross-sections (spaced approximately the average active channel width) were orthogonally traced to the channel axis and the number of channels occupied by water flow was visually determined for each section (Fig. 3a). The average number of wetted channels separated by sediment bars or vegetated islands represent B_i and A_i , respectively, of a reach. S_i was calculated as the ratio between the reach length measured along the channel axis and the rectilinear distance between the upstream limit of a reach and the downstream limit of a reach. Four morphological classes were considered: anabranching (i.e., multi-thread channel dominated by islands), braided (i.e., multi-thread channel dominated by bars), wandering (i.e., transitional channel with bars) and single-thread channels (i.e., meandering, sinuous or straight). Criteria adopted for determining the morphological configuration are summarised in Table 3. Image analysis allowed us to recognise the presence and extension of navigation structures and to date them as built before or after 1954.

3.2. Analysis of bed-level changes

To better understand the overall evolution of the Po River, we performed a detailed reconstruction of the morphological changes that occurred at the engineered river bends by integrating planimetric changes with bed-level changes. Eight sets of topographic cross-sections measured along the Po River between 1953 and 2006 (Table 2) were employed to determine the riverbed elevation over a period of 51 years

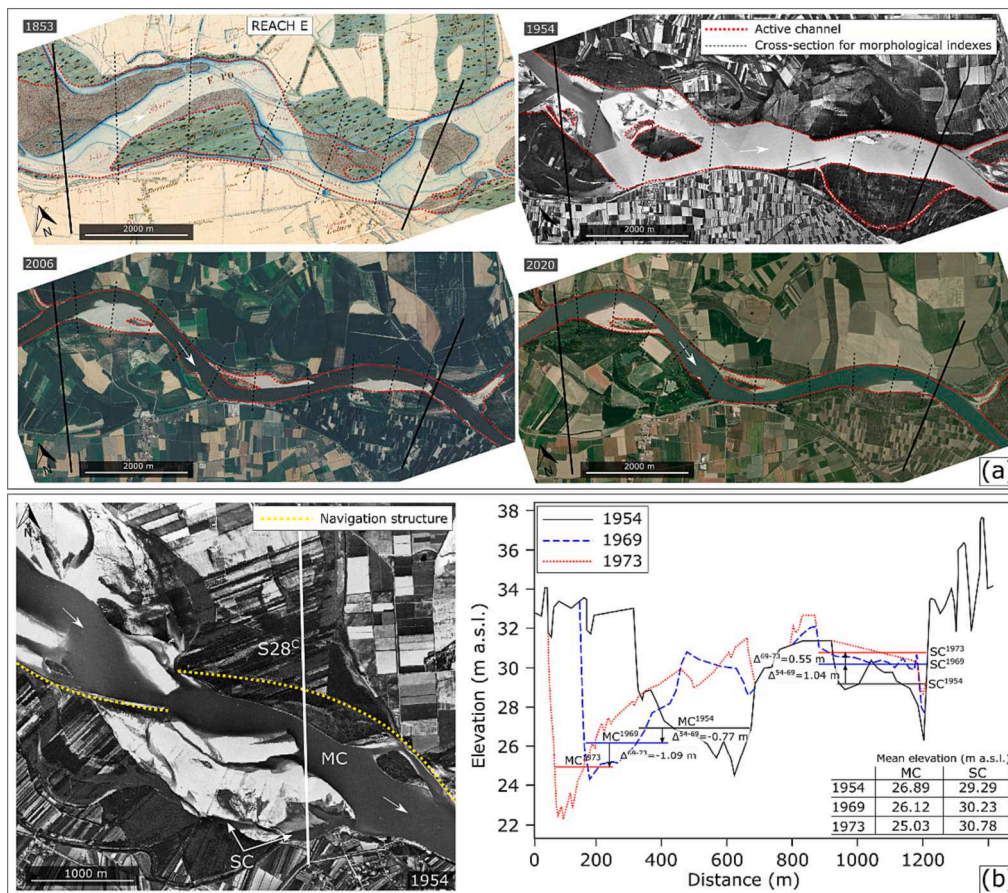


Fig. 3. (a): active channel digitalised at reach E for 1853 (cartografia Brioschi), 1954 (volo GAI), 2006 (aerial photograph) and 2020 (satellite image); (b): example of the cross-section (S28^C; the superscript associated with the section number indicates the reach in which the section is located) employed to determine the changes in riverbed elevation at the MC and SCs classified considering the 1954 planform configuration. The horizontal coloured lines represent the MC and SC widths and mean elevations at the three dates (i.e., 1954 shown in black, 1969 shown in blue, and 1973 shown in red). The white arrows indicate flow direction.

Table 3
Criteria adopted for determining the morphological configuration of a river reach. Thresholds of indexes are obtained from Rinaldi et al. (2016).

Morphological Configuration		Sinuosity Index (S_i)	Braiding Index (B_i)	Anabranching Index (A_i)
Multi-thread channels	Anabranching	–	Usually low	≥ 1.5
	Braided	–	≥ 1.5	< 1.5
Transitional channels	Wandering	< 1.5	$1.15 < B_i < 1.5$	$1 < A_i < 1.5$
	Meandering	> 1.5	≈ 1	≈ 1
Single-thread channels	Sinuuous	$1.05 < S_i < 1.5$	≈ 1	≈ 1
	Straight	$1 < S_i < 1.05$	≈ 1	≈ 1

(i.e., 1954 – 2005). We were mostly interested in analysing the channel evolution in correspondence of the river bends designed for navigation. For this reason, we considered 13 cross-sections distributed along the study sector (Fig. 1) that intersect the navigation structures. Riverbed elevation was calculated for each of the eight dates when cross-sections were available (Table 2) as the weighted average of the elevation of points measured within the channel(s) (i.e., from the bank toes) (Grabowski and Gurnell, 2016), distinguishing between the MC and the secondary channel(s) (SC(s)) (Fig. 3b). The difference in average bed elevation between two successive dates was calculated to quantify incision or deposition in different portions of the active channel. The five sets of aerial photographs available from 1954 to 2006 (Table 2) were employed to determine in the proximity of the cross-sections the planform arrangement of the active channel and the position of single channels, sediment bars and islands with respect to the position of navigation structures (Fig. 3b).

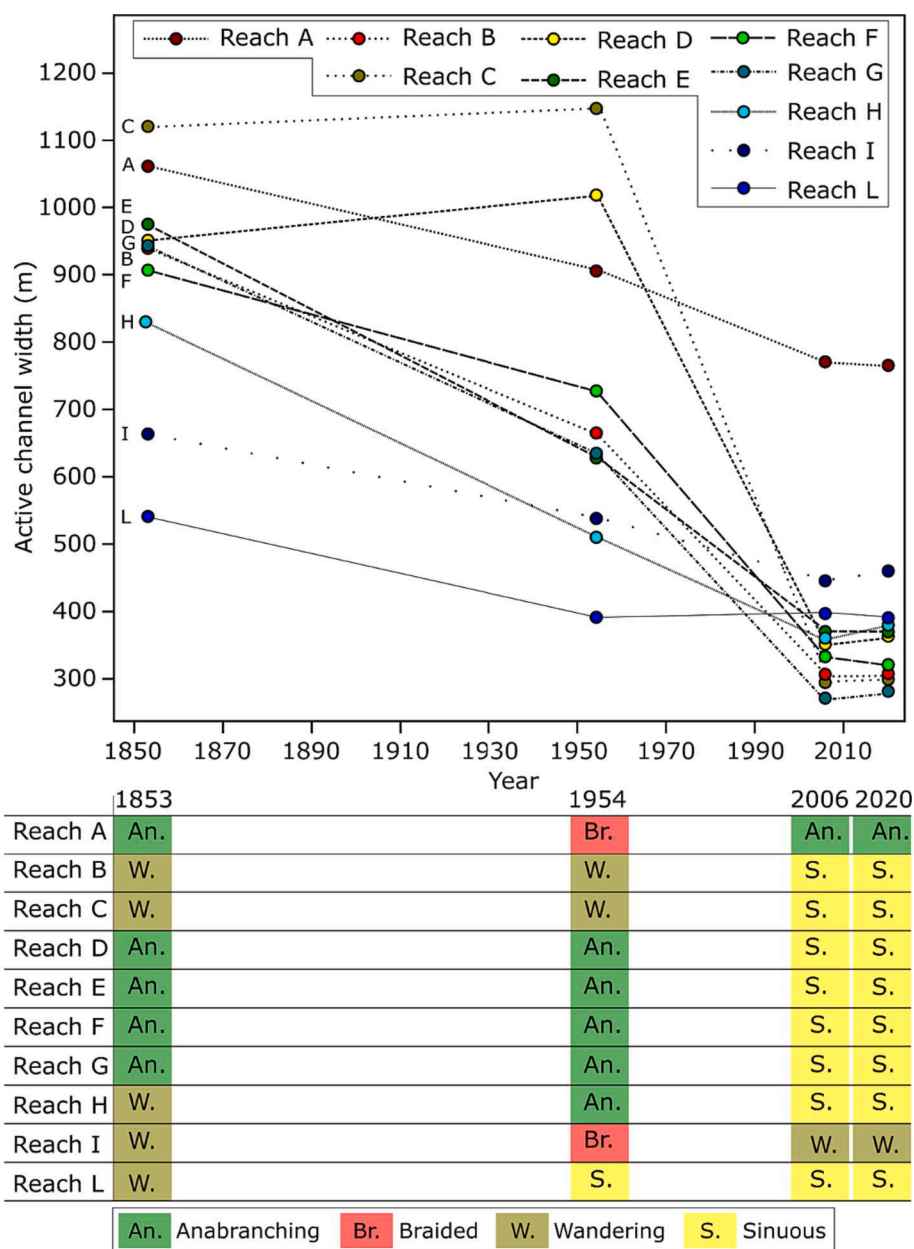


Fig. 4. The active channel width and morphological configuration determined for the reaches of the study sector in 1853, 1954, 2006 and 2020. Morphological indexes used to classify the planform pattern on the basis of thresholds of Table 3 are reported for each reach and date in Table S1 of the Supporting Material.

3.3. Hydrological analysis: Overflowing of navigation structures

The discharge currently required for the water to overflow the groynes was estimated for some channel sites and compared with the $1000 \text{ m}^3\text{s}^{-1}$ originally required immediately after construction of navigation structures. Planet satellite images (spatial resolution of 3 m/

pixel) available online in the frame of Planet's Education and Research Program (<https://www.planet.com>) with a temporal resolution of one or two days were employed. We considered the 2019 and 2020 daily discharges available for the study sector (ARPAE, 2020, 2021) and visually evaluated from the satellite images if the water overflows a groyne reaching the channel located behind the navigation structure.

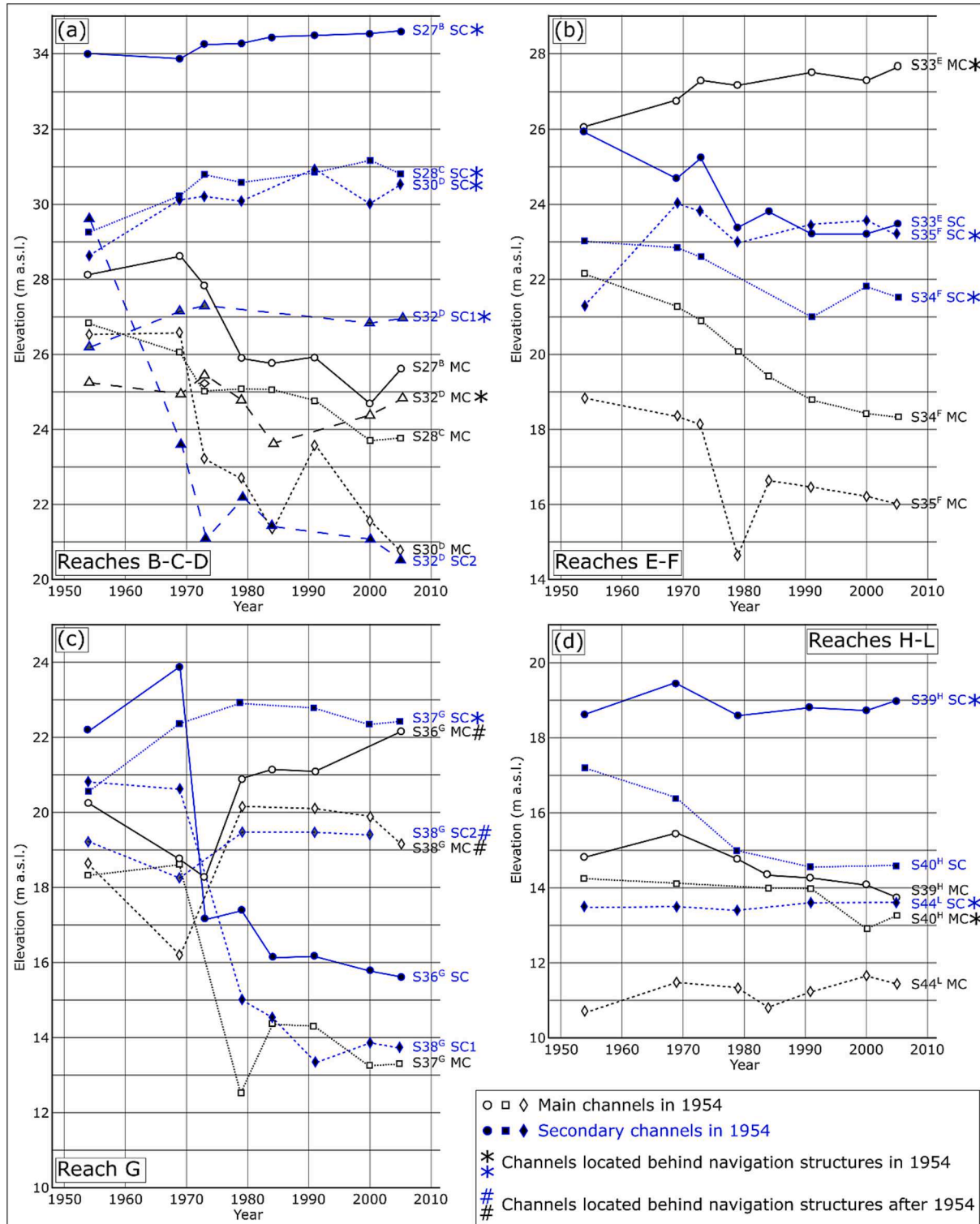


Fig. 5. Temporal evolution of average riverbed elevation determined for different portions of the active channel (MC: main channel; SC: secondary channel) and their position with respect to navigation structures [i.e., located behind groynes (* and #) or not behind groynes]. Each panel include sections located in a group of reaches [(a): reaches B, C, and D; (b): reaches E and F; (c): reach G; and (d): reaches H and L]. The superscript associated with the section number indicates the reach in which the section is located.

4. Results

4.1. Channel evolutionary trajectory

Active channel width and planform configuration of the Po River in 1954 were similar to 1853 along the entire study sector, with most of the reaches experiencing only a moderate narrowing (-19 % on average) over these 101 years (Figs. 3 and 4). Reaches from A to I displayed in 1954 a multi-tread or transitional configuration with channels predominantly divided by islands at reaches D to H, while reach L had a single-thread configuration. Between 1954 and 2006, the Po River underwent an intense narrowing phase and reduction of morphological complexity that affected most of the study sector (Fig. 4), with an average narrowing of -58 % estimated for reaches from B to H, which modified their planform patterns from predominantly anabranching or wandering to single-tread with sinuous geometry. Moderated narrowing and widening occurred over the same period at reaches I and L, respectively, which maintained their original morphological configurations. Over the most recent period (i.e., 2006 – 2020), most reaches did not significantly change in neither channel width nor planform pattern (Figs. 3 and 4).

The changes in bed-level were analysed by the historical cross-sections. Results are presented distinguishing between different portions of cross-sections that intercept the MC or SCs (considering the planform configuration in 1954) and the position of channels with respect to the navigation structures in different years (i.e., behind or not behind a groyne) (Fig. 3b). In general terms, dominant bed stability was observed between 1954 and 1969, with only some sections experiencing moderate incision (e.g., S34^F) or aggradation (e.g., S30^D) (Fig. 5). Among the few exceptions, an example is represented by a SC of S32^D (SC2 in Fig. 5a), where a remarkable incision of approximately 6 m occurred in this period. Between 1969 and the first half of the 1980 s, two distinct elevation trajectories were recognised for channels located behind the navigation structures and channels not protected by the groynes. The first group consists mainly of SCs and was characterised by dominant riverbed stability or moderate deposition (e.g., SC at section S27^B; Fig. 5a). High deposition (i.e., 3 – 4 m of increment in channel elevation) was observed only at MCs of sections S36^G and S38^G that were located behind groynes constructed after 1954 (Fig. 5c). Conversely, over the same period, remarkable bed lowering occurred at channels not protected by the navigation structures. An average incision of 1 – 3 m was determined for most of the channels, even if an incision of up to 6 – 7 m was recognised for the MC of section S37^G and SCs of sections S36^G and S38^G (Fig. 5c). During the 1980 s – 2000 s, modifications were more limited. Channels located behind groynes did not change their elevation or continued a moderate aggradation. Channels not protected by groynes stabilised their elevation or continued to undergo moderate incision, with few channels experiencing a temporary reversal behaviour (i.e., deposition), such as MCs of sections S30^D and S35^F (Fig. 5a and 5b). These evolutionary trajectories refer to the channel sections from S27^B to S38^G (reaches B – G; Fig. 5a, b and c), while more flat elevation trajectories were observed at sections S39^H, S40^H and S44^L (reaches H and L; Fig. 5d).

4.2. Detailed morphological evolution of some channel sites

Here we present three historical cross-sections and the relative channel sites (intended as a channel portion of hundreds of meters surrounding a cross-section) where a detailed reconstruction of morphological changes was carried out. These sites were chosen as representative examples of the different types of morphological responses observed along the study sector. The results obtained at the other sites are summarized in Fig. 5 and considered in Section 5.1 of the discussion.

Section S30^D is located in reach D (Fig. 1) at a channel site characterised by anabranching configuration in 1954 (Fig. 4). The 1954 section

intercepts the MC and a SC, which was approximately 2 m higher than the MC and located behind a groyne (Fig. 6). Bed stability is observed in the MC over the 1950 s and 1960 s, while a moderate aggradation (1.5 m) occurred in the SC. From 1969 to 1984, the MC underwent a 5.1 m incision, and the elevation difference with the SC increased up to 8.7 m. The SC deactivated (i.e., neither water nor exposed sediment are visible from aerial photographs) at the end of the 1980 s, and the channel took on a single-tread configuration with a sinuous channel that follows almost perfectly the local planform arrangement of the navigation structures. Currently, the area occupied in the past by the SC is disconnected from the active channel and transformed in a recent terrace that is not reached by waterflow also for discharge of approximately 4000 m³s⁻¹, i.e., a discharge occurring less than five days during one year at this river sector (ARPAE, 2021). The satellite image used for this estimation is available in Figure S2 of the Supporting Material. A similar morphological evolution was recognised at most of the investigated channel sites, i.e., those located near sections S27^B, S28^C, S33^E, S35^F and S37^G (Figs. 1 and 5).

A different channel evolution was recognised for section S32^D located in reach D (Fig. 1). The 1954 section intercepts the MC and two SCs (SC1 and SC2) but, differently from S30^D, a groyne built before 1954 deviates the water flow from the MC to SC2 (Fig. 7). SC2 underwent a large incision of 8.5 m from 1954 to 1973, while stability or a moderate aggradation occurred in the MC and SC1, which were located behind navigation structures. Starting from the late 1960 s, SC2 became the new MC, and the former MC evolved into a SC. Even if the overall morphological configuration of reach D evolved from anabranching in 1954 to sinuous in 2006 (Fig. 4), the Po River locally maintained the original multi-thread configuration at this channel site since the three channels remained recognisably active over the most recent periods (Fig. 7). Currently, the discharge required for overflowing the groynes and actively flowing into SC1 and the former MC is equal to approximately 1500 m³s⁻¹ (discharge occurring for approximately 70 days in one year at this sector of the Po River; ARPAE, 2021) and 2700 m³s⁻¹ (discharge occurring less than 20 days in one year at this sector of the Po River; ARPAE, 2021), respectively. Satellite images used for this estimation are available in Figure S3 of the Supporting Material. Comparable morphological evolution characterises channel sites located near sections S36^G and S38^G (Fig. 5), where the position of navigation structures built over the 1960 s forced the transformation of SCs into new MCs.

A peculiar evolution was reconstructed for section S34^F (reach F; Fig. 1), intercepting the MC and a SC whose bed was approximately 0.8 m higher than the MC bed in 1954 and located behind a groyne (Fig. 8). Dominant bed stability was observed for the entire channel during the period 1954 – 1969, followed by an incision of 2.5 m of the MC that occurred in the 1970 s and 1980 s. Differently from section S30^D, a bed lowering of 1.8 m also occurred in the SC during the same period. During the 1990 s and 2000 s, slight incision persisted in the MC, while aggradation of approximately 0.7 m occurred in the SC, leading to a maximum elevation difference of 3.2 m between the MC and SC in 2006. In accordance with this altimetric evolution of the riverbed, a water discharge between 2200 and 2700 m³s⁻¹ is currently required for allowing the water to flow into the SC (Figure S4, Supporting Material). The overall morphological configuration of this channel site did not change significantly over the investigated period.

The remaining sections S39^H, S40^H and S44^L, which are located in the downstream study sector (reaches H – L) (Fig. 1), were characterised by smaller variations of riverbed elevation (Fig. 5). Moreover, the planform pattern of these channel sites did not significantly change during the study period (Fig. 4).

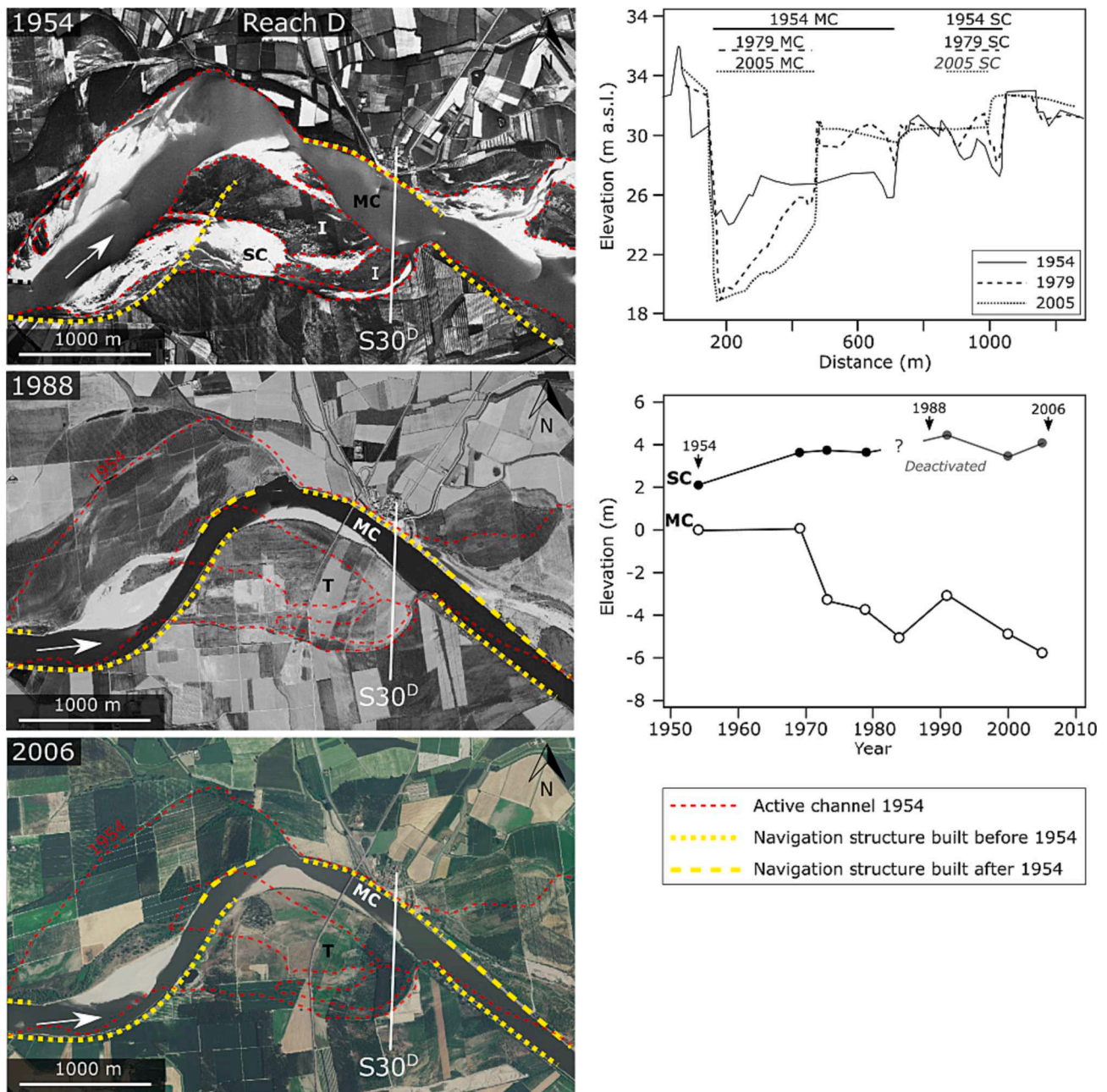


Fig. 6. Morphological evolution of the channel site at section S30^D. Three aerial photographs acquired in 1954, 1988 and 2006 are reported on the left part of the figure (MC: main channel; SC: secondary channel; I: island; and T: terrace). On the right part are presented three examples of historical cross-sections (1954, 1979 and 2005) considered for determining the evolution of the riverbed elevation and a graph summarising the temporal evolution of the average riverbed elevation for the MC and SC. Elevations are scaled associating a value of zero to the MC in 1954. The white arrows indicate flow direction.

5. Discussion

5.1. Evolutionary trajectory of the Po River and relationships with multiple anthropic pressures

The timing and intensity of anthropic pressures acting on the Po River over the 20th century was considered for inferring the cause-and-effect relationships between human activities acting on the river and its morphological evolution. The most common morphological evolution recognised in the study sector is that described in detail for section S30^D (Fig. 6) and recognised also at five other sections distributed along reaches B – G (Fig. 5). At these channel sites, SCs were located behind navigation structures built before 1954, while the MCs were not protected by groynes. Active channel width and planform configuration did

not substantially change from 1853 to 1954, with the channel preserving an anabranching or wandering pattern (Figs. 3 and 4). Over the 1950 s and 1960 s, we observed stability of the riverbed elevation at the MCs and a moderate aggradation of 1.5 m on average at the SCs (Fig. 9). Aggradation behind the navigation structures could be reasonably explained as a consequence of depositional processes and siltation promoted by the groynes, which locally limited the transport capacity of the flow and induced temporary slack-water conditions. Additional information about this dynamic could be achieved in future studies by analysing in detail the stratigraphy of the channel fill deposits by direct techniques (e.g., cores) or indirect techniques (e.g., near surface geophysics) (Maillet et al., 2005; Toonen et al., 2012) to determine the transport processes and hydraulic conditions that controlled the localised sedimentation. Significant incision (3.1 m on average) occurred at

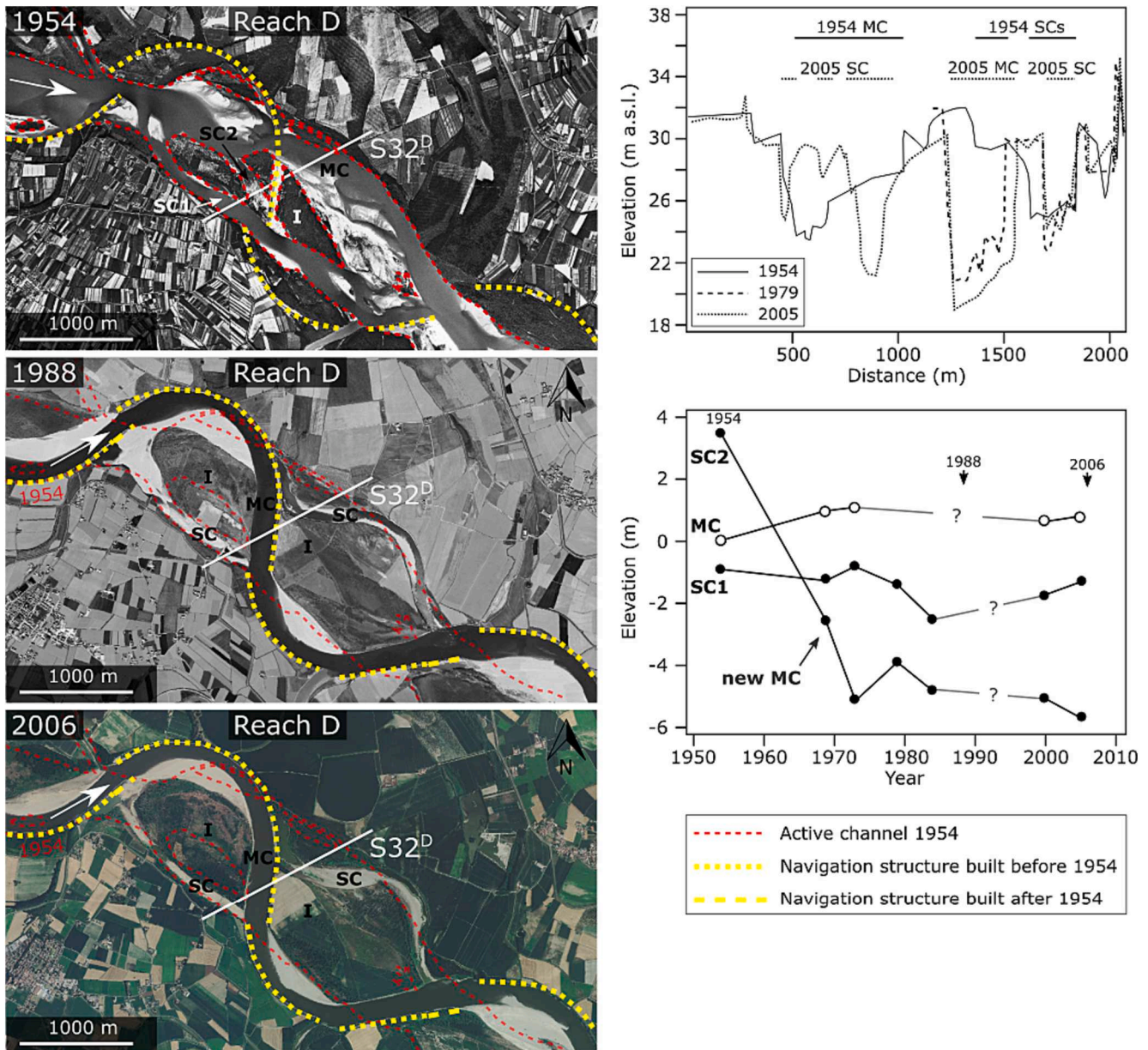


Fig. 7. Morphological evolution of the channel site located near section S32^D. Three aerial photographs acquired in 1954, 1988 and 2006 are reported on the left part of the figure (MC: main channel; SC: secondary channel; and I: island). On the right part are presented three examples of historical cross-sections (1954, 1979 and 2005) considered for determining the evolution of the riverbed elevation and a graph summarising the temporal evolution of the average riverbed elevation for the MC and SC1, which are located behind a groyne built before 1954, and SC2, which is not protected by navigation structures and transformed into the new MC during the late 1960 s – 1970 s. Elevations are scaled associating a value of zero to the MC in 1954. The white arrows indicate flow direction.

the MCs during the 1970 s, while the SCs stabilised or continued a moderate aggradation.

Riverbed lowering in the MCs started approximately two to three decades after the completion of most river training interventions (i.e., 1940 s – 1950 s) (Gorio, 1953; Galvani and Pellegrini, 2009), almost simultaneously with the most intense phase of in-channel sediment mining and shortly after the construction of the Isola Serafini Dam (Dal Cin, 1983; Marchetti, 2002; Surian and Rinaldi, 2003; Maselli et al., 2018; Parrinello et al., 2021) (Fig. 9). In-channel mining and closure of the Isola Serafini Dam induced a remarkable decrease in sediment availability along the study sector (Billi and Spalevic, 2022; Brenna et al., 2022). In accordance with the concept of Lane’s balance (Lane, 1955), a reduction of sediment input under conditions of substantially unchanged flow regime can produce an incision of the riverbed (Kondolf, 1997; Brandt, 2000). This response occurred in the Po River

(Rinaldi, 2021) but, at the considered channel sites, it exclusively affected the MCs not protected by groynes, where the flow competence and capacity were higher, while incision did not occur in the SCs located behind navigation structures. Consequently, the elevation difference between the MC and SCs dramatically increased from 2.5 m on average measured in 1954 to 7.3 m on average at the end of the 1970 s. Accordingly, the discharge required for water to flow into the channel portions located behind groynes progressively increased during this period, at least two or three times compared to the 1000 m³s⁻¹ required at the time of their construction (Gorio, 1953; Lanzoni, 2012) (Supporting Material). This dynamic reliably had positive feedback on promoting riverbed lowering in the MCs by concentrating water flow, sediment entrainment and consequently incision exclusively in the channel parts not protected by navigation structures. Most of the SCs located behind navigation structures deactivated during the 1980 s and

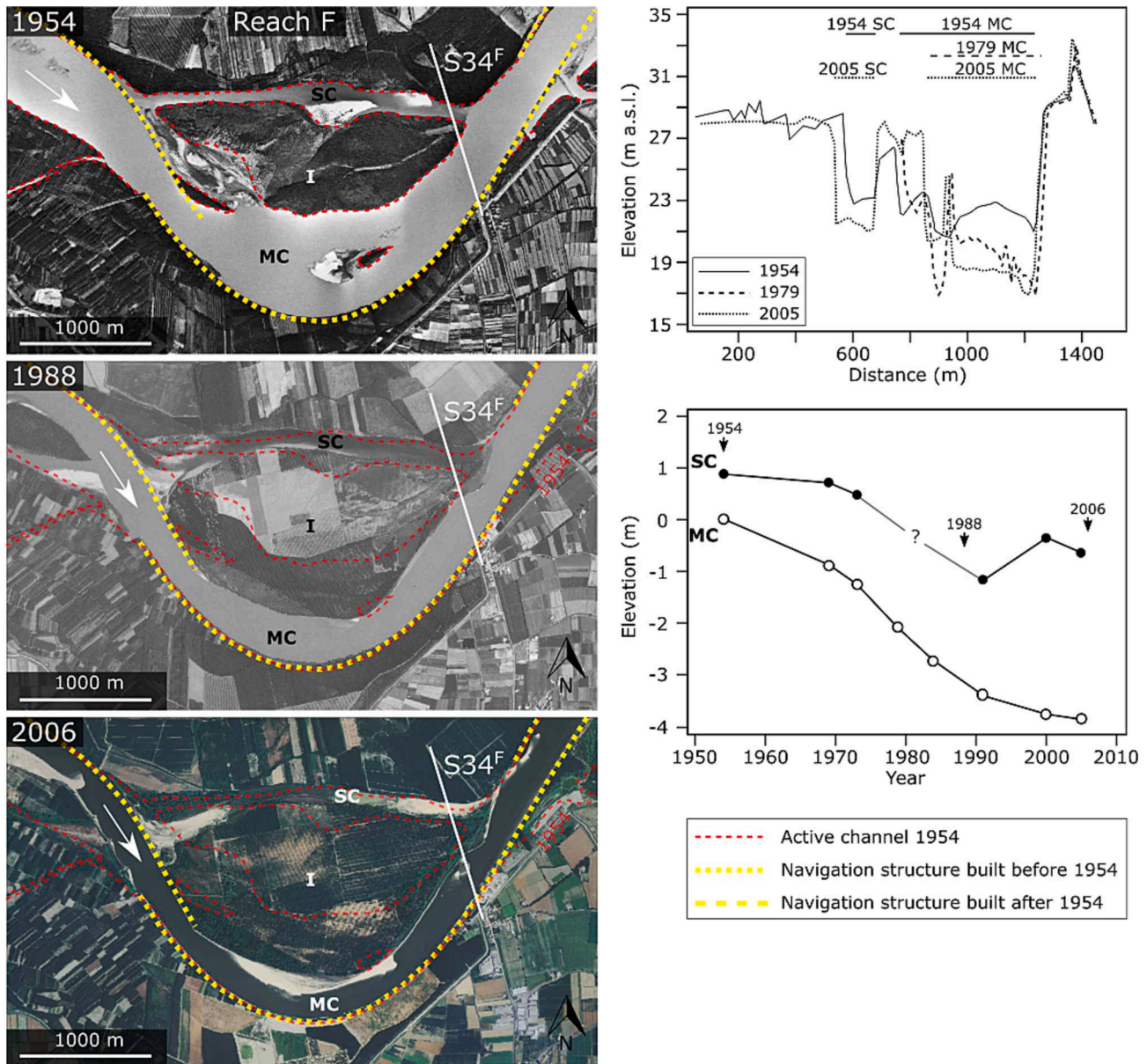


Fig. 8. Morphological evolution of the channel site located near section S34^F. Three aerial photographs acquired in 1954, 1988 and 2006 are reported on the left part of the figure (MC: main channel; SC: secondary channel; and I: island). On the right part of the figure are presented three examples of historical cross-sections (1954, 1979 and 2005) considered for determining the evolution of the riverbed elevation and a graph summarising the temporal evolution of the average riverbed elevation for the MC and SC. Elevations are scaled associating a value of zero to the MC in 1954. The white arrows indicate flow direction.

evolved into floodplains or recent terraces. Consequently, the channel configuration evolved from predominantly multi-thread sinuous and the active channel narrowed (Fig. 9). This morphological evolution corresponds with cases I and H of the model of channel adjustment proposed by Surian and Rinaldi (2003) and recently updated by Rinaldi (2021) based on an application of that model to some sectors of the Po River.

A peculiar trajectory regarding the evolution of a channel located behind a groyne was recognised at section S34^F, where the SC also underwent incision at a rate only slightly lower than the MC (Fig. 8), leading to a maximum elevation difference between the two channels of 4.1 m in 2000. This peculiar evolution could be explained in terms of the elevation difference between the MC and the SC before the occurrence of incision in the 1970 s, which was equal to 0.8 m (Fig. 8), i.e., a value significantly lower than the average 2.5 m measured at the other sections (Fig. 9). The lower elevation difference may have permitted the water to frequently flow also in the SC, the occurrence of incision also in

the channel part located behind the groyne and, consequently, the maintenance of activity in both channel portions with minor modifications locally affecting the planform configuration.

During the 1980 s – 1990 s, the incision rate of the MCs in these sites substantially decreased (Fig. 9), likely as the Po River reached a new morphodynamic quasi-equilibrium following a degradation-evolution path (Petts and Greenwood, 1985; Curtis et al., 2010), which was permitted by a progressive but substantial decrease in the in-channel mining rate that occurred in the Po River catchment approaching the end of the 20th century (Parrinello et al., 2021). During the last two decades, most reaches did not significantly change neither channel width nor planform pattern (Fig. 4), with the 2020 planform configuration of the channel that is very similar to the 2006 planform and is still strictly determined by the substantial modifications that occurred during the second half of the 20th century (Figs. 3 and 4). The substantial decrease in the in-channel mining rate was thus not sufficient to induce a significant morphodynamic recovery of the system. This inertia to the

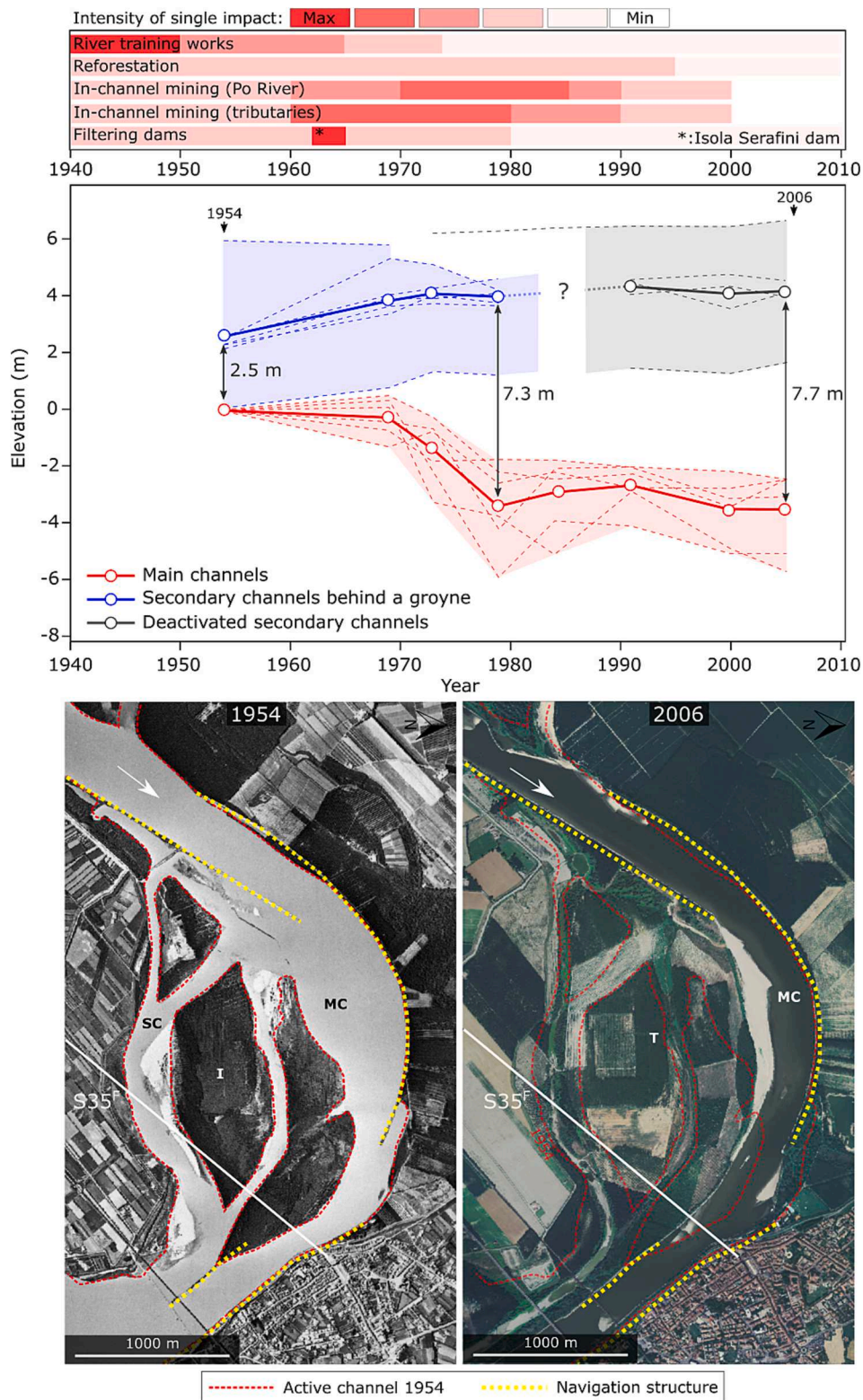


Fig. 9. Morphological evolution recognised for sections S27^B, S28^C, S30^D, S33^E, S35^F and S37^G, where the SCs were located behind navigation structures built before the 1954 and the MCs were not protected by groynes. Elevations are calculated as the mean value considering the data from the six considered sections (represented by dashed lines and reported in Fig. 5) and scaled associating a value of zero to the MC in 1954. The example of planform evolution represented in the two aerial photographs came from a channel site in reach F. Intensity and timing of anthropic impacts presented in the upper panel are retrieved from the literature review presented in Section 2. The white arrows indicate flow direction.

recovery could be influenced by the presence of the navigation structures, which limit the system's ability to morphologically respond to changes in sediment availability and fluxes.

A partially different evolution was observed for sections located at the few channel sites where the SCs were not protected by navigation structures and the MCs were located behind groynes (Fig. 7). In these

cases, the SCs, which were superelevated 2.6 m on average with respect to the MCs in 1954 (Fig. 10), experienced an extremely rapid incision of 8.5, 6.7 and 5.6 m at sections S32^D, S36^G and S38^G, respectively, immediately after the construction of the navigation structures that were built before 1954 at section S32^D and after 1954 (probably during the 1960 s) at sections S36^G and S38^G (Fig. 5). This incision seems to be

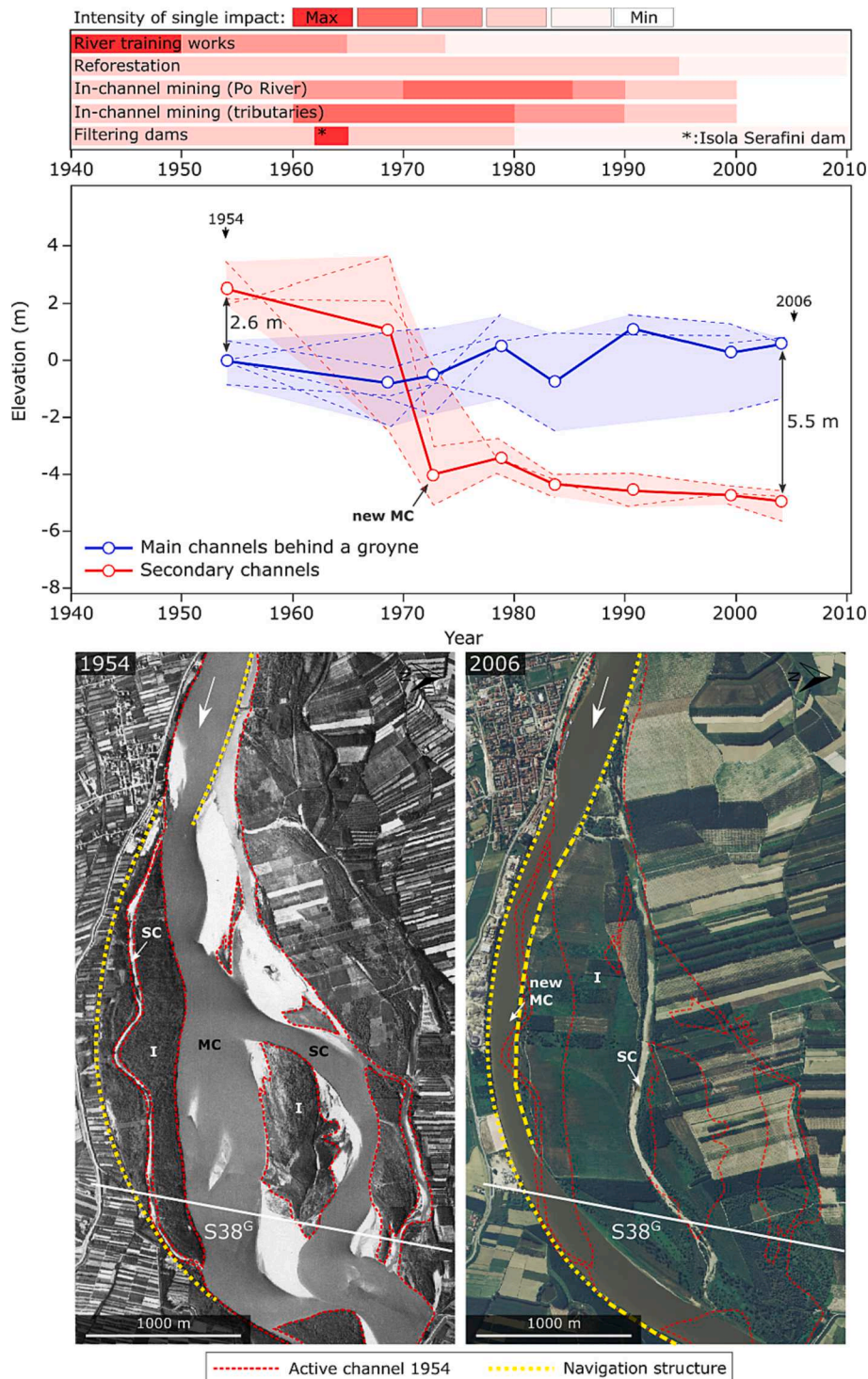


Fig. 10. Morphological evolution recognised for sections S32^D, S36^G, and S38^G, where the SCs were not protected by navigation structures and the MCs were located behind groynes. Elevations are calculated as the mean value considering the data from the three considered sections (represented by dashed lines and reported in Fig. 5) and scaled associating a value of zero to the MC in 1954. The example of planform evolution represented in the two aerial photographs was derived from a channel site in reach G. Intensity and timing of anthropic impacts presented in the upper panel are retrieved from the literature review reported in Section 2. The white arrows indicate flow direction.

directly related to the effects induced by the groynes on the direction of water flow, which was deviated into SCs that incised and widened in response to a remarkable increase of water flow and transformed in the new MCs (Fig. 10). After the incision, the elevation difference between the former MCs (that remained almost stable in terms of riverbed elevation) and the new MCs stabilised at approximately 5.5 m on average (Fig. 10). This elevation difference, as observed also for section S34^F (Fig. 8), was not sufficient to induce a complete deactivation of channels located behind groynes, which narrowed, transformed into SCs and are currently affected by water flow for discharge rates higher than $1500 - 2800 \text{ m}^3 \text{ s}^{-1}$ (Figure S3). Consequently, the channel morphology at these sites remained locally multi-thread, but this evolution is limited to few channel locations (i.e., S32^D, S36^G, and S38^G) along the study sector.

Putting the geomorphological dynamics described above into a wider spatial perspective, it is possible to assert that reaches B – G and, partially, reach H of the study sector underwent a profound modification of their morphological configuration during the second half of the 20th century, with higher intensity during the 1970 s. The deactivation of several SCs located behind groynes induced a significant narrowing of the active channel (-50 % on average) and a generalised reduction of the morphological complexity, with the predominantly anabranching or wandering configurations of the 1954 transforming into single-tread configuration with sinuous geometry (Fig. 4). An example of this dynamic is reported in Fig. 11, covering the entire reach G of the study sector and the two types of morphological evolutions described above in Figs. 9 and 10 (see the black boxes in Fig. 11). It seems that the sinuous channel of the Po River assumed a position during the morphological changes that almost exactly follows the planform arrangement of the river training scheme, also due to some bank erosions that occurred in

the external parts of the channel bends where the navigation structures were originally located on the floodplain (i.e., levees; see aerial photographs of Fig. 9 and the white box in Fig. 11). The current sinuosity of the study sector (Table S1) is consequently controlled by the geometry of the 51 river bends designed by the navigation structures.

The most downstream part of the study sector was characterised by a less dynamic morphological evolution. These sections displayed a flatter temporal tendency (Fig. 5d), and planform changes in terms of active channel width and morphological pattern were limited, with reaches I and L experiencing only a moderate narrowing (Fig. 4). We hypothesised that this trajectory can be explained by a lower decrease in sediment fluxes compared to the reduction affecting the upstream reaches, due to the greater distance between these reaches and the Isola Serafini Dam and the sites affected by more intense in-channel excavation, and, possibly, a sediment recovery from bed material evacuated from the upstream river reaches. Moreover, reach L was already typified by a single-thread pattern before the occurrence of anthropic impacts (Figure S5, Supporting Material). In the absence of SCs located behind navigation structures, the deactivation processes described in detail for several channel sites of reaches B – H (Fig. 9) are not physically possible. This interpretation is in accordance with the model of channel morphological adjustment proposed by Surian and Rinaldi (2003), which asserts that, with comparable impacts on sediment fluxes, the planform changes occurring in multi-tread or transitional channels are much more notable than those affecting single-thread channels.

In these last paragraphs, the discussion is focused on the dominant modifications observed in the upstream part of the study sector (reaches B – H; Figs. 6, 9 and 11). The loss of geomorphic diversity with an evolution from multi-thread configuration in 1954 to a single-thread pattern in 2006 has been interpreted as the result of an incision phase

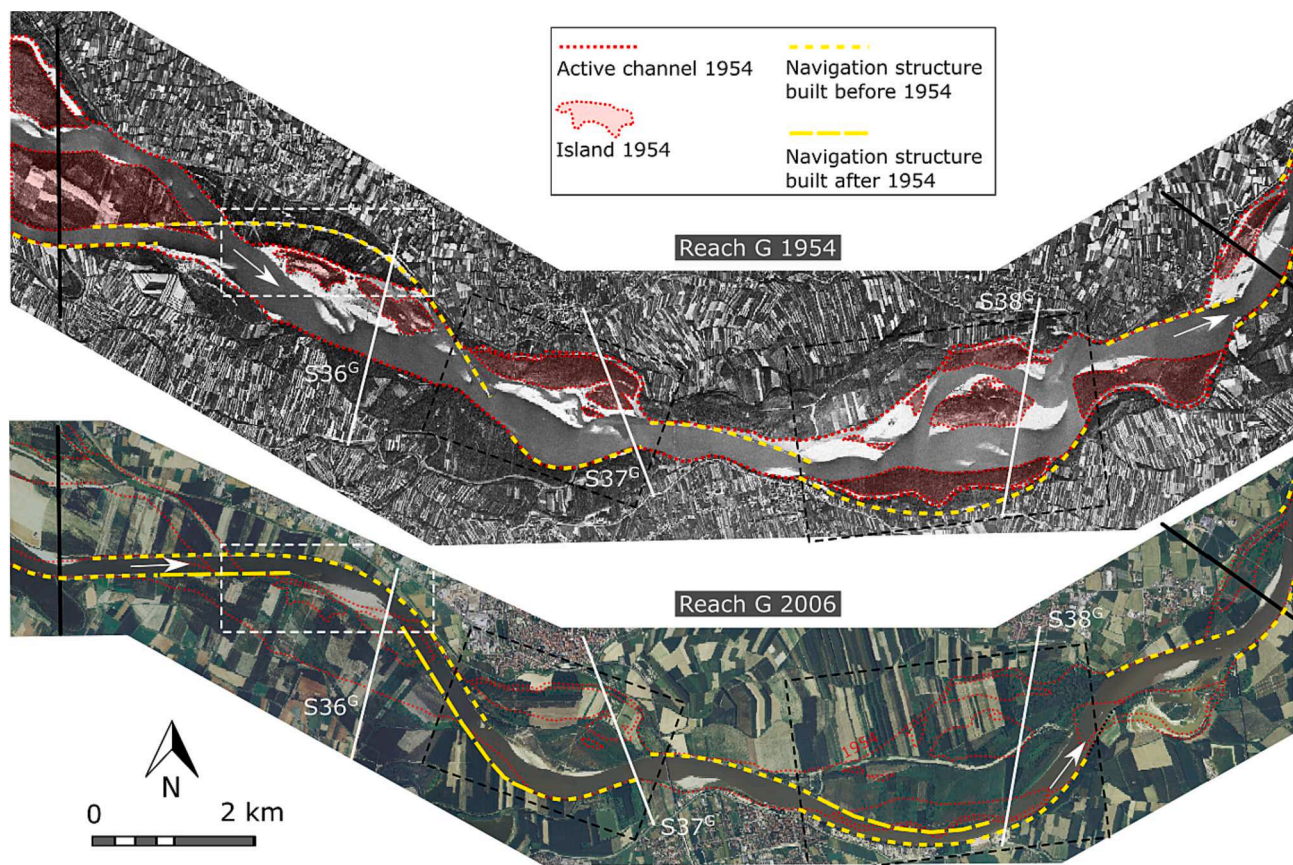


Fig. 11. Planform evolution occurred along reach G from 1954 to 2006. The white box highlights a site where bank erosion occurred leading the channel to reach the position of a levee that is part of the training scheme. The black boxes indicate two channel sites where the evolutions described in Figs. 9 and 10 occurred along reach G. The white arrows indicate flow direction.

that exclusively affected the channel portions not located behind navigation structures, inducing a progressive deactivation of the channels protected by groynes. Most of the training works were completed during the 1930 s and 1940 s (Gorio, 1953) and the river configuration of 1954 was comparable with that of the 19th century (Fig. 4). Moreover, riverbed lowering occurred with the highest rate during the 1970 s (Fig. 9), i.e., three to four decades after the building of navigation structures and almost simultaneously with the highest rate of in-channel mining and dam construction (Marchetti, 2002; Surian and Rinaldi, 2003; Parrinello et al., 2021). This time lag between the morphological changes and the training works cannot be explained in terms of absence of intense floods in the decades following the completion of the engineering interventions (i.e., 1940 s – 1960 s). In fact, as it can be observed in Fig. 1 and S1, the number and magnitude of major floods did not change significantly over the 1940 s – 2000 s period. We conclude that the training works alone did not directly cause significant modifications of the river morphodynamics and channel morphology. During implementation of the training scheme, the navigation structures were easily overflowable by water for a discharge of approximately $1000 \text{ m}^3 \text{ s}^{-1}$ (Gorio, 1953; Lanzoni, 2012), and consequently, the SCs were reachable by water almost half of the year, with flow dynamics affected only during very low discharge stages. In conditions of stable sediment fluxes, it is therefore reasonable to hypothesise that the morphological changes would have been negligible or only moderate, as suggested by the low modifications observed in terms of active channel width and planform configurations between the pre-training conditions (1853) and 1954 (i.e., 23 years after the beginning of the training scheme and 14 years after the completion of most of the navigation structures) (Fig. 4).

The human activities on the Po River for the exploitation of natural resources with higher intensity during the 1960 s – 1970 s induced a profound sediment starvation in the system (Dal Cin, 1983; Cencini, 1998; Billi and Spalevic, 2022; Brenna et al., 2022). As a result of this perturbation on sediment availability, in accordance with the works of Kondolf (1997), Brandt (2000), Lu et al., (2007) and Wyzga (2007), the active channels rapidly incised during the 1970 s, with major intensity where the flow competence and capacity were higher, that is, in the MCs not protected by groynes (Fig. 9). Similar short reaction times between human impacts and the river morphological response have been observed in other European case studies (e.g., Wyzga, 2007; Ziliani and Surian, 2012; Bollati et al., 2014; Scorpio and Roskopf, 2016; Brenna et al., 2021; Surian, 2022). The deactivation of the channel portions located behind navigation structures and the relative morphological simplification that produced a single-tread sinuous pattern (Figs. 9 and 11) were therefore the consequences of this riverbed lowering framed with the training works designed pattern. In summary, the extensive training works of the past acted as an anthropic predisposing condition for the subsequent morphological changes that were triggered and driven by the human-induced sediment starvation and by the consequent partial incision of the riverbed. Then, the geometry of the navigation structures controlled the planform position and sinuosity of the modified active channel.

Among the limitations affecting our interpretation, it is worth noting that it is based on inferring river morphodynamics from purely morphological evidence. Knowledge of the sedimentary processes and hydraulic forcing that led to the morphological changes is certainly worthy of further investigation. Moreover, the assessment of the weight of each anthropogenic impact on the evolution of the river system, included in Figs. 9 and 10 in terms of the intensity of a single impact during a certain period, is basically qualitative and deduced from the historical studies cited in Section 2.2 (e.g., Marchetti, 2002; Parrinello et al., 2021). A more quantitative assessment of the importance of various impacts, which would, for example, allow to distinguish the effects of Isola Serafini Dam from those of in-channel mining on sediment starvation, could be achieved by applying emerging models of network-scale sediment connectivity that can link sediment transport and river morphology (e.g., Gilbert and Wilcox, 2020; Bizzi et al., 2021;

Tangi et al., 2022). Indeed, validation of the results of such models could provide useful information about the relative weight of various anthropic impacts on bed material availability over the investigated period.

5.2. Unplanned morphological configurations

As discussed in the previous sections, the simplification of the river planform configuration was not straight due to the training scheme, which reliably has had only a minor direct effect on the morphodynamic functioning of the system (with the exception of where the SCs were forced to transform in the MCs; Figs. 7 and 10) and played the role of an anthropic predisposing condition to the subsequent morphological changes. The riverscape evolution was driven by the sediment starvation induced by in-channel mining and dam construction and the relative incision of the streambed (i.e., triggering factor), which could not homogeneously take place in the entire active channel but was exclusively concentrated in the channel portions not protected by navigation structures. In the absence of such groynes, we can speculate that the morphological rearrangement of the Po River would have been less significant, with homogeneous incision affecting almost the entire active channel and possible occurrence of narrowing, but with the maintenance of activity in most of the SCs and, therefore, preservation of the multi-tread or transitional morphologies originally characterising the Po River. Some examples of this type of response, corresponding with cases E, F, G and H of the model of channel adjustment proposed by Surian and Rinaldi (2003) and Rinaldi (2021), were recognized from Italian streams (e.g., Surian, 1999, 2006; Aucelli and Roskopf, 2000; Rinaldi, 2003) and from other countries and environments [e.g., Californian rivers, USA (Kondolf, 1995); Pyrenean rivers, Spain (Garcia-Ruiz et al., 1997)]. To further explore this hypothesis, future research efforts should focus on the evolutionary trajectory of the upstream part of the Po River course (e.g., along the braided sector encompassed by the confluence of the Sesia River and Ticino River; Fig. 1), where training schemes for navigation were not implemented. Data from Brenna et al. (2022) seem to support this theory (Fig. 12). Reaches B1-B3 of the Upper Po, starting from an active channel width of 500 – 600 m, narrowed approximately 10–25 % over the period 1954–1998 and maintained their original multi-thread planform configurations. In contrast, reaches E1 and F1 (corresponding to reaches A-H of the present work) characterised by an active channel width of 600 – 700 m in 1954, underwent in the same period a much more profound planform rearrangement, with a narrowing of approximately 50 % and a morphological simplification typified by an evolution from a multi-thread pattern to a single-thread pattern. However, more in-depth analyses are needed that take into account the specific anthropic pressures of these upstream reaches (e.g., was the in-channel mining equally intense?), the evolution of the riverbed elevation and the sediment dynamics in a steeper sector of the Po River with coarser bed material.

A landscape can be the result of a designed intervention aimed at changing a place in a desired way, such as in the case of land-levelling of a hilly area for agricultural purposes (Capolongo et al., 2008), the creation of a lake by stream damming (Fearnside, 2014), or the complete channelisation of a river that is deliberately transformed into an artificial canal (Slowik, 2013). In contrast, some anthropogenic riverscapes can be classified as “unplanned”, that is, not designed but generated by the feedback that occurred between multiple pressures that were not intended to modify the river configuration in the way that then actually happened. Being the result of interactions that occurred between diachronous anthropic impacts intended for different human purposes (i.e., navigation and exploitation of sediment and water resources), the current morphological configuration of the Po River study sector, although it is anthropogenic, can be accordingly defined as unplanned. Interestingly, in the absence of a deep understanding of the formative processes and geomorphological trajectory of the Po River, due to the similarity between the location of the navigation structures and the area currently

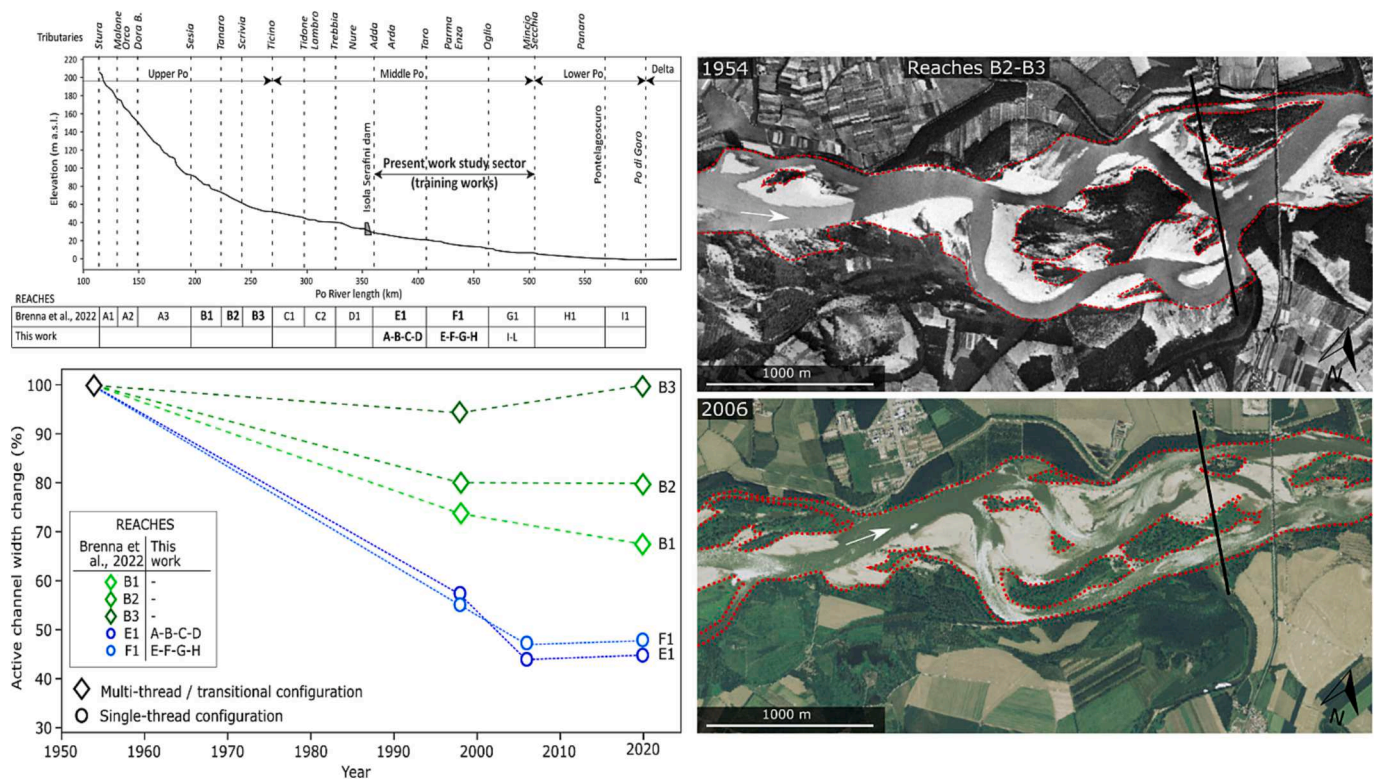


Fig. 12. Comparison of the evolution of the active channel width recognised by Brenna et al. (2022) at the upstream reaches of the Po River (B1, B2 and B3, located between the confluence of the Sesia River and Ticino River) with the evolution characterising the study sector analysed in this work (corresponding to reaches E1 and F1 of Brenna et al., 2022). The white arrows indicate flow direction.

occupied by the active channel, such morphological configuration could have been misinterpreted as the direct product of the training work interventions (i.e., designed river configurations), but this is not the case. To a certain extent, the morphological evolution of the study sector could also be defined as “unpredictable”, at least during training works implementation, when the following increment of anthropic pressures on the Po River that occurred two to three decades later was not expected.

Many river systems worldwide have been impacted by multiple and diachronous anthropogenic impacts comparable to those described for the Po River (Jain et al., 2016; Wohl, 2020; Surian, 2022). Many European rivers have been impacted by land-use changes, river-control works, channelization and instream mining. Channel adjustments include riverbed incision and narrowing, sometimes associated to sedimentation in inter-embankment zones (Wyżga, 1993, 2001; Lajczak, 1995; Marston et al., 1995; Kondolf et al., 2002; krzemiński et al., 2015). Among these rivers, an emblematic example is the Wisłoka River (southern Poland), which underwent a dramatic decrease in sediment supply during the second half of the 20th century due to the reduction of agricultural activity and reforestation in the catchment. Planform stabilisation of the river course by channelization works in the foothill reaches prevented the river from adjusting its transport capacity through an increment in sinuosity, and the sediment starvation (or energy excess) produced severe channel incision and concentration of flow into narrower channel sections (Wyżga, 2001b; Lach and Wyżga, 2002). Another interesting case is the Yangtze River (China), where the predominant type of impacts is represented mainly by dam construction. The intense riverbed scouring observed in the downstream sectors of the Yangtze River (Yang et al., 2022), however, is caused not only by the giant Three Gorges Project (i.e., the world’s largest hydropower project), but also by the cumulative effects induced by the presence of many other upstream cascade reservoirs, which acted as a predisposing condition to exacerbate the subsequent tendency of declining sediment load

(Yang et al., 2023). Many interesting examples could be cited from the U.S. rivers, in which channelization, flood control reservoir construction, dredging, straightening and mining actions exerted during the Anthropocene have been very impactful (e.g., Kondolf, 1995; Thorne, 1999; Downs et al., 2013; Wohl, 2020). Michalková et al. (2011) analysed the morphological evolution of the Sacramento River (California) observing a significant active channel narrowing and floodplain deactivation. They concluded that the observed changes were produced by a combination of dam impacts on sediment starvation and the increase in riprap protections which caused change in bank erodibility. The lesson learned from the Po River confirms that channel patterns generated by the feedbacks that occurred between multiple and diachronous pressures can represent a common type of riverscape in densely inhabited areas. In light of these insights and considering the socio-economic histories and evolutionary trajectories of the case studies above, we consider it appropriate to define the morphological configurations of the aforementioned rivers as shining examples of anthropogenic, unplanned channel patterns.

A comprehensive understanding of riverine sedimentary, hydraulic and geomorphological processes represents a crucial aspect for properly managing fluvial systems. To deeply understand the dynamics that recently occurred in channels affected by multiple anthropic pressures is therefore the key to properly living with rivers in the Anthropocene (García et al., 2021), and forecast the possible effects of human activities and managing strategies of fluvial systems, also with a view to identifying restoration strategies on highly impacted riverscapes (Slowik, 2013, 2015; Chardon et al., 2021). Although training works represent a predisposing condition but not the triggering factor for the morphological modification observed in the Po River, the presence of navigation structures should be considered a crucial element limiting the potential morphodynamic recovery of this system, also under conditions of increasing sediment availability in the future.

6. Conclusion

The evolutionary trajectory reconstructed in detail for the study sector, considered with available historical data on the anthropic pressures that acted over the 20th century on the Po River, allowed us to draw reliable interpretations about the complex morphological modifications that affected this sector of the river course and the relative causes. The main outcomes of this study are summarised as follows:

- 1) Two groups of anthropic pressures acted on the study sector: an extensive training scheme for navigation purposes implemented during the 1930 s and 1940 s and a series of human activities carried out with the highest intensity during the 1960 s and 1970 s for the exploitation of sediment and water resources.
- 2) The evolution from a multi-thread configuration in the 1950 s to a sinuous configuration at the beginning of the 21st century, accompanied by a remarkable narrowing of the active channel, has been interpreted as follows: The extensive training works of the past acted as an anthropic predisposing condition for the subsequent morphological changes, which were driven by the profound sediment starvation caused by in-channel mining and the construction of the Isola Serafini Dam, representing the triggering factors of the morphological modifications. Such sediment starvation caused an uneven riverbed lowering, in particular a remarkable incision in the 1970 s in the MCs not protected by groynes, with deactivation of the SCs located behind navigation structures.
- 3) The current morphological configuration of the study sector is anthropogenic, that is, its evolution has been determined by anthropic pressures that acted, and interacted, during the 20th century on this sector of the Po River. We speculate that the sediment starvation that occurred without the presence of training works may have generated a different geomorphological trajectory that likely conserved a multi-thread or transitional configuration. The morphological modifications that led to this result can also be defined as unplanned, that is, not designed but caused by multiple diachronous impacts on the same river sector, whose effects on the river system have interacted.
- 4) The lesson learned from the Po River suggests that anthropogenic, unplanned channel configurations can represent a common type of riverscape in densely inhabited areas in different regions of the Earth, significantly affecting (future) geomorphological trajectories of these fluvial systems and their recovery potential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.catena.2023.107598>.

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