

# The great decline of suspended sediment load in the Po River (Italy) over the last 100 years

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## ABSTRACT

This study investigates how a sequence of human impacts has profoundly altered suspended sediment yields in the Po River, the largest fluvial system in Italy, over the last 100 years. By integrating long-term data on suspended sediment transport with a detailed analysis of anthropogenic drivers—including land-use changes, in-channel mining, damming and river training works—we reconstruct the spatiotemporal trajectory of sediment dynamics across the river system. Results reveal a marked reduction in suspended sediment yields, occurring asynchronously along the Po River: declines of about –48% first emerged in the middle course during the 1920s–1940s, primarily due to dam construction in the western catchment, and later, with comparable intensity, in the lower course (1950s–1980s), largely driven by river training interventions, sediment deposition within the active channel, and sediment retention in flood detention basins along the Apennine tributaries. Considering the entire investigated time window (1924–2019), the river exhibits a substantial long-term reduction in annual suspended sediment yields, exceeding –72% at the catchment closure. These reductions in fine sediment transport have contributed to trigger substantial geomorphological transformations affecting the delta region. The findings underscore the complexity of interpreting sediment dynamics under overlapping anthropogenic pressures and highlight the need for integrated management strategies aimed at restoring sediment fluxes and connectivity. In particular, the partial reactivation of sediment deposits accumulated within anthropogenically induced traps along the main stem could represent a promising, though complex, strategy to mitigate sediment deficits and support more sustainable management of the delta.

## 1. Introduction

Rivers convey and export sediments generated by erosion processes within their drainage basins, playing a crucial role in shaping the Earth's surface and representing a key component of the global land-ocean sediment transfer (Walling, 1987; Milliman and Syvitski, 1992; Syvitski et al., 2003). Their sediment yields have also significant implications for human activities, including the management of reservoirs (Espa et al., 2019), river corridors and delta (Wohl, 2015; Besset et al., 2019), beaches (Cilli et al., 2021), flood hazards (Vázquez-Tarrafó et al., 2024), and pollutant dispersion (Förstner, 2004). Depending on the flow capacity and particle size, shape, and density, the fluvial transport of sediment can occur by two main mechanisms: as bedload, which is the movement of grains progressing by rolling, sliding, or bouncing over the riverbed (Haschenburger, 2013), or as suspended load, which is material carried within the water column by turbulent forces in the flowing fluid

without coming into contact with the bed (Turowski et al., 2010; Kuhnle, 2013). According to Church (2006), in the majority of fluvial systems, gravel, cobbles, and boulders are transported as bedload, silt and clay move in suspension, while sand can be transported by both mechanisms. In large rivers, the suspended load constitutes the quantitatively dominant component of solid transport, comprising approximately 85–99% of the total sediment load (Knighton, 1998; Babiński, 2005; Nittrouer et al., 2008).

It is notable that suspended sediment load remains difficult to estimate theoretically or through modeling, although recent studies have shown promising advancements in this area (e.g., Olyae et al., 2015; Shojaezadeh et al., 2024; Moradinejad, 2024). It is, however relatively easier to be accurately measured in the field (Hicks and Gomez, 2016). This is accomplished using a variety of techniques, including manual or automated samplers and sensors (e.g., Hicks and Gomez, 2016; Kuhnle, 2013; Latosinski et al., 2014; Doriean et al., 2019). Consequently, some

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countries have implemented suspended sediment load monitoring programs, which, since the early 20th century, have supplemented traditional monitoring of water discharges (Walling and Fang, 2003). Despite various challenges and uncertainties, such as the spatial distribution of monitoring sites, the continuity of time series, and the quality of data (Walling and Fang, 2003), the long-term datasets thus produced by government authorities have become precious, serving also as useful materials for scientific research.

Studies utilizing these data have focused on long-term (i.e., decades to centuries) changes in suspended sediment transport at global (e.g., Milliman and Meade, 1983; Jansson, 1988; Walling and Fang, 2003; Walling, 2006), regional (e.g., Poulos and Collins, 2002; Vanmaercke et al., 2014; Billi and Spalevic, 2022), and individual stream-catchment scales (e.g., Duan et al., 2013; Montanher et al., 2018; Sun et al., 2021; Das et al., 2025). The observed trends in suspended sediment transport vary widely, including increases (e.g., Kolyma River, Siberia; Walling and Fang, 2003), stable (e.g., Ob River, Russia; Walling and Fang, 2003), and complex patterns (e.g., Loushui River, China; Sun et al., 2016). However, a significant proportion of global case studies indicate substantial declines in suspended sediment loads, with decreases of up to 70–80% occurred during the 20th century and, in some cases, continuing into the present (Kesel, 1988; Walling, 2006; Meade and Moody, 2010; Li et al., 2018; Hoffmann et al., 2023). Such studies analyze the factors influencing the aforementioned temporal trajectories, enhancing the understanding of both natural and anthropogenic causes that affect suspended sediment yields in rivers over medium-to-long time intervals (Walling and Fang, 2003; Vercruyssen et al., 2017). Several authors have emphasized the importance of changes in hydro-meteorological factors, which are primarily associated with climatic fluctuations, as well as river discharge regime (Kettner et al., 2007; Rovira et al., 2015; Abbott et al., 2018). In addition to these variables, anthropogenic factors that can act at watershed scale or directly on a river's stem play a crucial role. These factors include dam and reservoir construction (Poulos and Collins, 2002; Walling, 2006), land use changes (Asselman et al., 2003; Abbott et al., 2018), dredging and mining activities (Chalov, 2014), navigation (Vilmin et al., 2015), implementation of soil, water and sediment control programs (Zhao et al., 1992; Hooke, 2006; Rustomji et al., 2008), and river-training schemes (Meade and Moody, 2010).

In the Italian context, numerous studies have been conducted on suspended sediment transport in rivers. However, these studies are often based on specific and relatively short-term sampling campaigns or on the application of empirical models (e.g., Van Rompaey et al., 2005; Bartolini and Fontanelli, 2009; Hinderer et al., 2013; Grauso et al., 2021). Despite the availability of historical datasets on suspended loads produced through monitoring by water agencies since the early 20th century, their scientific utilization remains limited. Only recently, Billi and Spalevic (2022) conducted a thorough analysis of the available data for nine rivers distributed across the country. Their main objectives were to investigate the effectiveness of catchment and hydrological parameters in controlling suspended sediment yields and to compare these data with those from other regions in the world. Their investigation of decadal variations in sediment yields, in accordance with results obtained from modeling approaches (Syvitski and Kettner, 2007), indicates a decrease in sediment load over the last decades. Such decrease is attributed to macro-drivers related to climate and land use changes, such as the decrease in annual precipitation and the expansion of forest cover. That said, identifying the factors that have controlled such suspended transport trajectories in the past is by no means a straightforward task. It requires careful analysis of the temporal trends in transport data and a detailed reconstruction of the factors—often anthropogenic—that may have driven such trends.

The present study uses long-term suspended transport monitoring data and is focused on the spatial and temporal evolution of the suspended load in the Po River that, extending 651 km, encompassing a drainage area of 75,000 km<sup>2</sup> and having an average daily discharge at

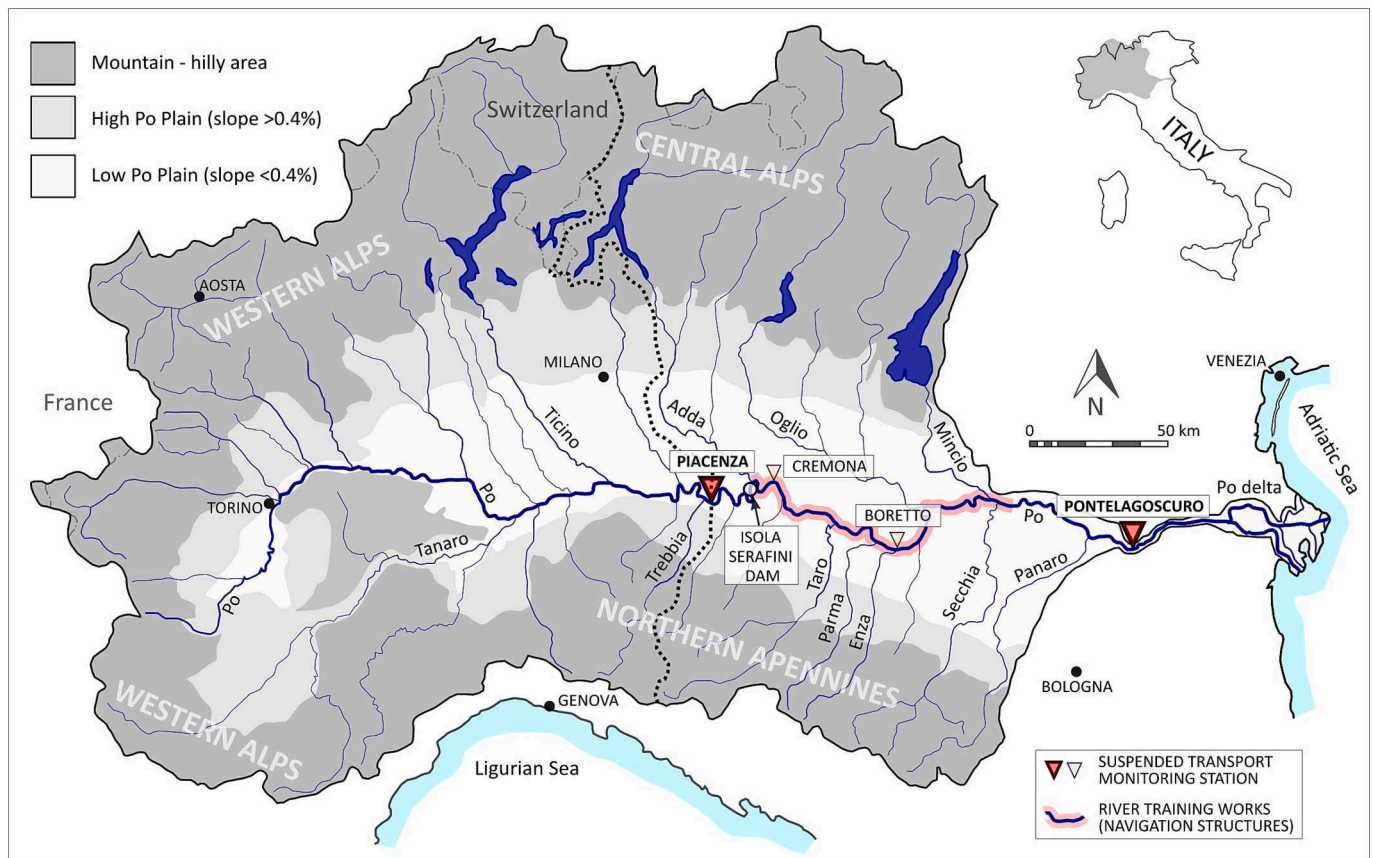
the catchment outlet of 1470 m<sup>3</sup>s<sup>-1</sup> (Zanchettin et al., 2008; Montanari, 2012), is the largest fluvial system in Italy (Fig. 1). The Po River represents the primary conveyance system for transporting sediment from the Alps and Northern Apennines uplands to the Adriatic Sea, substantially contributing to the total sediment load to the continental margin (Syvitski and Kettner, 2007; Tesi et al., 2013). The Po Plain has been highly attractive for human settlement and has experienced intensive agricultural, industrial, and urban development over the past centuries, peaking in the central decades of 20th century (Parrinello et al., 2021) when intensive in-channel sediment mining was conducted along both the Po River and its tributaries (Dal Cin, 1983; Marchetti, 2002; Surian and Rinaldi, 2003; de Sordi et al., 2025) and dams were constructed on the hydrographic network of the catchment (Bizzi et al., 2015; Parrinello et al., 2021). The catchment experienced also significant land use changes with a notable increase in forest cover during the same period (Marchetti, 2002; Surian and Rinaldi, 2003; Falcucci et al., 2007; Parrinello et al., 2021). Additional anthropogenic interventions on the Po River included a large-scale river training scheme implemented during the 1930s–50s (Gorio, 1953; Galvani and Pellegrini, 2009; Brenna et al., 2024) to ensure the permanent navigability of the main channel in the middle sector of the river. Accordingly, the Po River and its catchment area have undergone significant anthropogenic influences that have profoundly altered sediment production, connectivity and supply to river network, and transport capacity of the river (Billi and Spalevic, 2022; Brenna et al., 2022, 2024; de Sordi et al., 2025).

Owing to its socio-economic, ecological, and hydro-morphological significance within one of the most anthropogenically modified regions of Europe (the Po Plain), and its function as a major sediment supplier to the northern Adriatic coast, this study aims to elucidate how a sequence of diachronous human impacts, acting and interacting over time, have profoundly modified the suspended sediment yield of the Po River. As demonstrated by previous studies (e.g., Das et al., 2022), variations in suspended load can occur with different magnitudes and timings at distinct locations along a river system. For this reason, this study draws on data collected over the last 100 years from multiple sediment monitoring stations located along the middle and lower course of the Po River (Fig. 1), where temporal trends in suspended sediment yield were found to differ significantly. In light of these observations, the research adopted a detailed spatial framework to investigate the controlling factors driving these heterogeneous spatiotemporal trajectories of suspended sediment load. Indeed, the interpretation of such trends cannot rely solely on global drivers (e.g., climate change) or basin-wide processes; rather, it required in-depth consideration of local factors, such as in-channel mining, damming and river training works, that may have influenced the temporal evolution of suspended sediment transport along the Po River. Advancing knowledge of these dynamics in the Po River is particularly timely, given the fragile condition of its deltaic system. Accordingly, the results of this study are discussed in the light of ongoing plans for river restoration and renaturation projects within the Po River corridor and their contribution to preserving the delta from potential drowning through the mitigation of suspended sediment deficit.

## 2. Materials and methods

### 2.1. Discharge and sediment load data

The Po River was the first river in Italy subject to regular coupled hydrologic and suspended sediment monitoring at multiple sites situated along its course, initiated in the early decades of the 20th century by the National Hydrological Service. Systematic daily suspended sediment concentration measurements were conducted using a procedure that involved three water samplings along a river cross-section, utilizing a bottle sampler known as the “*Campionatore Rossetti*” (Russo et al., 2010). A first sample was taken at the centerline of the wet channel, approximately one-third of the depth below the water surface, while two



**Fig. 1.** The Po River catchment and the monitoring stations equipped for suspended sediment transport sampling. The dotted black line delineates the boundary of the drainage sub-basin closing at Piacenza.

additional samples were taken at the midpoint of the sub-sections identified by the centerline (Billi and Spalevic, 2022). As a consequence of the fixed-depth sampling strategy, it should be noted that this approach may under-sample the near-bed zone, where coarser suspended sediment fractions (e.g., medium sand) are commonly conveyed (Kleinhans and Ten Brinke, 2001; Wright and Parker, 2004). The average suspended sediment concentration (in  $\text{kg}/\text{m}^3$ ) was calculated following laboratory filtering, drying, and weighing of the collected samples to determine a daily suspended sediment concentration. The daily average suspended sediment transport (in  $\text{kg}/\text{s}$ ) was then calculated by multiplying the suspended sediment concentration by the average daily water discharge ( $\text{m}^3/\text{s}$ ) estimated at the same river section. For the Po River, these data were documented in the Hydrological Annals (*Annali Idrologici*), initially published by the National Hydrographic Service and more recently by the Emilia-Romagna Regional Environmental Agency (ARPAE; <https://www.arpae.it/it/temi-ambientali/meteo/report-meteo/annali-idrologici>). These documents report not only daily water discharge data but also monthly maximum, minimum, and average daily suspended sediment concentration and suspended sediment transport, along with the total monthly suspended sediment yields (ton) calculated at the sections as the sum of daily suspended transport values obtained from monitoring data.

The first two monitoring stations equipped for regular suspended sediment transport sampling were located in Piacenza and Pontelagoscuro (Fig. 1). The Piacenza section, situated in the Middle Po, drains an area of  $42,030 \text{ km}^2$  (56% of the total drainage area). The river is single-thread with a sinuous geometry and exposed sediment bars, and has an average slope of 0.027% and bed material primarily composed of medium sands (Brenna et al., 2022). The Pontelagoscuro section is located further downstream, near the catchment closure, draining an area of  $70,090 \text{ km}^2$  (94% of the total drainage area). This section also features a

single-thread, sinuous morphology, with an average slope of 0.003% and bed material mainly consisting of fine to medium sands (Brenna et al., 2022). For both river sections, we have downloaded, digitalized and statistically analyzed using the software Statgraphics Centurion XIX (<https://www.statgraphics.com/how-to-guides>) the water discharge and suspended sediment (i.e., concentration and transport) data available from the Hydrological Annals for the period from 1924 to 2019. The initial characterization involved the analysis of water discharge time series: utilizing daily discharge data, the river's hydrological behavior was characterized by examining the maximum flow rate ( $\text{m}^3/\text{s}$ ), mean flow rate ( $\text{m}^3/\text{s}$ ), and total water discharge ( $\text{m}^3$ ) calculated on an annual basis. During the period 1924–2019, we identify intervals when transport monitoring was not conducted, specifically from 1944 to 1955 due to the aftermath of World War II, and from 1992 to 2009 due to the transfer of responsibilities of river monitoring authority from the National Hydrological Service to regional Hydrological Services (Billi and Spalevic, 2022). Since 2020, the traditional monitoring described in the previous section has been discontinued, with plans currently underway to install new automatic turbidimeter probes along the river. In addition to the monitoring sections described, there are two further measurement sites located in Cremona and Boretto (Fig. 1), with shorter historical records. Due to the shorter temporal extent of these suspended load measurements, the present study focuses on the long-term monitoring data available from the Piacenza e Pontelagoscuro sections. Analysis of suspended sediment transport focused on two parameters provided by the Hydrological Annals at a monthly temporal resolution: average suspended sediment concentration ( $\text{kg}/\text{m}^3$ ) and suspended sediment yields (tons). These monthly data were aggregated to calculate the respective annual average values (i.e., the weighted mean of the monthly average suspended sediment concentration values for each year) and annual totals (i.e., the sum of the monthly suspended transport

values for each year) for the three periods during which transport monitoring was actually conducted, namely: 1924–1943, 1956–1991, and 2010–2019.

## 2.2. Reconstruction of the anthropogenic impacts

The reconstruction of anthropogenic impacts on the Po River system over the last century was primarily achieved through the analysis of historical documentation. Particular attention was given to drivers that, based on previous knowledge available for the Po catchment (e.g., Marchetti, 2002; Lanzoni, 2012; Parrinello et al., 2021; Billi and Spalevic, 2022; Brenna et al., 2022, 2024; de Sordi et al., 2025) and findings from studies on comparable fluvial systems (e.g., Loizeau and Dominik, 2000; Meade and Moody, 2010; Rovira et al., 2015), may have influenced the temporal trajectories of suspended transport. Specifically, our investigation focused on historical changes in catchment land use, dam and reservoir construction, and implementation of river training works.

With respect to land use data and its temporal changes, information from the European Corine project is only available from the 1990s onwards, whereas earlier historical cartographic sources cover only the Emilia-Romagna region and not the entire Po River basin. For this reason, this study utilizes land use data regularly published by the Italian National Institute of Statistics (ISTAT; <http://seriestoriche.istat.it/>), as previously synthesized by Niedertscheider and Erb (2014). These authors, using available regional statistics and integrating model-based assumptions where data were missing, developed land-use change diagrams for consistent land use classes across Italy, distinguishing among different portions of the peninsula (e.g., Northern Italy) over the period 1934–2007. Among the seven land-use categories available (i.e., annual cropland, permanent cropland, unproductive areas, forest land, grazing land, settlement areas and other land), we specifically considered changes in the percentages of forest cover and agricultural annual cropland—two land categories associated with low and high production of fine sediment, respectively (García-Ruiz et al., 1995; Liébault et al., 2005)—.

The construction of reservoirs and filtering dams represents a significant anthropogenic factor that can influence sediment transport throughout the hydrographic network. The geographic distribution of these structures within the Po River basin, along with their features and periods of construction, has been sourced from official documentation provided by the Italian Ministry of Infrastructure and Transport (“Ministero delle Infrastrutture e dei Trasporti”; [https://dgdighe.mit.gov.it/categoria/articolo/\\_cartografie\\_e\\_dati/\\_cartografie/cartografia\\_dighe](https://dgdighe.mit.gov.it/categoria/articolo/_cartografie_e_dati/_cartografie/cartografia_dighe)). This basic documentation that mainly considers large dams under central state jurisdiction has been further enriched with data from prior studies investigating the historical progression of anthropogenic activities in the Po River basin (e.g., Parrinello et al., 2021). The presence and characteristics of minor dams and transverse structures were not taken into account, as no comprehensive inventory is currently available.

In analyzing the river training scheme implemented during the 1930s to 1950s along the 123 km stretch of the Po River between the confluences of the Adda and Mincio rivers (Fig. 1), where the Po had exhibited a multi-threaded morphological configuration until the early 20th century (Brenna et al., 2024), we relied on the detailed documentation by Gorio (1953) and subsequent reviews (e.g., Galvani and Pellegrini, 2009), which provide historical maps, detailed engineering drawings, and archival photographs documenting the chronology, typology, dimensions, and locations of the interventions. The river training interventions, in addition to bank protections and levees, included the construction of navigation structures within the active channel (i.e., groynes) aimed at reducing flow in secondary channels and concentrating water in a single main channel, ensuring permanent navigability of this river sector also under low-flow conditions (i.e., discharge <math><1000\text{ m}^3/\text{s}</math>). As recently discussed by Brenna et al. (2024), between the 1950s and the 1980s, secondary channels located behind these navigation structures experienced bed aggradation due to

depositional processes and siltation phenomena facilitated by the hydrodynamic effects caused by in-channel groynes. In this study, we focus on the depositional bodies generated by these localized sedimentation processes, characterizing them as described in the following section.

## 2.3. Characterization of sediment trapped behind navigation structures

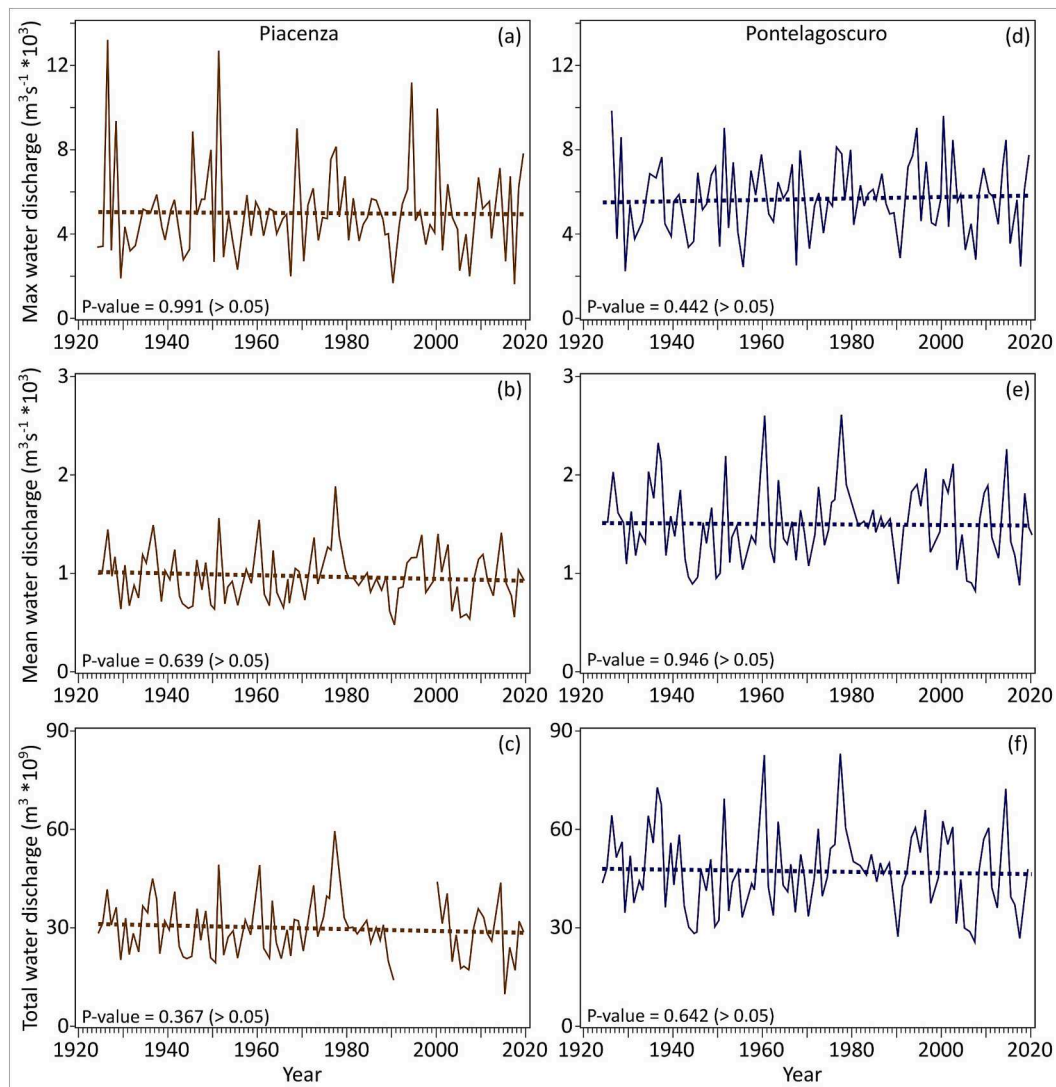
Our objective was to quantify the volumes and type of sediment deposited behind the navigation structures, constituting the infill bodies of the deactivated secondary channels. For the entire sector impacted by these river training interventions, we mapped the planimetric extent of the areas affected by deactivation, i.e., areas that were part of the active channel in the past and then evolved into external surfaces. To achieve this, we used two sets of aerial imagery: one from 1954 (“Volo GAI”, available as a Web Map Service from the Geoportal of the Lombardy Region, <https://www.geoportale.regione.lombardia.it>; spatial resolution of 0.7 m/pixel) and another from 2006 (available as a Web Map Service from the National Geoportal of Italy, <https://www.pcn.minambiente.it>; spatial resolution of 0.5 m/pixel). Based on these images, the active channel of the Po River, which, following Liébault and Piégay (2002), is defined as an area including low-flow channels and sediment bars, was manually delineated. We mapped areas that became inactive during this period (i.e., those that transitioned from active channels to geomorphic unit such as floodplains and terraces) and measured their area using QGIS 3.32. To estimate the volumes of deposited sediment, the thickness of these depositional bodies was measured. For this, we utilized two sets of topographic cross-sections measured along the Po River in 1954 and 2005, available from the Geoportal of the Interregional Agency for the Po River (AIPO; <https://www.geoportale.ageenziapo.it>). For each cross-section intersecting one of the deactivated areas described above, we calculated the average change in topographic elevation that occurred between 1954 and 2005. In cases where positive elevation changes were observed (indicative of net deposition, i.e., the most prevalent condition in such settings as described by Brenna et al., 2024), this value provided a localized estimate of the thickness of the depositional body accumulated between the two topographic surveys. For deactivated channel areas not intersected by topographic sections, the thickness of deposits was calculated by considering the average of the thicknesses derived for neighboring areas. By multiplying the areas by the thicknesses, we estimated for each site the volume of sediment that has been deposited since the construction of the navigation structures.

To characterize the sedimentological properties of the infill deposits, ten cores were manually drilled at four depositional sites situated behind the groynes (for their locations see Section 3.3) using a hand-operated corer equipped with a hollow auger tip, suitable for recovering medium- to fine-grained sediments to depths of several meters. The stratigraphic sequences were documented in the field, allowing differentiation of layers based on their grain-size composition, classified as predominantly cohesive (clay and silt) or non-cohesive sand. In addition, small sediment samples (approximately 200 g each) were collected from representative levels of the two aforementioned layers types for subsequent laboratory analyses, during which a laser granulometer (Mastersizer 3000) was used to obtain detailed grain size parameters.

## 3. Results

### 3.1. Spatiotemporal trajectories of water discharge and suspended load

Over the period 1924–2019, at the Piacenza gauging station, the observed annual maximum water discharges ranged from 1470  $\text{m}^3/\text{s}$  to 13,100  $\text{m}^3/\text{s}$ , mean flow rates varied between 459  $\text{m}^3/\text{s}$  and 1827  $\text{m}^3/\text{s}$ , and total annual discharges ranged from 10.2  $\text{Mm}^3$  to 59.2  $\text{Mm}^3$  (Figs. 2a-c). At the Pontelagoscuro monitoring station, the annual maximum recorded discharges ranged from 2220  $\text{m}^3/\text{s}$  to 9780  $\text{m}^3/\text{s}$ ,

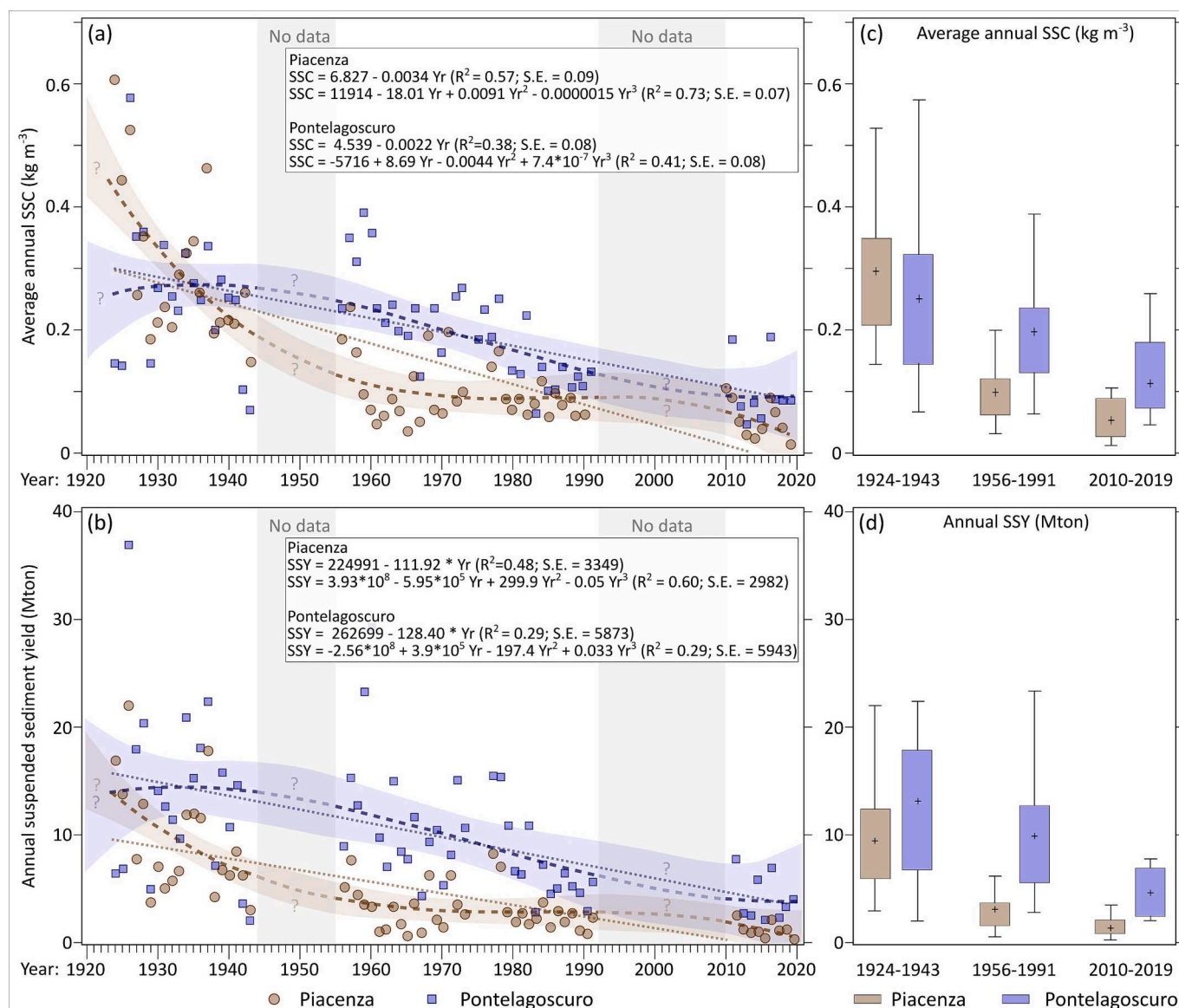


**Fig. 2.** Time series of water discharge recorded at Piacenza (a, b and c) and Pontelagoscuro (d, e and f) gauging stations over the period 1924–2019, expressed as annual maximum flow rate (a and d), mean flow rate (b and e), and total water discharge (c and f). Obtained linear regression relationships ( $P$ -values are reported) are plotted with dotted lines.

mean flow rates varied between 825 m<sup>3</sup>/s and 2620 m<sup>3</sup>/s, and total annual water discharges ranged from 25.9 Mm<sup>3</sup> to 83.0 Mm<sup>3</sup> (Figs. 2d-f). Although the values exhibit substantial year-by-year fluctuations, no clear long-term trends are evident in any of the parameters at the two gauging stations, as indicated by the little-sloping regression lines and the relative statistical metrics shown in the panels of Fig. 2. A basic linear regression analysis reveals only slight deviations from this pattern: a modest decline in the mean flow rate at Piacenza (Fig. 2b), and a slight increase in the maximum flow rate at Pontelagoscuro (Fig. 2d) occurring over the period 1924–2019.

At Piacenza station, average annual suspended sediment concentration (SSC) values during the entire analysis period ranged from a minimum of 0.013 kg/m<sup>3</sup> in 2019 to a maximum of 0.606 kg/m<sup>3</sup> in 1924. At Pontelagoscuro station, SSC values ranged from 0.045 kg/m<sup>3</sup> in 2013 to a maximum of 0.574 kg/m<sup>3</sup> in 1926 (Fig. 3a). Annual suspended sediment yields (SSY) also exhibit significant variation at both stations (Fig. 3b). At Piacenza, the yields ranged from a minimum of 0.4 Mtons in 2019 to a maximum of 22.0 Mtons in 1926. At Pontelagoscuro, the yields varied from a low of 2.1 Mtons in 1943 to a peak of 37.0 Mtons in 1926. In contrast to the observed water flow regimes (Fig. 2), clear temporal trends were identified in the suspended transport data. Simple linear regressions reveal a decrease in both parameters related to suspended

sediment transport over the period analyzed (Fig. 3). Analyzing the distribution of SSC values at the two stations across the three measurement periods, the average annual values exhibit a declining trend. At Piacenza, average SSC decreased from 0.296 kg/m<sup>3</sup> in the period 1924–1943 to 0.098 kg/m<sup>3</sup> in 1956–1991 and further to 0.054 kg/m<sup>3</sup> in 2010–2019 (Fig. 3c). Least Significant Difference (LSD) multiple range testing revealed a statistically significant difference (confidence level > 95.0%) between the average SSC values of the first period (1924–1943) and those of the subsequent two periods, which did not differ significantly from each other. Similarly, at Pontelagoscuro, the average SSC values declined from 0.256 kg/m<sup>3</sup> in 1924–1943 to 0.197 kg/m<sup>3</sup> in 1956–1991 and reached 0.097 kg/m<sup>3</sup> in 2010–2019. In this case, all periods exhibited statistically significant differences in their mean values. A comparable decreasing trend is observed in the mean annual suspended sediment yield (SSY). At Piacenza, the SSY decreased from 9.5 Mtons/yr in the period 1924–1943 to 3.1 Mtons/yr in 1956–1991 and further to 1.5 Mtons/yr in 2010–2019 (Fig. 3d). At Pontelagoscuro, the mean SSY values declined from 13.6 Mtons/yr in 1924–1943 to 9.9 Mtons/yr in 1956–1991, eventually reaching 4.3 Mtons/yr in 2010–2019. As observed for SSC, SSY in Piacenza showed statistically significant differences between the first period and the subsequent two periods, while at Pontelagoscuro all periods differed significantly.



**Fig. 3.** Temporal distribution of annual average suspended sediment concentration (SSC) (a) and suspended sediment yield (SSY) (b) at Piacenza and Pontelagoscuro Stations. Linear regression relationships for suspended load parameters over time are represented with dotted lines, while polynomial regression relationships are depicted with dashed lines, accompanied by their respective confidence intervals. The lighter-shaded portions of the polynomial regression curves, marked with a question mark, indicate segments of the time series for which no monitoring data on sediment transport are available; in these intervals, the reported trends should not be interpreted as representing actual patterns. The corresponding equations and their statistical parameters are provided for reference. Panels (c) and (d) present boxplots illustrating the distribution of annual average SSC and annual SSY values during three distinct periods (1924–1943, 1956–1991, and 2010–2019) at the two monitoring stations. The boxplot whiskers represent the 10th and 90th percentiles, the boxes mark the interquartile range (25th to 75th percentiles), and the mean values are indicated by crosses.

To further characterize these trends, polynomial regressions were performed to capture the temporal evolution of the suspended transport parameters at the two monitoring stations. The regression results indicate that the trends are not constant over the whole analyzed period and the trajectories observed at Piacenza and Pontelagoscuro differ substantially. In the case of suspended sediment yield (SSY), we considered three distinct time intervals, based on the availability of monitoring data: 1924–1943, 1956–1991, and 2010–2019. The changes in SSY for both stations were calculated within these intervals using the polynomial regressions reported in Fig. 3b. During the first period (1924–1943), SSY at Piacenza showed a marked decline (–48%), while values at Pontelagoscuro remained relatively stable, around 14.2–14.1 Mton/yr. In the subsequent period (1956–1991), the trend reversed: the rate of decline at Piacenza became less pronounced (–19%), whereas a much stronger decrease (nearly –50%) was recorded at Pontelagoscuro.

Finally, during the most recent period (2010–2019), SSY continued to decrease at both stations, though more sharply at Piacenza. Overall, considering the entire 1924–2019 time window, both monitoring sections exhibit a substantial long-term reduction in SSY, exceeding –85% and –72% at Piacenza and Pontelagoscuro, respectively. Comparable trends were observed at the monitoring stations when suspended sediment concentration (SSC) was analyzed using the polynomial regressions presented in Fig. 3a. Overall, a significantly greater reduction in SSC was evident at the Piacenza station during the earliest period (–54%), compared to Pontelagoscuro, where the regression indicates substantial stability in SSC between 1924 and 1943. In contrast, during the intermediate period, a more pronounced decline in SSC was observed at Pontelagoscuro (–48%), resulting in similar average SSC values (approximately 0.08–0.12 kg/m<sup>3</sup>) at both stations by the end of the period in 1991. The most recent period, however, reveals a sharper

decrease in SSC at the Piacenza station. Detailed numerical values for each period, parameter and monitoring station are provided in Table 1.

The final set of analyses examined the relationships between suspended sediment transport and water discharge data. As illustrated in Fig. 4, weak direct correlations between suspended transport parameters and hydrological data were observed. Especially in the case of SSY, this condition is likely attributable to a spurious correlation, as water discharge is one of the parameters used to compute sediment transport. In contrast, SSC represents a more reliable indicator for detecting system changes, as it is independent of discharge (Hoffmann et al., 2023). A more detailed analysis of data dispersion reveals a clear temporal pattern. At both stations, for the same annual total water discharge and/or maximum annual water discharge, SSC and SSY yearly values tend to

**Table 1**  
Temporal trends of suspended sediment yield (SSY) and concentration (SSC) for the three analyzed periods (1924–1943, 1956–1991, and 2010–2019) at the Piacenza and Pontelagoscuro monitoring stations.

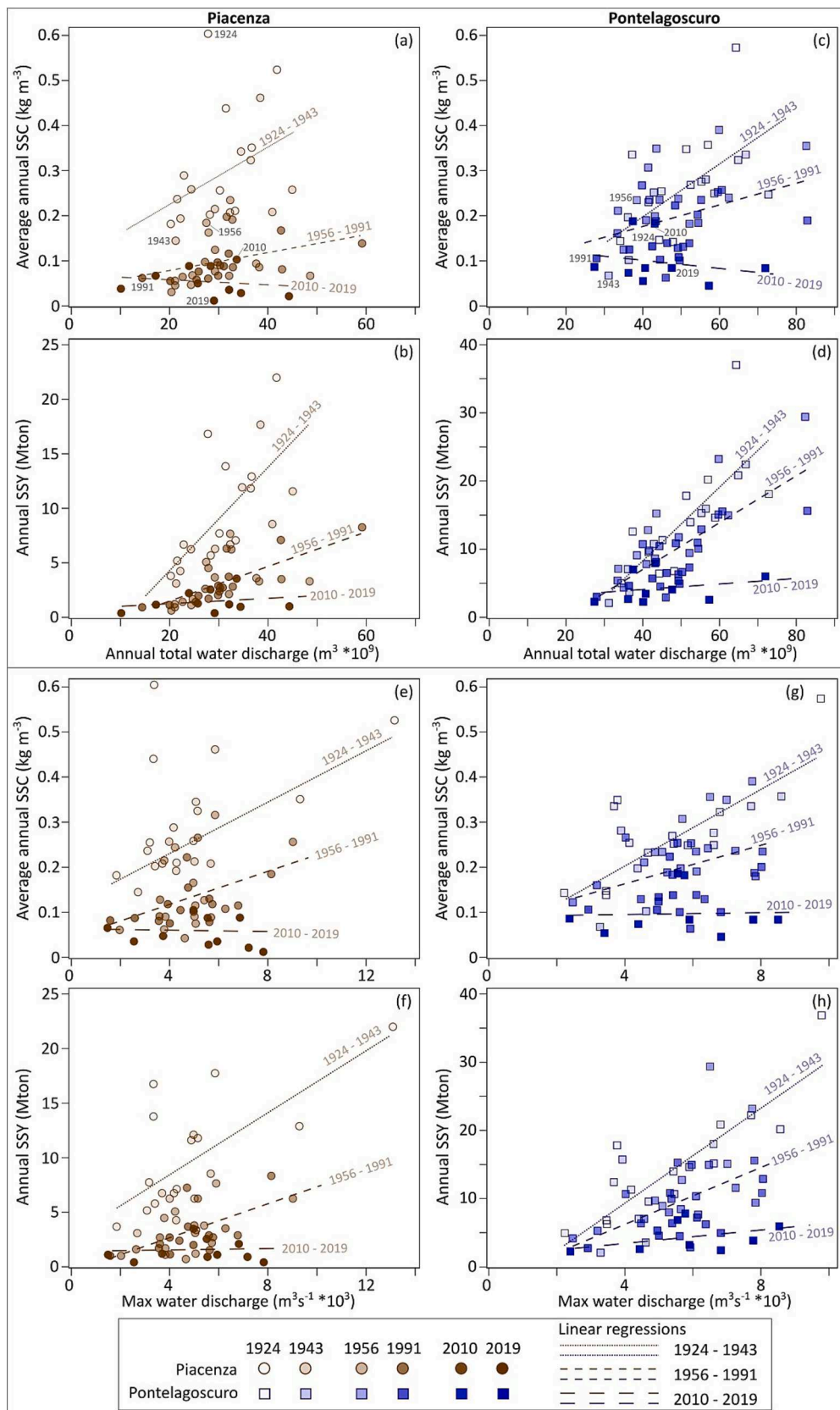
|                          |   |   | Piacenza  | Pontelagoscuro |        |
|--------------------------|---|---|---|----------------|--------|
| Suspended sediment yield | 1924–1943 (19 years)                            | Total annual SSY 1924 (10 <sup>3</sup> tons/yr) | 15,353  | 14,236         |        |
|                          |   | Total annual SSY 1943 (10 <sup>3</sup> tons/yr) | 8054  | 14,095         |        |
|                          |   | % Difference Average                            | -48%  | -1%            |        |
|                          |   | yearly change (10 <sup>3</sup> tons)            | -384  | -7             |        |
|                          |   | 1956–1991 (35 years)                            | Total annual SSY 1956 (10 <sup>3</sup> tons/yr) | 5734           | 12,575 |
|                          |   |   | Total annual SSY 1991 (10 <sup>3</sup> tons/yr) | 4616           | 6485   |
|                          |   |   | % Difference Average                            | -19%           | -48%   |
|                          |   | yearly change (10 <sup>3</sup> tons)            | -32   | -174           |        |
|                          |   | 2010–2019 (9 years)                             | Total annual SSY 2010 (10 <sup>3</sup> tons/yr) | 3676           | 4249   |
|                          | Total annual SSY 2019 (10 <sup>3</sup> tons/yr) |   | 2349  | 3981           |        |
|                          | % Difference Average                            |   | -36%  | -6%            |        |
|                          | yearly change (10 <sup>3</sup> tons)            | -147  | -30   |                |        |
|                          | Suspended sediment concentration                | 1924–1943 (19 years)                            | Average annual SSC 1924 (kg/m <sup>3</sup> )    | 0,42           | 0,25   |
|                          |   |   | Average annual SSC 1943 (kg/m <sup>3</sup> )    | 0,19           | 0,26   |
|                          |   |   | % Difference                                    | -54%           | 4%     |
| 1956–1991 (35 years)     |   |   | Average annual SSC 1956 (kg/m <sup>3</sup> )    | 0,12           | 0,24   |
|                          |   |   | Average annual SSC 1991 (kg/m <sup>3</sup> )    | 0,08           | 0,12   |
|                          |   | % Difference                                    | -29%  | -48%           |        |
| 2010–2019 (9 years)      |   | Average annual SSC 2010 (kg/m <sup>3</sup> )    | 0,06  | 0,09           |        |
|                          |   | Average annual SSC 2019 (kg/m <sup>3</sup> )    | 0,02  | 0,08           |        |
|                          |   | % Difference                                    | -61%  | -11%           |        |

be higher in the early years of monitoring (i.e., first decades of the 20th century) and gradually decrease over time. Consistent with the patterns shown in Fig. 3, the reduction in suspended transport parameters is more pronounced during the transition from the first (1924–1943) to the second (1956–1991) monitoring period at the Piacenza station (Fig. 4a, b, e and f). In contrast, at Pontelagoscuro, the most significant decline in SSC and SSY occurs later, specifically between the second (1956–1991) and the third (2010–2019) monitoring periods (Fig. 4c, d, g and h). The observed patterns are consistent with the double mass rating curves (Fig. 5) obtained considering cumulative annual water discharge and sediment load at each monitoring station (Walling and Fang, 2003). At Piacenza, the curve (Fig. 5a) exhibits a distinct negative deviation from its original slope at low cumulative discharges, reflecting an early (i.e., before 1943) reduction in sediment load relative to discharge. Conversely, at Pontelagoscuro, the curve (Fig. 5b) remains nearly constant in slope, though a pronounced decrease in suspended sediment flux emerges during a later phase (i.e., after 1956).

### 3.2. Spatiotemporal distribution of the anthropogenic impacts

The land-use data from Niedertscheider and Erb (2014) considered in this study pertains to the entire Northern Italy, encompassing not only the Po River Basin but also additional regions such as Trentino-Alto Adige, Friuli Venezia Giulia and Liguria. During the 1930s to 1950s, this territory was predominantly characterized by agricultural land, with annual crops covering more than 40% of the total area, while forest cover represented just over 20% (Fig. 6). A significant shift in land use began in the early 1960s, when agricultural land experienced a decline of approximately 10 percentage points over the course of a decade. Concurrently, forest cover began to increase gradually. Throughout the 1970s and 1980s, agricultural land remained marginally dominant in terms of area, until reaching parity with forest cover in 1989. Following this date, agricultural land continued to decline, while forest cover expanded correspondingly. By 2007, the latest year for which data are available, forest cover had increased to 31%, representing by far the dominant class within Northern Italy (Niedertscheider and Erb, 2014), while agricultural land had decreased to 22% (Fig. 6).

Among the large dams constructed along the hydrographic network of the Po River Basin, the earliest was completed in 1787 in order to regulate the outflow of water from Lake Pusiano (Fig. 7), which feeds the Lambro River. In the following decades, few additional structures were built within the study area, bringing the total number of dams to 13 by 1919 (Fig. 7). It was only in the decades immediately thereafter that a significant increase in dam construction occurred (Fig. 7). Specifically, 39 dams were completed in the 1920s, followed by 30 in the 1930s, 18 in the 1940s, and 31 in the early 1950s. These developments raised the total number of large dams in the Po River Basin to 132 by the end of the 1950s. In the following decades, the pace of dam construction slowed considerably, with only a few additional projects being carried out. By the early 21st century, dam construction had essentially ceased, stabilizing the total number of large dams in the basin at 161. The geographical distribution of dams within the Po River Basin is uneven (Fig. 7). Most of the dams, primarily constructed for hydroelectric purposes (Parrinello et al., 2021), are concentrated in mountainous and hilly regions. The number of dams located within the drainage sub-basin closing at Piacenza (109) is higher than that in the eastern sector of the basin (52). In the eastern sector of the drainage basin, many dams, built predominantly between the 1930s and 1950s, are situated upstream of the large pre-Alpine lakes of the Central Lombardy Alps. In contrast, some dams were constructed more recently, during the late 20th century and early 21st century, along the lowland sectors of the Apennine tributaries of the Po River (i.e., Tidone, Parma, Crostolo, Secchia and Panaro rivers), whose confluences are located downstream of Piacenza. These more recent structures are primarily designed for hydraulic protection, functioning as detention (dry pond) basins aimed at flood risk mitigation (see Gumiero et al., 2015; Brenna et al., 2021). Among the dams



**Fig. 4.** Average annual suspended sediment concentration (SSC) (a, c, e, g) and annual suspended sediment yield (SSY) (b, d, f, h) against total annual water discharge (a, b, c, d) and maximum annual water discharge (e, f, g, h) estimated at the two monitoring stations (a, b, e, f: Piacenza; c, d, g, h: Pontelagoscuro). The darker the color of the symbol, the more recent in time the data considered. Linear regression relationships for suspended load parameters over time are represented with lines, distinguishing three sub-sets of data referring to periods 1924–1943, 1956–1991 and 2010–2019.

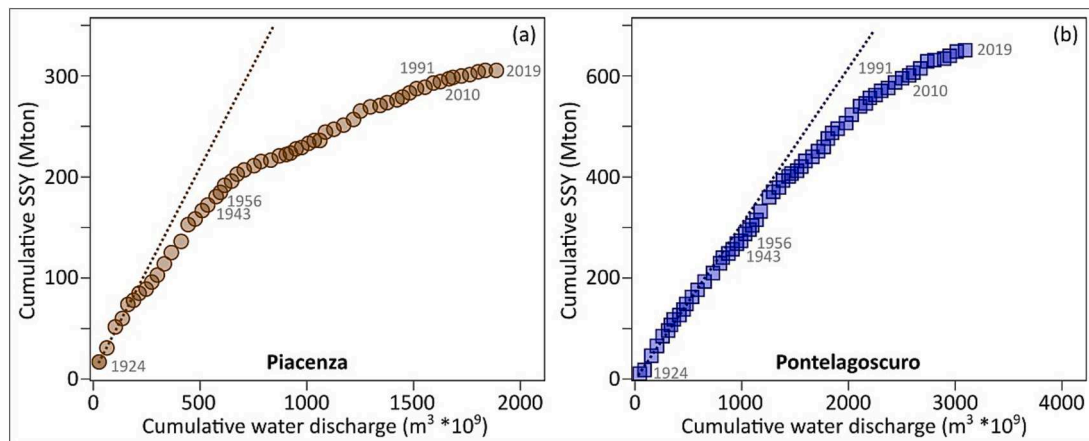


Fig. 5. Double mass rating curves illustrating the relationship between cumulative annual water discharge and suspended sediment yield at Piacenza (a) and Pontelagoscuo (b) monitoring stations. The grey numbers refer to selected years within the 1924–2019 interval.

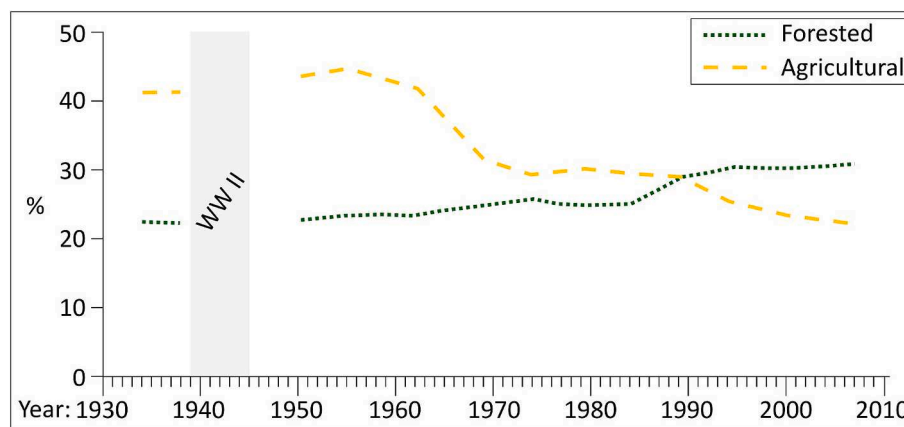


Fig. 6. Land-use changes in Northern Italy (1934–2007) considering the two most important land-use categories from a percentage coverage perspective.

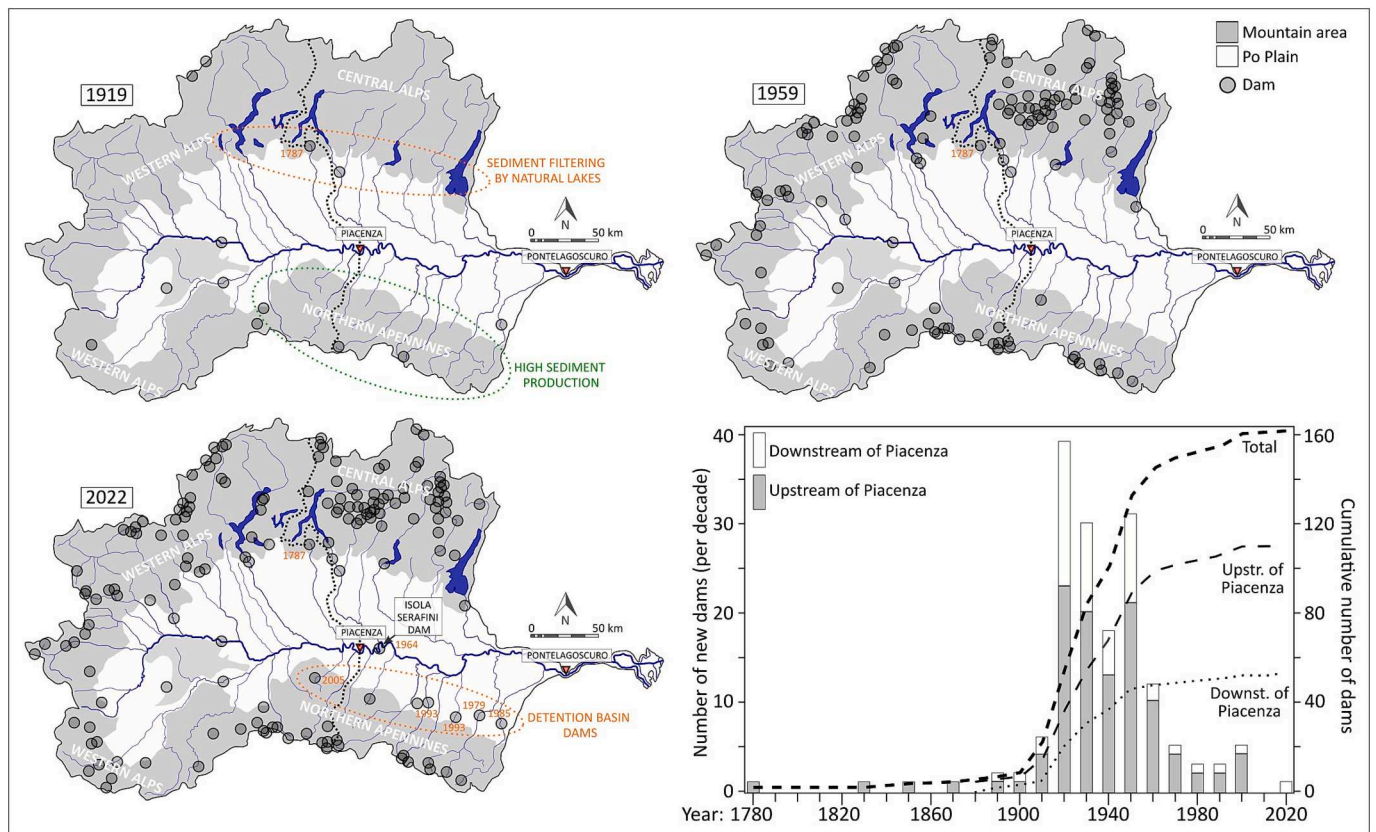
constructed within the Po River basin, the Isola Serafini dam, situated directly on the main stem of the Po River a few kilometers downstream from Piacenza, is particularly noteworthy. The construction of this dam, initiated in 1960 and completed in 1964, was primarily aimed at hydroelectric power generation (Lanzoni, 2012; Parrinello et al., 2021). The dam constitutes a significant interruption of the sediment transfer along the fluvial system (Bizzi et al., 2015; Maselli et al., 2018; Brenna et al., 2022).

### 3.3. Volume and type of sediments trapped behind navigation structures

A comparison of the Po River's active channels delineated for the years 1954 and 2006 identified 45 distinct areas between the confluences of the Adda and Mincio Rivers that experienced deactivation over the investigated period (Fig. 8). These areas consist of former secondary channels or side bars positioned behind navigation groynes that have evolved into floodplains or river terraces. The spatial distribution of these deactivated zones is relatively uniform along the sector influenced by river training schemes implemented to facilitate navigation (Fig. 8). However, the most extensive deactivated areas in terms of planimetric size are concentrated in the upstream portion of the sector where their surface areas often exceed  $1 \text{ Mm}^2$  (Table 2). Topographic cross sections measured in 1954 and 2006 intersected a total of 19 of these deactivated areas. The thickness of depositional bodies accumulated over this time interval ranged from a minimum of 0.50 m to a maximum of 3.40 m, with an average thickness of 2.35 m (Table 2). This average value, along with its standard deviation of  $\pm 1.0 \text{ m}$ , was used to estimate the thickness

of deposits in the remaining 26 areas where multi-temporal topographic data are not available, allowing the calculation of depositional volumes. By multiplying the measured or estimated areas and thicknesses of the deactivated zones listed in Table 2, we determined that the total volume of depositional bodies infilling the 45 deactivated areas amounts to  $96.1 \pm 16.8 \text{ Mm}^3$ .

The data obtained from the ten cores drilled at sections S28, S33, S35, and S36 (see Fig. 8 for locations), which intersect the deactivated areas identified by codes 280, 330, 350, and 360, respectively (see Table 2), provided insights into the sedimentological properties of the depositional bodies from a grain-size perspective. Across all four sections analyzed, the infill behind the navigation groynes predominantly comprises silty deposits in the upper layers, interspersed occasionally with sandy strata (Fig. 8). At greater depths, the sediment becomes progressively coarser. Notably, at depths ranging from 1 to 2 m below ground level, sand becomes the dominant grain-size fraction. In all cores that extended to the topographic surface of the 1954 active channel (i.e., S28\_3, S33\_1, S33\_2, and S36\_1), the materials beneath this surface were exclusively composed of sand (Fig. 8). Laboratory grain-size analyses were conducted on four samples: two classified as predominantly sandy and two as predominantly silty, based on field descriptions. These samples were collected from specific stratigraphic levels in cores S28\_1 and S36\_2 (Fig. 8). The predominantly sandy deposits exhibit median grain sizes ( $D_{50}$ ) ranging from 0.13 to 0.20 mm, classifying them as fine sand according to the Wentworth (1922) scale. These deposits are composed of approximately 85% sand-sized particles, with the remaining 15% consisting of silt. In contrast, the predominantly silty



**Fig. 7.** Distribution of large dams constructed along the hydrographic network of the Po River basin in different periods. In the bottom right graph dams are distinguished on the basis of their location in the western (sub-basin closed at Piacenza) or eastern part of the drainage basin. The bars indicate the number of new dams constructed in each decade, while the dashed lines show the progressive increase in the cumulative number of dams within the basin. Dates in orange refer to the year the hydraulic works were completed.

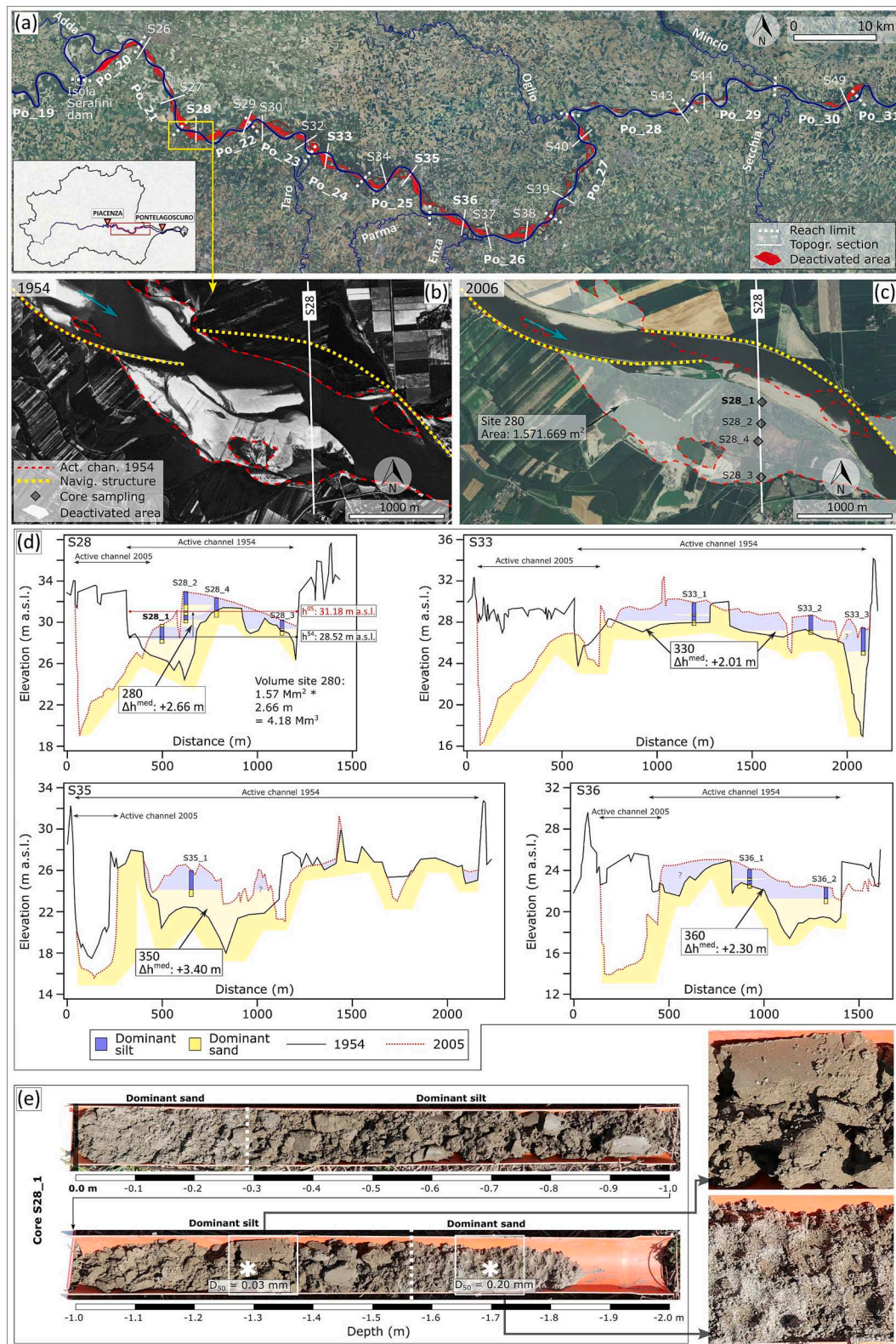
deposits have median grain sizes between 0.02 and 0.03 mm, corresponding to medium to coarse silt. Within these silty deposits, the sand content is lower than 10%. By extrapolating these data obtained from core stratigraphy and particle size analysis to the entirety of the depositional bodies, it can be estimated that of the total  $96.1 \pm 16.8 \text{ Mm}^3$  of material present in the deactivated areas located behind navigation structures, approximately half of it consists of silt, while the remainder is composed of sand. Although robust, this estimate relies on a relatively limited set of direct observations. Consequently, the percentage ratios between the two grain-size fractions may be further refined through additional investigations, either direct (e.g., coring) or indirect (e.g., geophysical surveys).

### 3.4. Relating controlling factors and spatiotemporal trajectories of suspended sediment load

The analysis of the suspended sediment transport time series from the Po River indicates a substantial decline in both suspended sediment concentration (SSC) and suspended sediment yield (SSY) over the past 100 years (Figs. 3 and 4). Notably, however, the temporal trends of these parameters differ significantly between the two monitoring stations located at Piacenza and Pontelagoscuoro. As illustrated in Figs. 3, 4, 5 and 9, the reduction in suspended transport was more pronounced at Piacenza between 1924 and 1943, with a 48% and 54% decrease in SSY and SSC, respectively. In contrast, at Pontelagoscuoro, after an initial period of relative stability, a similar reduction in suspended transport ( $-48\%$  SSY and  $-48\%$  SSC) occurred later, from 1956 to 1991, when Piacenza showed greater stability. These distinct trends observed at an upstream station (Piacenza) and a downstream station (Pontelagoscuoro) suggest that, besides basin-wide controlling factors, local factors likely played a

role on suspended sediment transport in different sectors of the Po River at different times. Identifying these factors could provide valuable insights into the spatial and temporal variability in sediment transport along the river system.

In contrast to suspended load observations from other river systems significantly impacted by changes in flow regimes (e.g., Kettner et al., 2007; Ai et al., 2015; Abbott et al., 2018), the data presented in Fig. 2 indicate that the maximum, average, and total flow rates of the Po River over the past 100 years exhibit no clear long-term trends at either Piacenza or Pontelagoscuoro gauging stations. Even the extensive dam construction that occurred during the first half of the 20th century (Fig. 7) does not appear to have affected the overall hydrological regime of the Po River delineated on the basis of annual data. This is likely due to the large size of the basin and the limited impact of temporary reservoir storage on the river's long-term water balance. The hydrological analyses conducted in this study are relatively simplified. Previous studies focusing on interannual patterns of peak and low flows in the Po River (e.g., Zanchettin et al., 2008; Montanari, 2012; Billi and Fazzini, 2017; Guo et al., 2025) indicate a moderate increase in flood and drought hazards in recent decades, particularly when compared with river behavior in the 19th century. However, regarding the period examined in this paper (1920s–2010s), these studies also underscore the absence of pronounced temporal trends, suggesting that long-term flow behaviors in the Po River remain not easily detectable (Montanari, 2012). This lack of a notable trend in flow metrics supports the exclusion of hydro-meteorological variability as the primary factor driving the substantial long-term decline in suspended sediment concentration and suspended sediment yield observed across the river system. To further corroborate this conclusion, the results presented in Figs. 4 and 5 are particularly informative. These results show that SSC and annual SSY



**Fig. 8.** Distribution of active channel areas that became deactivated between 1954 and 2006 (a). The boundaries of geomorphologically homogeneous river reaches (sensu [Brierley and Fryirs, 2005](#)) were derived from the official segmentation adopted by the Po River Basin Authority. Panels (b) and (c) show planform examples of the deactivated area identified as code 280 (see [Table 2](#)), based on aerial photographs from 1954 (b) and 2006 (c). Panel (d) presents topographic cross-sections from 1954 and 2005 intersecting the deactivated areas 280 (section S28), 330 (section S33), 350 (section S35), and 360 (section S36). For section S28, the areal extent, mean elevations at both survey dates ( $h^{54}$  and  $h^{05}$ ), the average elevation change induced by sediment deposition ( $\Delta h^{med} = h^{05} - h^{54}$ ), and the calculated volume of depositional site 280 are reported as example. The locations of four cores drilled at section S28 (area 280) are also indicated in (c). Panel (d) includes the stratigraphic logs of ten cores collected at sections S28, S33, S35, and S36, together with a reconstruction of the sedimentological characteristics of the deposits forming the infill of the deactivated areas 280, 330, 350, and 360. The lower panel (e) shows photographic examples of one core (S28\_1) collected at section S28. White asterisks mark the sampling points of materials analyzed in the laboratory for grain-size distribution.

**Table 2**

Detailed characteristics of the 45 deactivated areas. Names of geomorphologically homogeneous river reaches are derived from the official segmentation adopted by the Po River Basin Authority. N/A: not available.

| Area Code | Reach        | Topographic section | Area (m <sup>2</sup> ) | Measured thickness (m) | Estimated thickness (m) | Volume (Mm <sup>3</sup> ) |
|-----------|--------------|---------------------|------------------------|------------------------|-------------------------|---------------------------|
| 254       | Po_20        | N/A                 | 683,257                | –                      | 2.35 ± 1.00             | 1.61 ± 0.68               |
| 255       | Po_20        | N/A                 | 783,089                | –                      | 2.35 ± 1.00             | 1.84 ± 0.78               |
| 260       | Po_21        | S_26                | 238,072                | 2.13                   | –                       | 0.51                      |
| 261       | Po_21        | N/A                 | 740,860                | –                      | 2.35 ± 1.00             | 1.74 ± 0.74               |
| 262       | Po_21        | N/A                 | 1,104,529              | –                      | 2.35 ± 1.00             | 2.60 ± 1.10               |
| 263       | Po_21        | N/A                 | 392,481                | –                      | 2.35 ± 1.00             | 0.92 ± 0.39               |
| 270       | Po_21        | S_27                | 723,729                | 1.08                   | –                       | 0.78                      |
| 271       | Po_21; Po_22 | N/A                 | 1,872,661              | –                      | 2.35 ± 1.00             | 4.40 ± 1.86               |
| 280       | Po_22        | S_28                | 1,571,669              | 2.66                   | –                       | 4.18                      |
| 281       | Po_22        | N/A                 | 1,478,157              | –                      | 2.35 ± 1.00             | 3.47 ± 1.47               |
| 282       | Po_22        | N/A                 | 566,462                | –                      | 2.35 ± 1.00             | 1.33 ± 0.56               |
| 290       | Po_22; Po_23 | S_29                | 1,619,373              | 3.04                   | –                       | 4.92                      |
| 300       | Po_22; Po_23 | S_30                | 386,250                | 1.80                   | –                       | 0.70                      |
| 301       | Po_23        | S_30                | 237,001                | 3.05                   | –                       | 0.72                      |
| 302       | Po_23        | N/A                 | 2,123,302              | –                      | 2.35 ± 1.00             | 4.99 ± 2.11               |
| 320       | Po_23        | S_32                | 714,146                | 3.26                   | –                       | 2.33                      |
| 321       | Po_23; Po_24 | S_32                | 1,451,994              | 3.30                   | –                       | 4.79                      |
| 330       | Po_24        | S_33                | 2,067,071              | 2.01                   | –                       | 4.15                      |
| 331       | Po_24        | N/A                 | 400,654                | –                      | 2.35 ± 1.00             | 0.94 ± 0.40               |
| 332       | Po_24; Po_25 | N/A                 | 681,053                | –                      | 2.35 ± 1.00             | 1.60 ± 0.68               |
| 340       | Po_25        | S_34                | 1,325,552              | 3.18                   | –                       | 4.22                      |
| 350       | Po_25        | S_35                | 2,542,645              | 3.40                   | –                       | 8.64                      |
| 351       | Po_25; Po_26 | N/A                 | 1,251,144              | –                      | 2.35 ± 1.00             | 2.94 ± 1.25               |
| 360       | Po_26        | S_36                | 2,063,234              | 2.30                   | –                       | 4.75                      |
| 370       | Po_26        | S_37                | 1,035,299              | 0.63                   | –                       | 0.65                      |
| 380       | Po_26        | S_38                | 2,912,960              | 2.26                   | –                       | 6.58                      |
| 381       | Po_26        | N/A                 | 140,955                | –                      | 2.35 ± 1.00             | 0.33 ± 0.14               |
| 382       | Po_26        | N/A                 | 215,226                | –                      | 2.35 ± 1.00             | 0.51 ± 0.21               |
| 383       | Po_26; Po_27 | N/A                 | 526,237                | –                      | 2.35 ± 1.00             | 1.24 ± 0.52               |
| 390       | Po_27        | S_39                | 539,705                | 0.50                   | –                       | 0.27                      |
| 391       | Po_27        | N/A                 | 728,644                | –                      | 2.35 ± 1.00             | 1.71 ± 0.73               |
| 392       | Po_27        | N/A                 | 551,162                | –                      | 2.35 ± 1.00             | 1.30 ± 0.55               |
| 393       | Po_27        | N/A                 | 867,055                | –                      | 2.35 ± 1.00             | 2.04 ± 0.86               |
| 400       | Po_27        | S_40                | 1,044,674              | 2.73                   | –                       | 2.85                      |
| 401       | Po_27        | N/A                 | 350,448                | –                      | 2.35 ± 1.00             | 0.82 ± 0.35               |
| 402       | Po_28        | N/A                 | 297,165                | –                      | 2.35 ± 1.00             | 0.70 ± 0.30               |
| 403       | Po_28        | N/A                 | 61,128                 | –                      | 2.35 ± 1.00             | 0.14 ± 0.06               |
| 404       | Po_28        | N/A                 | 471,571                | –                      | 2.35 ± 1.00             | 1.11 ± 0.47               |
| 405       | Po_28        | N/A                 | 114,786                | –                      | 2.35 ± 1.00             | 0.27 ± 0.11               |
| 430       | Po_28        | S_43                | 395,624                | 3.29                   | –                       | 1.30                      |
| 440       | Po_29        | S_44                | 570,825                | 2.61                   | –                       | 1.49                      |
| 441       | Po_29        | N/A                 | 240,022                | –                      | 2.35 ± 1.00             | 0.56 ± 0.24               |
| 442       | Po_29        | N/A                 | 141,084                | –                      | 2.35 ± 1.00             | 0.33 ± 0.14               |
| 443       | Po_30        | N/A                 | 102,484                | –                      | 2.35 ± 1.00             | 0.24 ± 0.10               |
| 490       | Po_30        | S_49                | 2,535,327              | 1.00                   | –                       | 2.54                      |

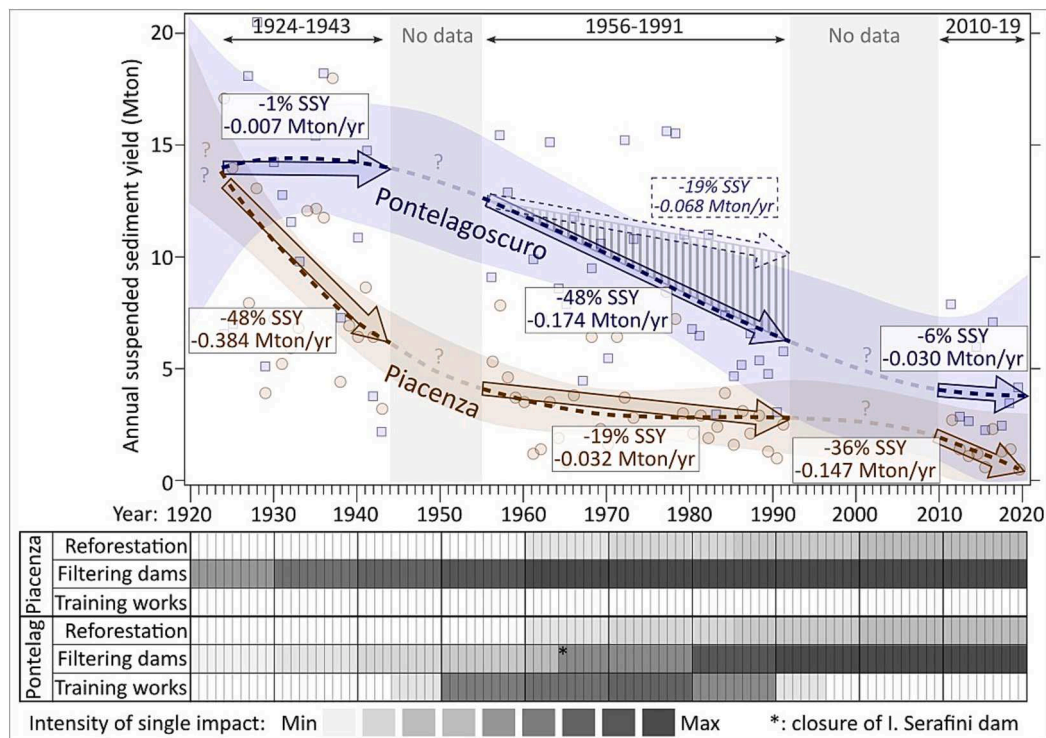
exhibit a pronounced decline over time for the same total water discharge and/or maximum water discharge calculated on an annual basis at the two monitoring stations. This confirms that the hydrological variables alone do not exert a major influence on suspended sediment transport processes in the Po River and, in particular, on their spatio-temporal evolutions. In the following sections, the individual datasets previously presented are analyzed in greater spatial and temporal detail in order to identify, for each period, the factors that best explain the observed evolutionary trends.

### 3.4.1. Period 1924–1943: The golden age of hydroelectric dams

During the initial monitoring period from 1924 to 1943, land use within the Po River catchment has remained strongly dominated by agricultural use (Fig. 6) but there was an extensive deployment of dams, primarily constructed since the 1910s and 1920s, concentrated in the upper and western part of the catchment (Fig. 7). This period also saw substantial dam construction in the central Alpine region, particularly upstream of the large pre-Alpine lakes. In contrast, dam installations along the Apennine tributaries of the Po River were markedly limited and concentrated in the head portions of their catchments (see Fig. 7). It is well-established that filtering dams can substantially disrupt the longitudinal transfer of sediment within river systems, including sediment transported in suspension (e.g., Rovira et al., 2015; Wang et al.,

2018). The Northern Apennines, with land-use, soil types and lithologies that promote high rate of erosion and production of fine-grained particles (e.g., Pieri et al., 2009), constitute a major sediment source for the Po River system. In contrast, sediment input from the Alpine chain, especially Central Alps, is lower, owing to the low-erodible geology of the mountains, glacial coverage, and natural sediment-trapping function of the pre-Alpine lakes (Hinderer, 2001; Fanetti and Vezzoli, 2007; Fanetti et al., 2008; Hinderer et al., 2013) (Fig. 7). The dams constructed in the early 20th century reduced sediment contributions from the Western Alps to the Po River system. Conversely, sediment inputs from the Central Alps and Northern Apennines were likely less affected due to the following reasons: (i) in the case of the Central Alps, sediment input was already limited by natural lakes, minimizing the impact of dams; (ii) dam construction along the Apennine tributaries was sparse during this period, resulting in minimal disturbance to sediment flow from these sources.

In the Piacenza sub-basin, sediment supply to the Po River is primarily sourced from the Western Alps, with a lesser contribution from the Apennines (see Fig. 1). Intensive dam construction in these regions of the basin resulted in a localized but substantial reduction in sediment delivery to the fluvial system, aligning with a marked decrease in suspended sediment yield (–48% SSY) recorded at the Piacenza station between 1924 and 1943 (Fig. 9). By contrast, sediment transport at



**Fig. 9.** Temporal trend of annual suspended sediment yield (SSY) represented by the polynomial regressions reported in Fig. 3 for the two monitoring stations. For each of the three periods considered (1924–1943, 1956–1991 and 2010–2019) the percentage changes in annual SSY and the relative annual rate of change (Mton/yr) are shown. Details regarding the significance of the vertically striped triangle can be found in Section 4.1.2. The lower part of the figure schematizes the temporal intensity of each anthropogenic impact having a potential controlling role on suspended transport along the Po River.

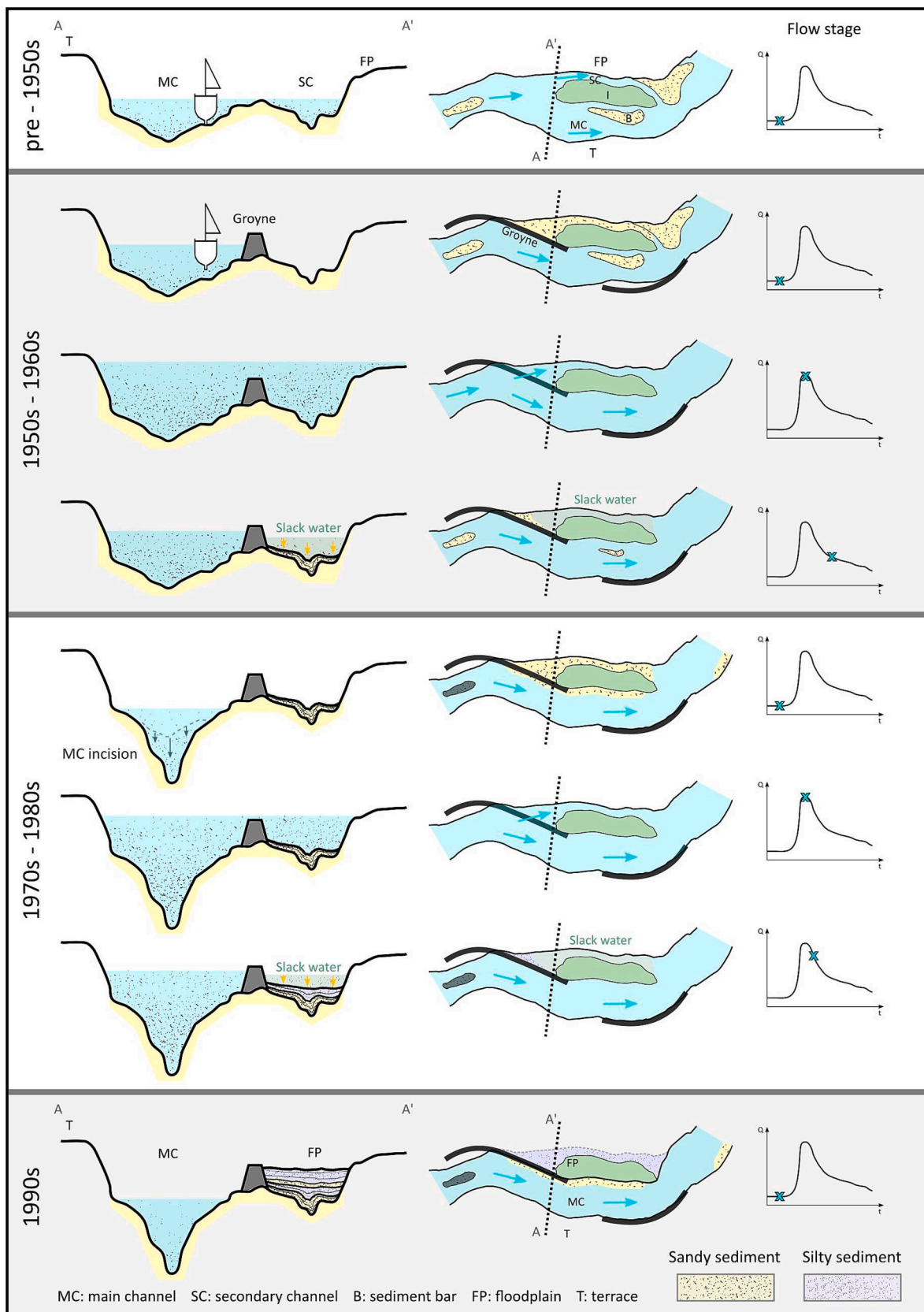
Pontelagoscuro was strongly influenced by sediment input from the Northern Apennines, where numerous tributaries characterized by high suspended load (e.g., Taro, Parma, Enza, Secchia; see Raiteri, 1995) contributed to maintaining a high input, and consequently the sediment load, in the Po River. Limited dam construction along these Apennines tributaries during the 1924–1943 period resulted in minimal alteration to sediment supply, as reflected by the near-constant suspended sediment yield (–1% SSY) observed at the Pontelagoscuro station during the first monitoring period (Fig. 9).

### 3.4.2. Period 1956–1991: The implementation of the major Po River training scheme

Since the late 1950s, new dam construction in the western Po River basin has almost halted (Fig. 7). Aside from a gradual increase in forest cover replacing agricultural land beginning in the 1960s (Fig. 6), which may have resulted in a decrease of sediment production at the basin scale (e.g., Bakker et al., 2008; Ward et al., 2009), no other significant impacts have affected the Po River sub-basin draining to Piacenza. As a result, the rate of decrease in SSY observed at the Piacenza station slowed during the period 1956–1991: SSY, which had been heavily reduced in the 1920s–1940s, declined by only 19% between 1956 and 1991 (Fig. 9). Sediment transport observed at Piacenza in the most recent period remained very low and closely resembles levels recorded at the end of the 20th century (Fig. 9). The additional decline observed over this short timeframe is likely attributable to the recent progression of reforestation processes in the mountain areas of the western Po River basin (Anselmetto et al., 2024).

The trajectory of suspended sediment transport at Pontelagoscuro is notably much more complex over these decades, with a dramatic SSY and SSC decline observed between 1956 and 1991. In this case, in order to explain such decrement affecting the transport exclusively at Pontelagoscuro, it is essential to consider local factors that may have specifically influenced suspended sediment transfer downstream of Piacenza

station. The first local factor analyzed here involves the morphodynamic processes initiated since the late 1940s and 1950s in response to river training scheme implemented along a 123 km stretch of the Po River extending between the confluences of the Adda (approximately 30 km downstream of Piacenza) and Mincio River (see Fig. 1). Between the 1950s and 1980s, areas of the active channel situated behind navigation groynes, which concentrate water flow into a single wet channel during low discharge conditions, experienced depositional processes, leading to bed aggradation and their progressive deactivation (Brenna et al., 2024) (Fig. 10). From a sediment dynamics perspective, high flow conditions carry water laden with suspended sediment into secondary channels located behind the navigation structures. As discharge rates—and thus water stages—decrease below to approximately 1000 m<sup>3</sup>/s accordingly to Gorio (1953) and Lanzoni (2012), flow in these zones becomes disconnected from the main channel, creating a low-energy environment (slack water) in which sediment deposition occurs. In the initial decades following the construction of these training works (1950s–1960s), before the main channel incision began due to intense in-channel mining in the 1970s (Brenna et al., 2024), sand particles, partially mobilized in suspension during floods but classified as part of the Po River's bed material (Brenna et al., 2022), were also able to reach and accumulate in these areas together with finer silty particles (Fig. 10). However, with the progression of main channel incision in the 1970s and 1980s, which increased the elevation difference between the main channel bed and the crests of the groynes, only finer particles (silt and very fine sand) constituting the wash-load of the Po River could enter into the areas behind the navigation structures for progressively higher flow rates (i.e., 1500–3000 m<sup>3</sup>/s). This shift is evident in the cored deposits (Fig. 8): older and deeper layers are predominantly sandy, while more recent, shallower layers are mainly silty. As long as the dynamics described above persisted, the areas behind the groynes acted as sediment traps, gradually filling between 1950s and 1980s, initially trapping fine sand and later silt. This material was consequently



**Fig. 10.** Scheme of sediment trapping processes induced by navigation structures (groynes), with special reference to the backside deposition, local deactivation of active channel areas and relative morphological changes.

removed from the regular downriver transport of suspended sediment, suggesting that these processes may have contributed to the decline in suspended sediment concentration and load observed during the same period at the Pontelagoscuero station.

To test this hypothesis, we attempted a quantitative comparison between the volumes of sediment trapped in these depositional areas (Table 2) and the decrease in suspended sediment transport observed at Pontelagoscuero. For this purpose, we calculated the cumulative suspended sediment yield over the period 1956–1991 ( $SSY_{56-91}$ ), amounting to approximately 344 Mtons. Next, we calculated the  $SSY_{56-91}$  that would have occurred at Pontelagoscuero if the reduction in sediment transport there had matched that observed at Piacenza, which was a 19% decrease between 1956 and 1991. This calculation yielded a  $SSY_{56-91}$  value of 410 Mtons. The difference between the actual and simulated cumulative values is 66 Mtons (see vertically striped triangle in Fig. 9), which, assuming a sediment density of  $1800 \text{ kg/m}^3$  adequate for silty-sandy deposits, corresponds to a volume of approximately  $37 \text{ Mm}^3$  of sediment. This value is lower than the sediment volume of  $96.1 \pm 16.8 \text{ Mm}^3$  that forms the sedimentary bodies located behind the groynes but better compares to the volume of the silt component alone, estimated to be about half of this amount, which is  $48 \pm 8.4 \text{ Mm}^3$  (see Section 3.3). Considering the sampling method used in the Po River to measure suspended sediment concentration—specifically, the use of the “*Campionatore Rossetti*” positioned one-third of the depth below the water surface as described in Section 2.1—it is likely that the sampled material primarily represented the finer fraction of suspended load (silt and very fine sand), which tends to remain near the water surface, unlike medium sand mostly constituting the bed material of the Po River, which, though partially transported in suspension and/or by saltation during floods (i.e., suspended bed-material load), generally moves closer to the riverbed (Hicks and Duncan, 1997; Wright and Parker, 2004; Kuhnle, 2013). Consequently, the transport values considered in this study primarily pertain to the wash-load of the Po River, comprising silt or very fine sands that, accordingly with the definition provided by Church (2006), are transported for a long distance in suspension and are found in minor quantities in the bed of the river. These considerations conceptually support the comparison between the calculated sediment transport of  $37 \text{ Mm}^3$  and the estimated  $48 \pm 8.4 \text{ Mm}^3$  referring exclusively to the silty infill deposited behind the navigation structures, as both values primarily reflect the wash-load component of the Po River. The modest discrepancy between these volumes likely reflects the combined uncertainties associated with both sediment-transport monitoring—e.g., limited by the daily collection of only three samples across river sections exceeding 150 m in width (Kleinhans and Ten Brinke, 2001)—and the reconstruction of trapped fine-sediment volumes, which relied on a restricted number of cross-sections (19 for 45 deactivated areas; see Table 2) and ten sediment cores. Despite these uncertainties, which prevent treating these results as a true “mass balance”, the general consistency between the two estimates (i.e., 37 and  $48 \pm 8.4 \text{ Mm}^3$ ) supports the hypothesis that depositional processes induced by the navigation structures were a primary controlling factor contributing to the marked reduction in suspended sediment transport observed in the Po River at Pontelagoscuero between the 1950s and 1980s. Assuming that the  $48 \text{ Mm}^3$  deposition occurred progressively over these four decades, we estimate an annual deposition rate of approximately  $1.2 \text{ Mm}^3$ , corresponding to 2.2 Mton of sediment accumulated per year. Given an average annual suspended sediment transport of the Po River of approximately 9.9 Mton between 1956 and 1991 (Fig. 3), we conclude that sediment trapping behind the groynes was capable of capturing approximately 18% [i.e., 2.2 Mton of the 9.9 Mton (remaining) + 2.2 Mton (lost)] of the yearly river's suspended sediment load during the 1950s to 1980s.

Accumulation of material transported as suspended load commonly occurs in alluvial plains adjacent to large rivers, where fine particles are temporarily deposited by overbank flows (e.g., Asselman and Middelkoop, 1995; He and Walling, 1998; Thonon et al., 2007). The

anthropogenic configuration of the Po River corridor, particularly modified by the training works conducted in the 1940s along a 123-km river stretch, and subsequent riverbed incision due to in-channel mining in the 1960s to 1980s, established a series of 45 extremely effective sediment traps located behind navigation groynes that have significantly enhanced the fine sediment sequestration processes, rendering subsequent remobilization processes highly improbable (Fig. 10). A similar dynamic has also been hypothesized for the Mississippi River by Meade and Moody (2010), who highlighted the crucial role played by engineering structures that were part of a complex river-training scheme operated in the 1950s in modifying the configuration of the riparian sediment-storage sites and increasing their efficacy in trapping the downriver suspended sediment transfer.

#### 3.4.3. Period 2010–2019: Implementation of flood detention basins on Apennine streams

By the late 1980s and early 1990s, the areas behind the groynes had become largely inactive due to complete sediment infilling (see Figs. 8 and 10) and/or significant incision of the main channel, which in some cases effectively disconnected these areas from active channel dynamics, except during exceptionally high flood events (Brenna et al., 2024). This shift drastically reduced the filtration and trapping processes of fine sediments and an increase in suspended sediment transport could be expected in the following period at Pontelagoscuero, approaching the values recorded during the first half of the 20th century (i.e., annual  $SSY > 10 \text{ Mton}$ ). However, observational data (Figs. 3 and 9) indicate that suspended sediment concentration and load have continued to decrease during the last decades of the 20th century and has remained stably low in the 2010s at Pontelagoscuero (i.e., annual  $SSY < 5 \text{ Mton}$ ; see Fig. 9).

The causes of this behavior should be investigated in relation to other factors that may limit the production and transfer of fine sediment throughout the river system. These factors likely acted in conjunction with, or in temporal succession to, the aforementioned trapping effects of the navigation structures, and their influences can be regarded as multiplicative effects. Among these, it is important to note the progressive increase in forest cover at the basin scale since the 1960s, which has intensified notably since the 1990s (Fig. 6). More critically, however, the construction of dams at various sites within the Po River basin during the 1960s and increasingly in the late 20th century (Fig. 7) appears to have played an even more influential role. In this regard, it should be noted that our data on major dams represent a minimum estimate of the total number of barriers, as several smaller transverse structures—likely built during the same decades—should also be considered. Their cumulative capacity to retain substantial quantities of sediment is certainly significant (e.g., Fencl et al., 2015). A comprehensive and detailed inventory including information on construction dates, typologies, and structural characteristics would therefore be highly desirable (Belletti et al., 2020). The completion of the Isola Serafini dam in 1964 deserves close consideration. Although, to the best of our knowledge, its actual filtering capacity on the transit of both bed material and wash-load has not yet been quantified, previous studies, considering the technical and operational characteristics of this run-of-river power plant and its morphological effects on the upstream and downstream river reaches, have demonstrated its substantial capacity to impact downriver sediment transfer (Bizzi et al., 2015; Maselli et al., 2018; Brenna et al., 2022). Thus, it is reasonable to infer that the long-term effects of this dam on suspended sediment transport in the downstream sector of the Po River have overlapped, since the late 1960s, with the impacts attributed to the training works discussed above.

A significant influence on the suspended load at Pontelagoscuero may have been exerted by the construction of numerous dams and flood detention basins along the Apennine tributaries of the Po River (Fig. 7). These hydraulic structures, completed predominantly between the 1980s and 1990s, have at least partially disconnected the main stem and the sector of the Po River catchment (i.e., Northern Apennine) with the highest production of fine sediments (Syvitski and Kettner, 2007; Pieri

et al., 2009). Suspended sediment monitoring, conducted by the Emilia-Romagna Regional Environmental Agency on a limited number of Apennine tributaries of the Po River, has been available only for the period 2010–2019, but a comparison of suspended sediment transport during the monitored decade for two similar Apennine streams—the Parma River and the Enza River (Fig. 1)—offers valuable insights. The Parma River, with a drainage area of 600 km<sup>2</sup> at the monitoring station (maximum elevation: 1852 m a.s.l.; mean elevation: 646 m a.s.l.; distance from the confluence with the Po River: 39 km; average annual rainfall: 1340 mm), is geographically adjacent to and geologically and climatically similar to the Enza River (drainage area: 648 km<sup>2</sup>; maximum elevation: 2016 m a.s.l.; mean elevation: 616 m a.s.l.; distance from the confluence with the Po River: 20 km; average annual rainfall: 1210 mm). The key distinction between these two rivers lies in the presence of a detention basin regulated by a dam in the middle course of the Parma River. This hydraulic structure, situated a few kilometers upstream of the sediment monitoring station, has been operational since 2005 and is activated during flood events to enhance the hydraulic safety of the City of Parma (Brenna et al., 2021). In contrast, the Enza River is currently free from any major filtering transverse structures that could intercept the downstream transfer of water and sediment. Data from the Hydrological Annals indicate that the average annual SSY for the Enza River during the 2010–2019 period is approximately  $248 \times 10^3$  tons, whereas the Parma River exhibits a significantly lower value of approximately  $119 \times 10^3$  tons per year—less than half that of the Enza. This substantial disparity highlights the profound impact of hydraulic infrastructures implemented since the 1980s–1990s on the sediment transfer from regulated Apennine tributaries to the Po River. This evidence provides a compelling explanation for the ongoing decline in suspended sediment transport observed in recent years at Pontelagoscuro, even if the filtering effects of the navigation works mentioned earlier have been drastically reduced.

Based on these considerations and taking into account the findings of Syvitski and Kettner (2007), it is possible to estimate the current

suspended sediment input and transfer dynamics within the Po River basin (Fig. 11). The average SSY at Piacenza is approximately 1.5 Mtons per year (Fig. 3), a part of which is retained by the Isola Serafini reservoir. Consequently, it is reasonable to estimate that the downstream contribution of the western drainage basin (mainly Western Alps) to the Po River's annual suspended sediment transport is about 1 Mtons. Given that the average annual SSY at Pontelagoscuro is approximately 4.3 Mtons (Fig. 3), it can be inferred that the observed 3–4 Mton downstream increase in suspended sediment transport comes from a limited number of unregulated Apennine tributaries, such as the Enza River and the Taro River (Fig. 7). These tributaries drain areas of high sediment production and remain unregulated by dams and detention basins (Fig. 11). In contrast, the suspended sediment contributions from Apennine tributaries regulated by dams (e.g., the Parma, Secchia, and Panaro rivers) and from Alpine tributaries located downstream of pre-Alpine lakes (e.g., the Adda, Oglio, and Mincio rivers) are low. Preliminary calculations estimate that these tributaries collectively supply the Po River with an annual SSY ranging between 1 and 2 Mtons (Fig. 11). This estimate is supported by data from the Hydrological Annals of the Emilia-Romagna Regional Environmental Agency. No monitoring data is currently available regarding the suspended sediment transport of the Alpine tributaries of the Po River, although it is known that they are characterized by low suspended sediment concentration (Raiteri, 1995).

#### 4. Discussion

##### 4.1. Geomorphic implications of the decline in wash-load to the deltaic region

Wash-load, not involving the bed material (i.e., the material that forms the bed and lower banks of an alluvial river), typically plays a minor role in shaping the morphology of the active channel of alluvial rivers. However, the finer sediment transported as wash-load

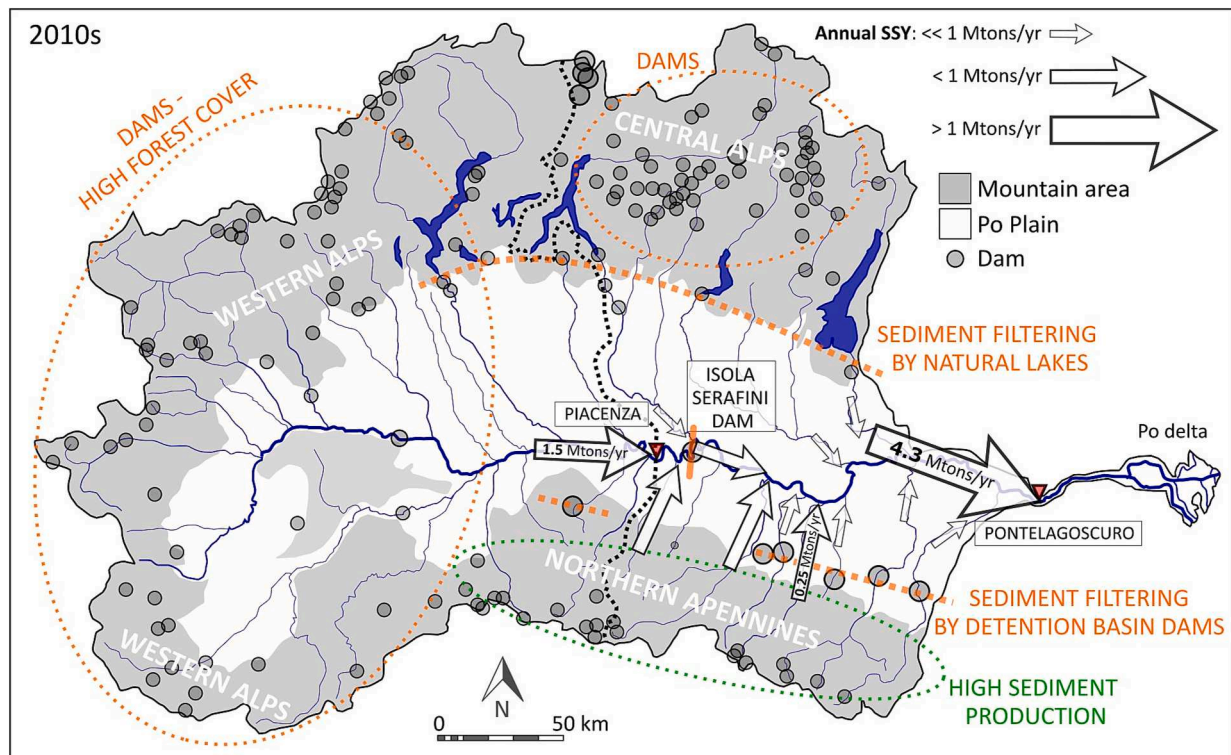


Fig. 11. Schematic diagram of current suspended sediment load dynamics in the Po River basin with particular reference to the sector between Piacenza and Pontelagoscuro, showing the main controlling factors on the production and transfer of fine material.

(commonly referred to as “wash material”) constitutes a substantial portion of the deposits in the floodplains as the result of sedimentation during overbank floods (Church, 2006). Among the environments where geomorphic dynamics are strongly influenced by wash-load supply and potential accumulation, river deltas are particularly prominent (Willis and Griggs, 2003; Syvitski and Saito, 2007; Liang et al., 2016; Kim et al., 2017; Kondolf et al., 2022). The potential aggradation of subaerial delta topsets is in fact closely linked to the overbank sediment deposition in the delta plains, which is mostly supplied by the wash-load delivered through the river's distributary channels (Syvitski et al., 2005).

The Po River, at its outlet in the Adriatic Sea, has developed one of the largest deltas in the Mediterranean region (Fig. 1), encompassing an emerged area of approximately 700 km<sup>2</sup> (Cencini, 1998; Ninfo et al., 2018). The formation of the delta is recent, dating back roughly 4000–5000 years, with rapid progradation shaping the modern delta only beginning in the 17th century (Cencini, 1998; Stefani, 2017). During the 20th century, deltaic progradation slowed. The delta reached its maximum extent in the 1930s; however, a pronounced retreat ensued, progressing at rates of tens of meters per year and peaking negatively during the 1950s–1970s (Cencini, 1998). Previous studies have underscored the critical role of anthropogenic impacts in driving this retreat. Key factors include pronounced regional subsidence, exacerbated by methane and groundwater extraction, and a reduction in sediment yield from the Po River (Simeoni and Corbau, 2009; Corbau et al., 2019a, 2019b; Da Lio and Tosi, 2019; Parrinello et al., 2021). Compounding these challenges are rising mean sea levels and increasing coastal flooding driven by global climate change (Day et al., 1995; Reimann et al., 2018).

The findings of this study enable a more precise contextualization of the connections between the decline in wash-load observed in the Po River at Pontelagoscuro—located just upstream of the delta—during the 1950s to 1980s (−48%), and the concurrent maximum retreat rate of the delta. This reduction in fine sediment supply, along with an embankment development that has limited the lateral connectivity of channel processes in the deltaic environment including those related to subaerial delta topset flooding and overbank sedimentation (Syvitski et al., 2005; Teatini et al., 2011; Corbau et al., 2019b; Brunetta and Ciavola, 2024; Finotello et al., 2025), prevented this area from compensating by delta-plain aggradation for the lowering of topographic surfaces caused by intense subsidence occurring during those years. Although subsidence has slowed in recent decades following the cessation of methane and groundwater extraction activities, relative sea level rise remains an ongoing challenge (Fiaschi et al., 2018; Corbau et al., 2019a; Da Lio and Tosi, 2019).

Drawing from the results presented herein, it can be concluded that the principal anthropogenic drivers that have led to the century-long decline in wash-load (i.e., dam impoundments, detention basins, and extensive land-use changes) are still largely active across the basin (Fig. 9). The sediment-trapping capacity of navigation works has likely diminished, yet the overall sediment connectivity of the fluvial system remains severely constrained. Consequently, the Po River will likely persist in supplying its delta and the Northern Adriatic beaches with sediment-depleted waters, exhibiting suspended sediment concentration levels more than 50% lower than those recorded in the early 20th century. Under these conditions, combined with ongoing relative sea level rise, the potential for the delta to preserve its subaerial plain through fine-sediment accretion appears limited, suggesting an unfavorable prognosis for its long-term morphological stability and raising serious concerns about the persistence of this fragile environment. Similar situations of delta drowning caused by an imbalance between sediment supply and rates of relative sea-level rise have been observed and described in various regions of the world, for example, in relation to the Mississippi Delta (Blum and Roberts, 2009), the Mekong Delta (Kondolf et al., 2018) and the Rhone Delta (Arnaud-Fassetta, 2003).

#### 4.2. Insights on sediment load restoration in the Po River system

The case of the Po River is particularly significant, as it exemplifies how a series of diachronous anthropogenic impacts have progressively led to a decline in suspended sediment yields along the river's course. This decline has, in turn, substantially contributed to trigger major geomorphological transformations particularly in the deltaic region, which is currently at risk of drowning. In light of this, and considering the significant social implications that such morphodynamic phenomena may entail (Ashmore, 2015; Parrinello and Kondolf, 2021; Parrinello et al., 2021; Kondolf et al., 2022; Gorostiza et al., 2023), it would be highly desirable to adopt water and sediment management strategies that incorporate a vision for the potential restoration—at least partial—of suspended load dynamics and lateral sediment-water connectivity within the Po River system, including the delta.

While basin-scale interventions aimed at enhancing sediment production and longitudinal connectivity, such as dam removal, are feasible (e.g., East et al., 2015; Major et al., 2017), they remain highly ambitious. In this regard, management policies should at least aim to preserve the catchments of those tributaries that currently provide the most significant contributions of suspended sediment load to the main stem of the Po River, foremost among them the limited number of Apennine rivers still free from major transverse- sediment-trapping structures (Fig. 11). Conversely, actions more directly focused on the river corridor not only represent a potentially effective strategy for increasing the availability of sediment and promoting channel lateral mobility but are also generally more practical to implement. In the specific case of the Po River, it has been observed that areas of the active channel deactivated during the second half of the last century represent a reservoir containing approximately 96 Mm<sup>3</sup> of silty and sandy sediments, which was effectively removed from downriver transfer processes mainly during that period. Part of this material could potentially serve as a source for reintroduction of sediment into the fluvial system. The “Renaturation of the Po Area” program (*Programma di Rinaturazione dell'area del Po*), coordinated by the Po River Basin Authority (<https://www.adbpo.it/pnrr-rinaturazione-po/>) and inspired to modern geomorphological approaches (e.g., Piégay et al., 2005; Biron et al., 2014; Buffin-Bélanger et al., 2015) and comparable interventions conducted in other countries (e.g., Schiemer et al., 1999; Lamouroux et al., 2015; Groll, 2017), aligns with this objective by proposing the reactivation of some of the river's former side branches. This would involve the partial removal or lowering of transverse (groynes) and longitudinal (bank protections) navigation structures that have caused the disconnection and deactivation of secondary channels (Brenna et al., 2024), as well as the reopening of these secondary branches. These interventions, in addition to locally increasing the morphological complexity of the channel with associated eco-hydromorphological benefits (e.g., Haase et al., 2013; Belletti et al., 2015), are expected to promote localized erosion processes (Florsheim et al., 2008). Such erosion would facilitate the re-mobilization of trapped sediment, contributing to replenishing the currently starved sediment load of the Po River and its sedimentary input to the delta and Northern Adriatic beaches.

Specifically, the sands found in the lower stratigraphic levels (Figs. 8 and 10) represent sediment that is dimensionally compatible with the typical riverbed material of the middle and lower segments of the Po River (Brenna et al., 2022). Once mobilized—either as bedload or as temporary suspended bed material load—these sediments would contribute to increasing the river's bed material load, potentially aiding the replenishment of bars and incised channels. As widely documented in the literature, such morphological units have undergone remarkable erosion over recent decades due to sediment starvation, primarily caused by in-channel sediment mining, which has caused riverbed incision reaching 4–5 m within the main channel zone (Lanzoni, 2012; Rinaldi, 2021; Brenna et al., 2024; de Sordi et al., 2025).

The silty materials stratigraphically overlying the sands (Figs. 8 and 10), on the other hand, correspond to the typical wash-load of the Po

River having a rapid downstream transfer along the fluvial system. Reintroduction of silty material into the riverine sediment dynamic could lead to a moderate increase in suspended sediment concentration. Assuming, for instance, a reactivation scenario involving the remobilization of approximately 50% of the material sequestered within the sediment traps distributed along the middle course of the river, this would correspond to about 48 Mm<sup>3</sup> of total sediment, of which roughly half (~24 Mm<sup>3</sup>) consists of silty material. If such remobilization were to occur progressively over a two-decade timespan—a reasonable window considering the long morphodynamic response times typically observed in lowland rivers undergoing restoration projects (e.g., Gore and Shields, 1995; Grabowski et al., 2014; Kristensen et al., 2014)—this would result in an additional average sediment input of approximately 1.2 Mm<sup>3</sup>/yr, equivalent to around 2 Mton/yr of wash-load, representing an increase of nearly 50% compared to the current annual SSY of 4.3 Mton yr<sup>-1</sup> (Fig. 3).

A first-order quantitative assessment of the effects of these interventions on the delta dynamics was carried out by applying the empirical relationship (Eq. 1) between delta area ( $A_D$ ; km<sup>2</sup>), mean water discharge ( $Q_{av}$ ; m<sup>3</sup>/s), total sediment load ( $Q_{s+b}$ ; kg/s), and shelf depth ( $D_{sh}$ ; m) proposed by Syvitski and Saito (2007):

$$A_D = \frac{1.07 Q_{av}^{1.1} Q_{s+b}^{0.45}}{D_{sh}} \quad (1)$$

Assuming a constant mean annual water discharge of 1470 m<sup>3</sup>/s (Montanari, 2012) and a shelf depth of 30 m (Correggiari et al., 2005; Syvitski and Saito, 2007), we varied the sediment load parameters to estimate the expected areal extent of the delta. From our study, only the fine suspended sediment component is available; however, in the terminal sector of the Po River this fraction accounts for the vast majority (>95%; see Syvitski and Saito, 2007) of the total sediment load ( $Q_{s+b}$  = suspended + bedload). For the early decades of the 20th century, mean annual SSY values of 13.6 Mton (corresponding to 430 kg/s) would yield an estimated delta area ( $A_D$ ) of about 1650 km<sup>2</sup>, i.e., a value higher than the documented maximum delta extent of roughly 1050 km<sup>2</sup> in the 1930s (Syvitski and Saito, 2007). To obtain consistent areal estimates, assuming an equilibrium condition for the delta, it is necessary to introduce a sediment retention rate (i.e., the fraction of the delivered sediment that effectively reaches the delta plain) of about 0.3–0.4, reducing the effective sediment load to about 150 kg/s. This value is coherent with the normal dynamics of overbank sedimentation and suggests that, accordingly with the long history of human pressures affecting this area (Corbau et al., 2019b), even in the early 1900s the lateral connectivity within the deltaic environment might already have been partially artificially limited. Under the altered sediment regime of the modern period (annual SSY = 4.3 Mton, corresponding to 135 kg/s), while keeping  $Q_{av}$  and  $D_{sh}$  constant and slightly reducing the sediment retention rate to 0.2–0.3 due to the increased presence of anthropogenic structures limiting lateral connectivity across the delta (Brunetta and Ciavola, 2024; Finotello et al., 2025), the resulting delta areas ( $A_D$ ) obtained from Eq. 1 range between 480 and 580 km<sup>2</sup>. This highlights that the present delta area, roughly 700 km<sup>2</sup>, is no longer in equilibrium with current sediment-supply conditions. Unless artificially maintained through ongoing reclamation and localized replenishment efforts (Corbau et al., 2019a; Brunetta and Ciavola, 2024), the delta is thus potentially subject to partial disassembly and drowning. A 50% increase in SSY over the coming decades, as hypothesized in the reactivation scenario discussed above, with average transport values of approximately 200 kg/s, would have the potential to restore a more balanced morpho-sedimentary regime. Under such conditions, the theoretical delta area would increase to about 570–690 km<sup>2</sup>, and could further expand to roughly 780 km<sup>2</sup>—consistent with the present delta extent—if the sediment retention rate rose to around 0.4 as a result of enhanced lateral connectivity of depositional processes. Finally, delta sustainability is further threatened by relative sea-level changes (i.e., the

combined effects of eustatic rise and land subsidence). Under the hypothesized restored sediment supply scenario (SSY = 6.3 Mton/yr), assuming a sediment retention rate of 0.4 and uniform distribution across the delta surface, the potential vertical accretion rate would be approximately 2 mm/yr. This value is comparable to the estimated total relative sea-level rise for the Northern Adriatic expected over the 21st century, which—depending on the selected climate-change scenario and the magnitude of regional subsidence—ranges between 1.4 and 4.9 mm/yr (Scarascia and Lionello, 2013). In conclusion, when sediment-enriched floodwaters reach parts of the emerged deltaic region, this process would supply the fine-grained material whose overbank deposition is necessary for vertical delta-plain accretion, which is crucial to mitigate the ongoing sinking of the area. Such dynamics will only be possible if delta management strategies include also an increase in lateral connectivity between the distributary channels and the subaerial delta topset, which is currently severely restricted by the presence of extensive levee systems (Brunetta and Ciavola, 2024; Finotello et al., 2025).

The considerations presented here represent preliminary reflections on the topic. The transition phase associated with the implementation of renaturation and restoration interventions in a large river system such as the Po is inherently complex and typically spans several decades (Gore and Shields, 1995; Rohde et al., 2004; Habersack and Piégay, 2007). Forecasting the outcomes—even through numerical modeling approaches—is highly challenging due to multiple interacting processes. For instance, migration of the active channel can simultaneously mobilize and deposit sediments, while reconnecting the channel to the floodplains may even locally enhance fine-sediment trapping. Moreover, deltaic dynamics are controlled by a range of hydrological, sedimentary, and anthropogenic factors, which can substantially alter the effectiveness and outcomes of restoration measures. Therefore, during both the implementation phase and the subsequent years, it will be essential, in our view, to conduct a detailed monitoring program. Monitoring should encompass both the morphological component (e.g., observations of the planimetric and altimetric evolution of the fluvial system, considering also the submerged part of the active channel) and sediment transport dynamics (e.g., measurements of coarse and fine sediment fluxes), as these two aspects are known to be closely interrelated in the context of alluvial river systems (Church, 2006; Church and Ferguson, 2015; Latrubesse et al., 2021). Moreover, any potential increase in suspended sediment concentration and water turbidity must be carefully monitored to ensure the maintenance of adequate physico-chemical environmental quality conditions (Lloyd, 1987).

## 5. Conclusion

The Po River exhibits at present significantly less turbid waters compared to the past century, with substantially lower suspended sediment yields exceeding –85% and –72% at Piacenza and Pontelagoscuro stations, respectively, at similar water discharge regimes. These reductions in fine sediment transport occurred asynchronously along the river's course. Initially (1920s–1940s), more pronounced decreases (halving of annual SSY) occurred upstream (i.e., Piacenza), primarily driven by the construction of dams, which proliferated extensively in the western portion of the river catchment beginning in the 1920s. Subsequently (1950s–1980s), reductions became evident (halving of annual SSY) further downstream (i.e., Pontelagoscuro), influenced by multiple factors. Among these, the most significant include the deposition of fine sediment within the active channel, promoted by river training works during the 1950s–1980s, and the construction of numerous sediment-filtering flood detention basins along the Apennine tributaries, which, until the early 1980s, represented a major source of sediment to the Po River.

This study exemplifies how a series of anthropogenic impacts have led to a great decline in suspended sediment yields along the Po River. This decline has contributed to trigger major geomorphological

transformations in the delta region during the 20th century. In light of this, it would be highly desirable to adopt water and sediment management strategies that incorporate a vision for the potential restoration of sediment dynamics and lateral sediment-water connectivity within the Po River system. In this context, the considerable volumes of silty and sandy sediment deposited over the past century within anthropogenically induced sediment traps along the main course of the river—particularly in areas located downstream of navigation infrastructure—may represent a potential source of sediment that could be reintroduced into the system, which could contribute to preserving the delta from potential drowning. River management plans should carefully take these aspects into account, also incorporating monitoring programs aimed at tracking the temporal evolution of the system's overall morphodynamics, i.e., considering both sediment dynamics and associated morphological changes.

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### CRediT authorship contribution statement

**Andrea Brenna:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Bizzi:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Nicola Surian:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the readability of some sentences of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrea Brenna reports financial support was provided by Autorità di bacino distrettuale del Fiume Po. Simone Bizzi reports financial support was provided by Autorità di bacino distrettuale del Fiume Po. Nicola Surian reports was provided by Autorità di bacino distrettuale del Fiume Po. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Data availability

Suspended sediment load in the Po River (Italy) over the last 100 years (Original data) (Mendeley Data)

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