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RESEARCH ARTICLE

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Four decades of suspended particulate matter concentrations in the Po River revealed by landsat satellites

Fan Yang[a,b,c], Mariano Bresciani[c], Claudia Giardino[c], Nicola Ghirardi[c,d], Monica Pinardi[c], Daniele Nizzoli[e], Edoardo Cavallini[e], Baoyin He[a] and Qi Feng[a]

[a]Key Laboratory for Environment and Disaster Monitoring and Evaluation of Hubei, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, People's Republic of China; [b]University of Chinese Academy of Sciences, Beijing, People's Republic of China; [c]CNR – Institute for Electromagnetic Sensing of the Environment, Milan, Italy; [d]CNR – Institute of BioEconomy, Sesto Fiorentino, Italy; [e]Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parma, Italy

ABSTRACT

Suspended particulate matter (SPM) is a key indicator of both sediment transport and water quality in river environments. In this study, a comprehensive long-term analysis of SPM concentrations in the Po River, the longest in Italy, was carried out over the period 1984-2024 by applying a well-established semi-empirical SPM retrieval algorithm to multispectral satellite imagery collected from Landsat-5, -7, -8 and -9. The spatial distribution, seasonal variations and temporal trends of Landsat-derived SPM concentration, that strongly matched field data ($R^2 = 0.86$) were then combined with hydrological observations. The results show that SPM concentrations in the Po River have ranged from 1.2 to 55.9 mg/L over the past four decades, and that the concentration values generally increased downstream and peaked in the spring. Time-series decomposition showed consistent seasonal patterns and long-term trend changes, characterized by a gradual increase until 2005, followed by a marked decline. A non-linear relationship was observed between SPM and discharge. This study demonstrates the efficiency of satellite remote sensing as a tool for watershed management and environmental assessment, and provides a scientific basis for large-scale, long-term water quality monitoring in the Po River.

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Introduction

Suspended particulate matter (SPM) plays a crucial role in aquatic environments by influencing light penetration, nutrient cycling, pollutant adsorption, and microbial activity, thereby shaping the structure and functioning of freshwater ecosystems (Bilotta & Brazier, 2008; He et al., 2021; Walch et al., 2022). High SPM concentrations can reduce water transparency, disrupt aquatic food webs, and facilitate the downstream transfer of contaminants, while low concentrations may indicate sediment depletion and lead to erosion or instability in riverbeds (Misset et al., 2019). Therefore, accurate and timely observations of the spatial and temporal variability of SPM are essential for riverine ecosystem management and for understanding watershed responses to climate and land-use change.

Traditional in-situ monitoring techniques, such as fixed-station sampling and manual filtration, provide high-quality point measurements but are inherently constrained in both spatial coverage and temporal resolution, particularly across large and hydrologically dynamic river systems (Droujko & Molnar, 2022). Most existing monitoring methods rely on a limited number of observation sites, operate with relatively low sampling frequency, and cover only short temporal periods, which hampers the detection of spatial heterogeneity, seasonal variability, and long-term trends in sediment dynamics (Cassidy & Jordan, 2011). Furthermore, discrete field measurements often fail to capture short-term fluctuations in SPM

CONTACT Qi Feng fengqi@apm.ac.cn Key Laboratory for Environment and Disaster Monitoring and Evaluation of Hubei, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430077, People's Republic of China
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concentrations caused by transient hydrological events such as floods, high-flow pulses, or rapid discharge variations. In this context, satellite remote sensing of water colour has emerged as a powerful and complementary technique, providing synoptic, spatially continuous, and temporally repetitive observations of SPM across extensive areas. Over the past two decades, a variety of retrieval methodologies have been developed and refined, ranging from simple empirical regressions based on spectral band ratios or indices to semi-empirical formulations utilising single or multiple bands (Nechad et al., 2010), semi-analytical inversions of bio-optical models applicable from riverine to coastal waters (Han et al., 2016), and more recently, advanced machine-learning algorithms and multi-sensor data-fusion approaches that enhance retrieval accuracy in optically complex and highly turbid environments (Duan et al., 2022). Large-scale implementations have demonstrated the potential of satellite remote sensing to generate consistent global SPM datasets (Wei et al., 2021), to construct multi-decadal time-series for lakes, estuaries, and coastal zones (Bortolin et al., 2022), and to evaluate the influence of sensor revisit frequency on long-term water-quality monitoring (Cao et al., 2019). Collectively, these advances highlight the growing maturity and robustness of satellite-based SPM retrieval and underscore its capability to overcome the spatial and temporal constraints inherent to traditional in-situ monitoring networks.

Nevertheless, significant challenges remain. First, accurate atmospheric correction over optically complex inland waters continues to be a major source of uncertainty, particularly when using land-oriented processors for highly turbid rivers (Bi et al., 2018). Second, many previous studies have focused on small lakes, estuaries, or deltaic environments and relatively short observation periods (Han et al., 2016; Walch et al., 2022). Few investigations have generated consistent, multi-decadal SPM records spanning the full longitudinal extent of a major river, while explicitly linking satellite-derived SPM dynamics to hydrological drivers such as discharge and water-level variations (Jiang et al., 2025; Tavora et al., 2023).

The Po River drains a densely populated and intensively farmed basin, subject to substantial anthropogenic pressures and climate-driven variability. Despite its socio-ecological significance, SPM monitoring in the Po River remains fragmented: available data primarily derive from short-term field campaigns at a limited number of fixed stations, providing insufficient spatial and temporal coverage to resolve basin-scale patterns or long-term trends. Consequently, there is a clear knowledge gap regarding the long-term, basin-scale dynamics of SPM in the Po river basin.

In this study, we present a 40-year (1984–2024) dataset of SPM concentrations derived from Landsat along the 652 km length of the Po River. Our objectives are to: (i) analyse the spatial and seasonal distribution of SPM supported by independent validation using in situ measurements; (ii) investigate long-term temporal trends using decomposition techniques; and (iii) assess how river discharge and water level affect SPM variability. By integrating satellite data with hydrological information, this study provides new insights into sediment transport processes in the Po River and demonstrates the potential of remote sensing for long-term water quality monitoring in complex river systems.

Materials and methods

Study area

The Po River, Italy's longest river (approximately 652 km), flows from the Western Alps to the Adriatic Sea in the east and drains a basin of over 70,000 km^2 (Figure 1). Its catchment is characterised by intensive agriculture, dense population, and expanding industrial activity (Mosello, 2015; Viaroli et al., 2018). These anthropic pressures along with meteorological and climatic factors, significantly influence sediment transport in the Po River (Cavallini et al., 2024; Simeoni & Corbau, 2009; Tesi et al., 2013).

The hydrological characteristics of the Po River exhibit pronounced seasonal and interannual variations, with flow peaks in spring due to Alpine snowmelt and in autumn from frontal rainfall, while summer and winter generally correspond to low-flow conditions (Boldrin et al., 2005; Mombrini et al., 2025). At Pontelagoscuro, approximately 96 km upstream from the estuary, the Po River has an average discharge of about 1,470 m^3/s, with observed values ranging from 275 to 10300 m^3/s, reflecting substantial hydrological variability (Montanari, 2012). Its hydrological regime results from a combination of natural hydroclimatic variability and human regulation through reservoirs, irrigation, and flood control. Recent

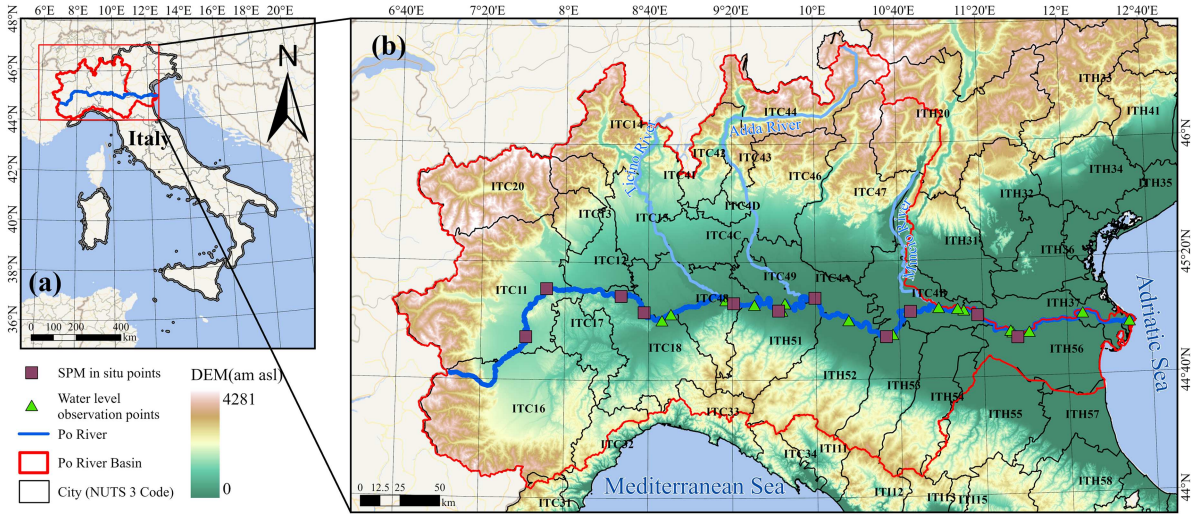


Figure 1. Location map of the study area.

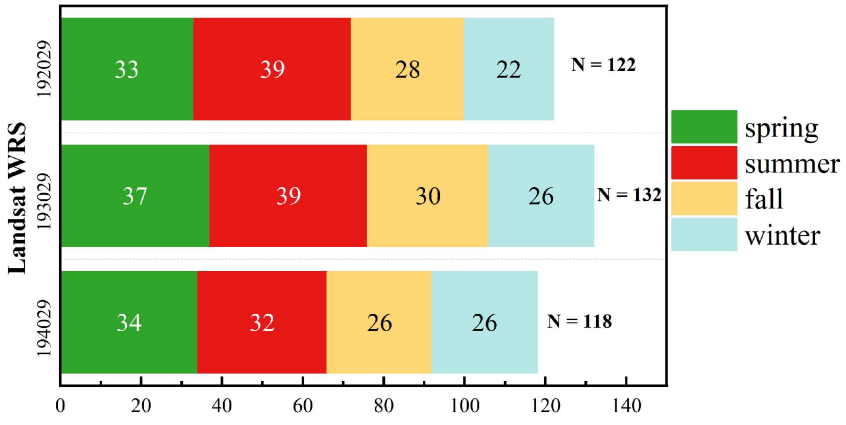


Figure 2. Number of Landsat images in different seasons.

analyses highlight increasing drought frequency and intensity, particularly in the western basin, linked to altered precipitation regimes and rising temperatures (Mombrini et al., 2025).

These hydroclimatic changes, together with anthropogenic channel and floodplain modifications, substantially influence sediment supply and transport within the Po River system. Sustained sediment delivery has promoted continued delta progradation and expansion into the Adriatic Sea (Ninfo et al., 2018). As a major pathway connecting the Alpine to the coastal zone, the river plays a critical role in delivering sediments and associated materials to the delta and the northern Adriatic Sea (Braga et al., 2017). Monitoring SPM in this system is essential for understanding sediment dynamics and their downstream impacts.

Landsat data

A total of 372 cloud-free Level-1 (L1) images from Landsat-5 TM (169 scenes from 1984 to 2011), Landsat-7 ETM+ (98 scenes from 1999 to 2019), Landsat-8 OLI (89 scenes from 2013 to 2024), and Landsat-9 OLI-2 (16 scenes from 2021 to 2024) covering the Po River were acquired from the United States Geological Survey for 1984–2024. Despite the comprehensive coverage of the Landsat archive, suitable imagery was unavailable for certain seasons due to persistent cloud cover, acquisition gaps, or incomplete data records. In particular, valid scenes were missing for spring 1984 and 1986; fall 1984, 1991, 1993, and 1994; and winter 1984, 1987, 1988, 1990, 1992, 1997, and 2024 (Figure 2). Detailed information on Landsat images is provided in Appendix A.

Remote sensing reflectance ($R_{rs} = \rho_w/\pi$, ρ_w is the surface level reflectance for water pixels) is widely used for retrieving various water quality parameters (Braga et al., 2017; Hou et al., 2022; Volpe et al., 2011). Due to its capability in performing the atmospheric correction of Landsat data in diverse aquatic conditions (Ghirardi et al., 2023; Pahlevan et al., 2021), we employed the ACOLITE software (Vanhellemont & Ruddick, 2018), which is particularly suitable for inland and optically complex (non-transparent) waters. ACOLITE was used to correct for ozone and water vapour absorption, thereby generating R_{rs} for water pixels. The atmospheric correction was carried out using ACOLITE's Dark Spectrum Fitting (DSF) algorithm, with processing conducted under the default DSF settings of ACOLITE version 20231023. Following atmospheric correction, pure water pixels were isolated using a Normalised Difference Water Index (NDWI) threshold of >0.1, and a 3×3 mean filter was subsequently applied solely to these masked areas to mitigate high-frequency noise from transient features such as ships, bridges, and surface waves (Zhou et al., 2019). Due to differences in the central wavelengths of spectral bands among Landsat series sensors, we adopted a wavelength-based naming convention—for example, R_{rs}(Red) refers to R_{rs}(660) for TM, R_{rs}(661) for ETM+, R_{rs}(655) for OLI, and R_{rs}(654) for OLI-2. It is worth noting that specific coefficients are assigned to each central wavelength within the retrieval algorithm to reduce systematic errors between sensors (Table 1).

Field and ancillary data

Chemical and physical quality data from stations along the Po River course for the period 1992–2022 were collected by the Regional Agencies for Environmental Protection (ARPA) of the Piemonte, Lombardia and Emilia-Romagna regions. Data collection, standardisation and harmonisation were performed by the University of Parma under an agreement between the Po River District Authority (ADBPO) and the Universities of Parma, Ferrara and Torino. For this study, SPM concentrations measured at 11 monitoring stations distributed along the entire river shaft were considered. At each station, water samples were collected and filtered using pre-weighed Whatman GF/F fibre filters. All sampling sites are typically freshwater stations. The filters were then rinsed with deionized water to remove any potential salt residues, dried, and reweighed to gravimetrically determine the SPM concentration, following the protocol described by Strömbeck and Pierson (2001) and the standardised procedures adopted by the regional environmental agencies (ARPA).

Water level data have been provided by the Theia Hydroweb Operational Altimetry River Water Level dataset, that offers satellite altimetry-derived observations of river water levels (Da Silva et al., 2010; Normandin et al., 2018). The dataset is organised into virtual stations, defined to the intersection between a satellite theoretical track and river centerline, and containing a geolocation and the corresponding water level timeseries. For the specific case of Po River, the water level observations are available at over 17 stations, distributed along the entire stream for the time range between 2016–2024.

Daily water discharge data are freely available from the ARPAE online repository DEXT3R (https://simc.arpae.it/dext3r/). Data for the Po River at its closing station in Pontelagoscuro were downloaded for the period 1984–2024. Missing data for time intervals shorter than three days were replaced by linear interpolation using the zoo R package (Zeileis & Grothendieck, 2005), whereas missing data for longer periods were estimated from discharge data of the Ficarolo station as suggested by Cavallini et al., 2024. Regressions were performed using data from analogous periods and with discharge values similar to the missing ones.

Table 1. Coefficients for the Landsat series of satellites.

Sensors	Band	A	C
TM	R_{rs} (Green)	93.16	0.1449
	R_{rs} (Red)	327.84	0.1708
	R_{rs} (NIR)	2543.56	0.2105
ETM+	R_{rs} (Green)	104.2	0.1449
	R_{rs} (Red)	327.84	0.1708
	R_{rs} (NIR)	2379.77	0.2103
OLI/OLI2	R_{rs} (Green)	104.2	0.1449
	R_{rs} (Red)	289.29	0.1686
	R_{rs} (NIR)	2971.93	0.2115

SPM retrieval algorithm

To retrieve SPM concentrations from Landsat imagery, this study applied a semi-empirical, multi-conditional algorithm framework following Novoa et al., (2017), which integrates three single-band formulations originally proposed by Nechad et al. (2010). Developed and validated for coastal waters spanning a broad turbidity range (SPM ≈ 1 to >1000 mg L^{-1}), the Novoa algorithm dynamically switches or blends single-band models according to reflectance thresholds, allowing flexible adaptation to varying optical conditions.

Although rivers exhibit rapid and spatially heterogeneous changes in optical properties, the underlying processes governing light scattering and absorption by suspended particles remain analogous to those in coastal systems (Gardner et al., 2020). Nechad et al., (2010) algorithm's adaptability across wide turbidity gradients and its demonstrated robustness in optically complex waters make it well suited for riverine environments such as the Po River, characterised by high sediment loads. Its successful applications in other turbid inland waters (Renosh et al., 2020; Tavora et al., 2020) further demonstrate its transferability. The single-band Nechad formulation is expressed as follows:

$$SPM = \frac{A \cdot \rho_w}{1 - \left(\frac{\rho_w}{C}\right)} \tag{1}$$

where: ρ_w is the surface level reflectance for water pixels (dimensionless), A and C are calibration coefficients specific to each wavelength. The coefficients used in this study were derived from Nechad et al., (2010) and adapted to the characteristics of the Landsat series of satellite sensors, with the specific parameters shown in Table 1.

To accommodate the wide dynamic range of SPM concentrations observed in the Po River, the algorithm dynamically selects or blends output from the three bands based on the reflectance in the red band (ρ_w) (Novoa et al., 2017). The decision rules are defined by a set of conditional thresholds:

(1) When $\rho_w^{\mathrm{Red}} < 0.007$, the green-band algorithm is used.
(2) For $0.007 \leqslant \rho_w^{\mathrm{Red}} < 0.016$, a combined algorithm between green and red bands is used.
(3) For $0.016 \leqslant \rho_w^{\mathrm{Red}} < 0.08$, the red-band algorithm is used.
(4) For $0.08 \leqslant \rho_w^{\mathrm{Red}} < 0.12$, a combined algorithm between red and NIR bands is used.
(5) When $\rho_w^{Red} \geqslant 0.12$, the NIR-band algorithm is used.

This multi-conditional structure enables smooth transitions between algorithms across a continuum of turbidity levels, thereby avoiding abrupt discontinuities in the retrieved SPM products. This algorithmic framework, combining physical simplicity and optical adaptability, enables the accurate characterisation of sediment dynamics in a complex river system such as the Po River, while ensuring continuity across sensors and over decadal time scales.

Statistical analyses

The Pearson correlation coefficient squared (R^2) (Equation (2)) (Pearson, 1896), the root mean square error (RMSE) (Equation (3)), absolute and relative biases (Equation (4) and (Equation (5))) (Willmott, 1982) were used to perform statistical analyses.

$$R^2 = \left(\frac{\mathrm{cov}(x, y)}{\sigma x \sigma y}\right)^2 \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{3}$$

$$\text{Absolute Bias} = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \tag{4}$$

$$\text{Relative Bias (\%)} = \frac{1}{n}\sum_{i=1}^{n}\frac{y_i - x_i}{x_i} \times 100\% \tag{5}$$

where n is the number of sample pairs, the subscript i denotes individual sample points, and x and y represent the retrieved and measured SPM values.

In addition to correlation and error metrics, the Mann–Kendall (M-K) trend test (Mann, 1945) was applied to assess the significance of temporal trends in SPM concentrations. The M-K test is a non-parametric method commonly used for detecting monotonic trends in hydrological and environmental time series without requiring the data to follow a specific distribution. To analyse the long-term temporal dynamics of average SPM concentrations in the Po River, the Seasonal-Trend decomposition based on Loess (STL) method was applied to the remote sensing-derived time series spanning from 1984 to 2024. STL is a robust decomposition technique that separates a time series into three distinct components: trend, seasonal, and residual, thereby facilitating a more nuanced understanding of temporal variability (Qian et al., 2000; RB, 1990). In addition, we used the Mann-Whitney *U*-test (Mann & Whitney, 1947) to test the difference between the two groups of SPM concentration data during high and low water level periods.

Results

Validation of the SPM algorithm

To assess the accuracy of SPM concentrations obtained from Landsat imagery, an independent validation was conducted using in situ SPM measurements. Since SPM in riverine environments exhibits high spatial and temporal variability due to hydrodynamic processes, sediment resuspension, and external inputs, only field observations collected on the same day as the corresponding Landsat overpasses were selected for validation. A total of 18 valid matchups (Appendix B, Table S1) between field measurements and cloud-free Landsat scenes were identified and used to evaluate the performance of the retrieval algorithm.

As shown in Figure 3, the SPM concentration retrieved by Landsat is significantly correlated with the measured value ($R^2 = 0.86$; $p < 0.05$), and the RMSE is 5.6, the Bias is −3.4 (−28%), which indicates that the established retrieval model is able to effectively characterise the temporal and spatial variations of the SPM concentration in the Po River.

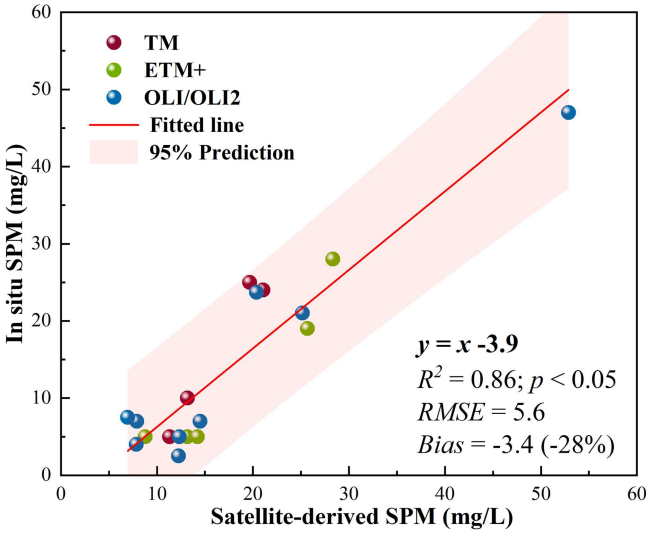


Figure 3. Validation of SPM concentration retrieval algorithm.

Spatial and temporal variation in SPM concentrations

The distribution characteristics of the average SPM concentration in the Po River are shown in Figure 4. Over the past four decades, SPM concentrations in the Po River have exhibited considerable temporal variability, ranging from 1.2 to 55.9 mg/L. The highest recorded SPM concentration occurred in the fall of 2000 near the city of Piacenza (265 km from the estuary), while the lowest value was observed during the winter of 1985 near the city of Parma (225 km from the estuary). SPM concentrations in the Po River during different seasons are shown in Table 2.

SPM concentrations in the Po River generally increase along the west-to-east flow direction (Figure 5a). Since 1984, the SPM concentration in the Po River has exhibited a statistically significant declining trend at a rate of 0.14 mg/L/yr (Figure 5b, $Z = -1.99$, $p < 0.05$), with a multi-year average of 23.3 mg/L. The highest mean SPM concentration is 33.1 mg/L in 2000, and the lowest mean SPM concentration is 13.9 mg/L in 2022.

Time series of SPM concentrations in the Po River

Figure 6 shows the STL decomposition results for the SPM concentration time series in the Po River. Figure 6(a) presents the original time series, revealing pronounced intra- and interannual fluctuations in SPM concentrations, with values generally ranging between 10 and 50 mg/L. Figure 6(b) shows the long-term trend component. Between 1984 and approximately 2005, there was a gradual but consistent increase in SPM concentrations, with the trend rising from approximately 21.5 mg/L to a peak of around 25.5 mg/L. This upward phase was followed by a declining trend from 2005 to 2024, during which SPM concentrations decreased back to values near or slightly below those observed in the early 1980s. Figure 6(c) displays the seasonal component, which remains highly regular and consistent throughout the 40-year time series. This indicates a stable intra-annual pattern in SPM concentrations, with recurring peaks in spring and troughs in autumn. Such regularity suggests that the dominant seasonal drivers—such as snowmelt-induced discharge in spring—have maintained their influence on sediment dynamics over the entire study period. SPM concentrations exhibit strong seasonal periodicity, with the highest values typically occurring in spring, followed by summer, winter, and autumn. Figure 6(d) presents the residual component, which represents short-term variability and irregular fluctuations not accounted for by the trend or seasonal components. Several prominent anomalies are evident, high residual values were observed in the fall of 2005 and 2020, while low values appeared during the winters of 1984, 1987, and 1988. These anomalies reflect departures from the expected seasonal-trend pattern and indicate periods of unusually high or low SPM concentrations.

Impact of water level and discharge changes on SPM

Changes in water level and flow are key hydrological factors that regulate SPM concentrations in rivers (Moatar et al., 2017; Montanari, 2012). In these systems, the transport and distribution of SPM are mainly affected by sediment input, sediment resuspension and hydrodynamic conditions. In general, when water level and discharge increase, the in-channel flow velocity in the river is enhanced and the bottom-bed shear is elevated, which intensifies the disturbance and resuspension of bottom sediments, promotes the erosion of bank slopes and floodplains, and significantly increases the concentration and transport flux of SPM. On the other hand, under low water level and discharge conditions, the kinetic energy of the water column is insufficient to maintain particulate matter suspension, and SPM is prone to sedimentation and its concentration decreases. Therefore, the fluctuations of water level and flow not only control the transient changes of SPM, but also determine the sediment transport pattern and water quality status of the river on a larger spatial and temporal scale (Mozzi et al., 2020).

For the Po River, SPM concentrations were significantly higher during periods of high-water levels compared to low-water levels (Figure 7, $p < 0.05$), indicating that fluctuations in water level are a key driver of temporal variability in SPM. This pattern was particularly evident in spring, typically driven by snowmelt and concentrated precipitation in the upper Alpine region, which lead to increased flow velocity and bed shear stress (Lenzi et al., 2003). These hydrodynamic conditions enhance not only the river's

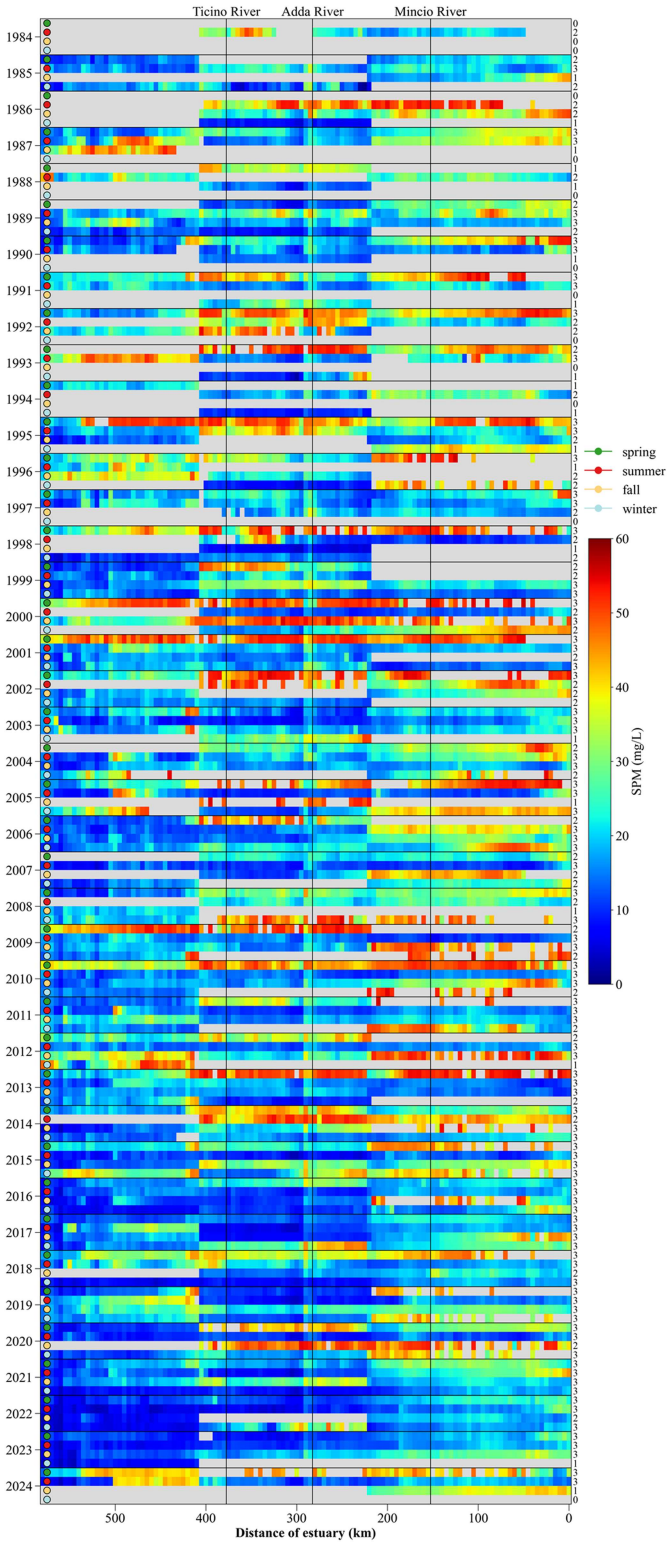


Figure 4. Distribution of SPM concentrations in the Po River, 1984–2024, each raster is 5 km. Horizontal lines indicate different years and vertical lines indicate important tributaries. The numbers on the right are the number of Landsat images. Grey areas indicate no data.

capacity to transport sediments, but also promote resuspension of bottom materials and bank erosion, collectively contributing to seasonal peaks in SPM concentrations.

The relationship between SPM concentrations and river discharge (Q) exhibited pronounced seasonal variability in both sensitivity and scaling behaviour (Figure 8). Log–log regressions revealed positive

Table 2. Satellite-derived SPM (mg/L) for different seasons.

	Mean ± Std.	Range	Median	Q_{25}–Q_{75}
Spring	29.6 ± 13.7	3.5–55.8	27.3	19.3–42.1
Summer	19.4 ± 10.4	2.9–54.7	16.4	12.2–23.8
Autumn	23.2 ± 11.3	2.8–55.9	19.9	15.2–28.8
Winter	20.3 ± 11.9	1.2–55.4	16.7	11.5–26.5

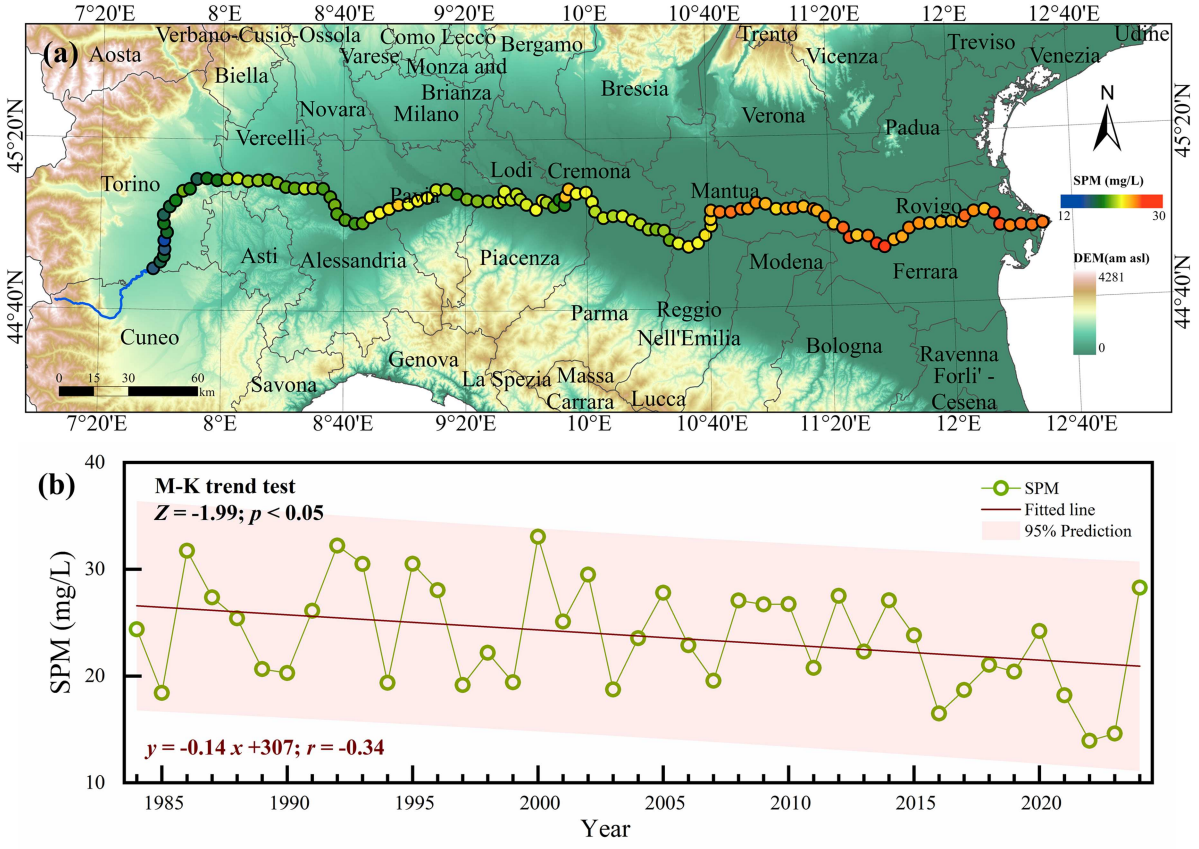


Figure 5. (a) multi-year average SPM concentration in the Po River from 1984 to 2024 (each point represents 5 km); (b) inter-annual variability of SPM concentrations in the Po River.

relationships across all seasons, with the slope of the regression reflecting the responsiveness of SPM to changes in discharge. The strongest response occurred in autumn, the first season of the hydrological year, with a slope of 1.64, reflecting a supra-linear relationship in which modest increases in flow lead to disproportionately large SPM mobilisation. The slope slightly decreases in winter with an intermediate slope of 1.31, demonstrating elevated sensitivity of SPM to discharge even under generally low-flow conditions and then in spring, with a slope of 1.03 indicating an approximately linear response. The lowest values was founded in summer, when the slope decreased to 0.79, indicating a sub-linear response, where SPM increases less than proportionally with discharge, likely due to lower sediment availability under dry-season conditions. These seasonal differences in slope highlight the combined effects of hydrological regime, sediment availability, and land surface conditions on sediment transport, with autumn conditions producing the most efficient sediment mobilisation per unit increase in discharge.

Discussion

Characterisations of SPM concentrations in the Po River

Based on the results of the STL time series analysis, 2005 represents an inflection point in the long-term trend of SPM concentrations in the Po River. Before 2005, SPM concentrations exhibited a gradual increase, while after 2005, a marked decline became evident. This turning point likely reflects the

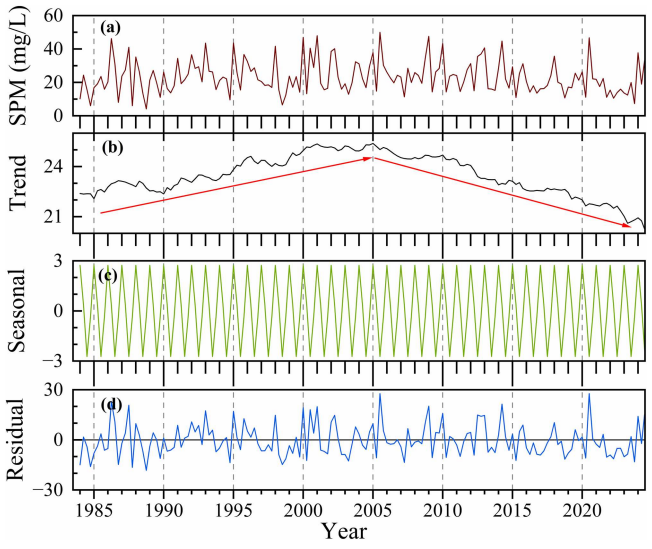


Figure 6. Time series variation of SPM concentrations in the Po River by season (every 3 months), 1984–2024. (a) satellite-driven SPM concentration values; (b) smoothed trend; (c) seasonal variation; (d) decomposed residuals. The missing parts were estimated by interpolation of SPM data in the same season of the previous year and the next year. The raw data in the figure can be found in Appendix C.

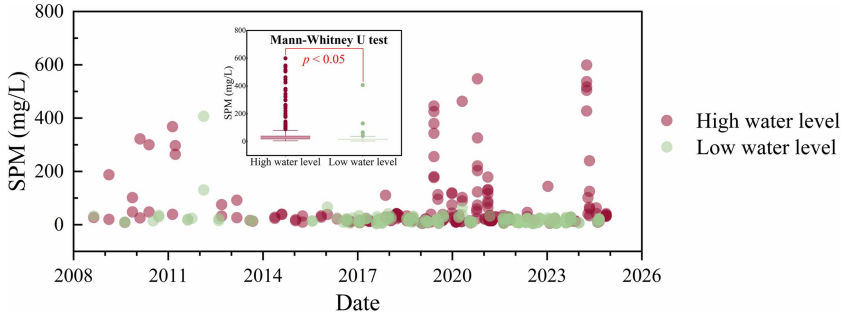


Figure 7. Tests of difference in SPM concentrations in the Po River under high and low water level.

combined effects of hydrological alterations, upstream sediment retention, and changes in land management practices. During the early 2000s, intensified construction of sediment-trapping structures (e.g. dams and bank protections) and gravel mining limitations began reducing the downstream delivery of sediments (Dethier et al., 2022; Maselli et al., 2018). Concurrently, expanded soil conservation measures and land use changes—including afforestation and no-till agriculture—reduced catchment-scale soil erosion, further limiting sediment supply to the river system (Gherardi et al., 2009).

The lowest SPM concentrations were observed in 2022, during the worst hydrological drought year in nearly two centuries (Montanari et al., 2023). The Po River experienced historically low discharge values, with upstream snowpack depletion, reduced spring meltwater, and prolonged summer dryness severely restricting sediment mobilisation (Cavallini et al., 2024). The combination of reduced runoff and decreased erosive energy resulted in minimal suspended sediment transport, as reflected in satellite-derived observations. Such extreme drought conditions have been increasingly linked to ongoing climate change and are expected to become more frequent in Mediterranean-climate basins (Luppichini et al., 2024).

Comparative analysis with other major international rivers

The spatiotemporal patterns of SPM observed in the Po River exhibit both commonalities and distinctive features when compared with other major river systems worldwide. Seasonally, the Po River exhibits a

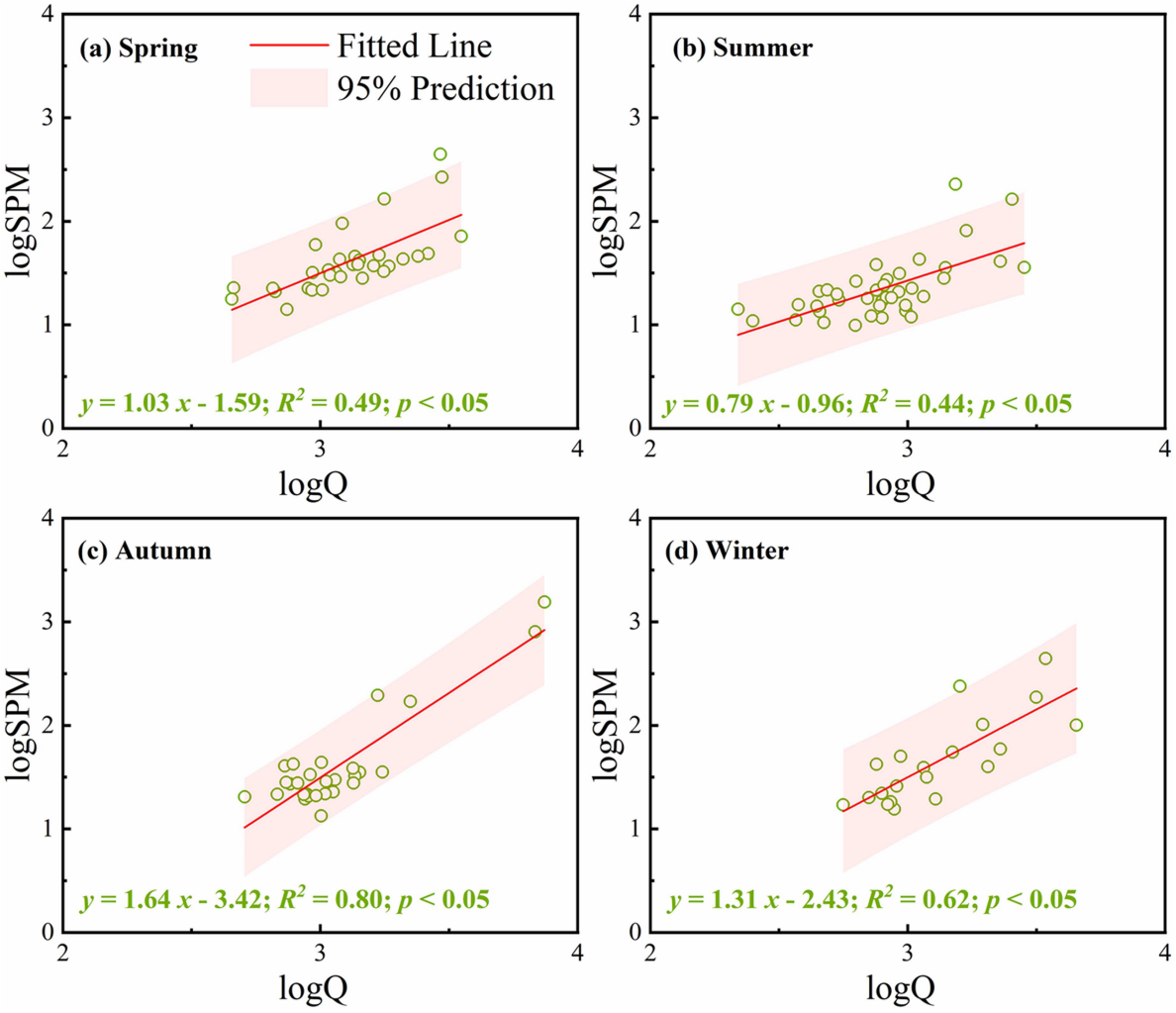


Figure 8. Response of SPM concentrations to changes in discharge in the Po River during different seasons.

pronounced peak in SPM concentration during spring, primarily driven by snowmelt in the upper Alpine catchments. This pattern is consistent with observations from other snow-fed rivers in Europe, such as the Danube River and Rhone River, where high spring discharges mobilise substantial sediment loads (Grzywna et al., 2024; Lepage et al., 2022). In contrast, tropical and monsoon-dominated river systems, such as the Amazon River and Mekong River, typically experience peak SPM concentrations in late summer or autumn, coinciding with intense seasonal precipitation (Feng et al., 2024; Gomes et al., 2021).

From a long-term perspective, the observed decline in SPM concentrations in the Po River since the mid-2000s is consistent with trends reported for several other rivers, such as the Yellow River and Rhone River, which have experienced reduced sediment loads due to improved soil conservation, dam construction, changing land use practices (Dethier et al., 2022), and reduced precipitation driven by climate change (Luppichini et al., 2024). Nevertheless, the magnitude of decline in the Po River (approximately 0.14 mg/L/year) is relatively moderate compared to the drastic sediment reductions (58%) observed in heavily regulated systems like the Yellow River (Liu et al., 2020).

The positive log-log relationship between river discharge and SPM concentrations indicates that increases in discharge consistently promote the mobilisation of suspended sediments ad soil erosion as have been documented in other European rivers (Moatar et al., 2017) (Figure 8). However, the strength of this relationship varies by season decreasing from the Autumn to Summer. This reflects the presence of different sediment mobilisation processes, that varying across temporal and spatial scales, interacting with catchment characteristics—such as land use, geology, and hydrological connectivity (Musolff et al., 2015; Speir et al., 2024; Vercruysse et al., 2020).

The optimum condition for SPM export occurs when uncovered soils (both natural and agricultural) are exposed to intense rainfall events with high erosive potential (Moatar et al., 2020; Vercruysse et al., 2017). In the Po river basin, this condition is present during autumn, which explains why the strongest cQ relationship was observed. Conversely, the weakest cQ slope occurs during summer, which is characterised by being the driest season and presenting the highest soil cover by vegetation, meaning SPM is mobilised and transported with less probability (Cavallini et al., 2024; Moatar et al., 2017; Vercruysse et al., 2017). Winter and spring represent transitional phases with mixed drivers. The cQ response is moderated by the complex interplay of snow accumulation during winter, gradual snowmelt during spring, and the onset of vegetation cover in late spring, resulting in intermediate slopes (Schmidt et al., 2022; Vercruysse et al., 2020).

Limitations and future endeavours

This study demonstrates the advantages of using satellite remote sensing to monitor SPM dynamics over large spatial and temporal scales. Unlike traditional field methods, the use of long-term Landsat data provided consistent coverage of the entire Po River, enabling the detection of multi-decadal trends, seasonal patterns, and responses to extreme events. These results highlight the value of remote sensing for capturing sediment transport processes that would be difficult to observe through ground-based monitoring alone.

There are some limitations to this study. First, the use of Landsat satellite imagery is valuable for long-term retrospective analyses but is limited by its relatively low temporal and spatial resolution (16 days, 30 m). In the Po River, SPM concentrations fluctuate rapidly due to hydrometeorological events, snowmelt, and episodic flooding (Braga et al., 2017; Tesi et al., 2013). The presence of cloud cover further reduces the effective number of available observations, introducing a temporal gap that may underestimate SPM concentrations. Future studies may benefit from satellite data with higher temporal and spatial resolution, such as Sentinel-2 (10 m, 5 days), to improve the temporal density and dynamical tracking of SPM changes (Ghirardi et al., 2023; Renosh et al., 2020). Second, the model validation relied on 18 in-situ measurement campaigns that spanned different seasons, hydrological conditions, and years. While this dataset provides reasonable coverage of the major hydrological regimes, it may not fully represent the entire range of sediment dynamics, particularly during short-lived extreme events or under varying human-induced forcings such as dredging or flow regulation. Consequently, the reported accuracy metrics should be interpreted as representative of average conditions rather than all possible scenarios. To strengthen model robustness, future validation efforts should incorporate additional field measurements collected during high-flow and low-flow extremes, as well as continuous high-frequency monitoring data. The combination of these datasets with satellite observations would help better constrain uncertainties and improve the reliability of long-term SPM estimates across diverse hydrological and anthropogenic conditions. Third, differences in radiometric calibration and spectral response among the Landsat TM, ETM+ , OLI, and OLI-2 sensors may cause systematic biases in the retrieved SPM concentrations and affect long-term trend analysis. In this study, sensor-specific coefficients were applied to each central wavelength in the retrieval algorithm; however, inter-sensor differences cannot be completely removed. Previous studies have shown that the Landsat sensor series is suitable for long-term inland water quality monitoring even without strict cross-sensor calibration (Yan et al., 2025; Yang et al., 2026; Yin et al., 2021). Nonetheless, improving inter-sensor consistency remains an important challenge for future research.

Due to the frequent cloud cover and the length of the Po River, it is difficult to obtain a full scene cloud-free image of the entire watershed on a single date. To construct a complete seasonal mosaic, we selected high-quality scenes from different dates in the same season. While this approach ensures comprehensive spatial coverage, it also introduces inconsistencies in surface reflectance due to variations in different Landsat sensors. This inconsistency can manifest itself as an artificial gradient or discontinuity in the SPM distribution, especially in parts with high spatial and temporal variability (Huang et al., 2018). To address this issue, future work should employ advanced coordination techniques prior to mosaicking, such as pseudo-invariant feature (PIF)-based normalisation, atmospheric invariant pixel correction, or deep-learning-based radiometric fusion (Zhang et al., 2017; Zhou et al., 2016). These methods can enhance the spatial coherence and radiometric consistency of composite SPM products.

While the study primarily focused on hydrological drivers such as river discharge and water level, other potentially important factors—such as land use and land cover changes, riverbed engineering works (e.g. dredging, levees, and channelization), and upstream sediment management practices—were not quantitatively assessed in the study. To address these limitations, future investigations should adopt a multivariate modelling framework that explicitly incorporates both natural and anthropogenic controls on sediment dynamics. For example, high-resolution land use/land cover datasets, combined with historical records of river engineering projects and sediment management interventions, could be integrated as covariates in statistical or machine learning models to assess their individual and combined effects on SPM variability. Additionally, the implementation of process-based sediment transport models, calibrated with both satellite-derived SPM and in-situ measurements, would allow exploration of feedback mechanisms among hydrology, sediment supply, and human interventions. By coupling these models with spatiotemporal satellite observations, it would be possible to simulate long-term SPM patterns under varying hydrological regimes, land use scenarios, and management strategies, thus providing a more comprehensive understanding of the drivers of sediment dynamics in the Po River basin and informing evidence-based river management practices.

Conclusions

This study employed a semi-empirical, multi-conditional algorithm to retrieve SPM concentrations in the Po River using Landsat imagery from 1984 to 2024. A total of 372 cloud-free scenes were used to construct a long-term SPM dataset, with validation showing high accuracy ($R^2 = 0.95$; MPE = –5.3%). The results revealed a long-term decreasing trend in SPM at a rate of 0.14 mg/L per year, with concentrations generally increasing downstream and peaking near Piacenza (265 km from the estuary, 55.9 mg/L). Seasonal variation was pronounced, with the highest concentrations in spring (29.6 mg/L), likely driven by snowmelt and elevated discharge. Time series decomposition identified an inflection point around 2005, after which SPM concentrations declined steadily. A log-linear relationship exists between SPM concentrations and river discharge, with variations in flow significantly influencing SPM concentrations. Overall, this study highlights the effectiveness of combining satellite remote sensing with hydrological data for long-term monitoring of sediment dynamics, providing a valuable tool for managing water quality in large, complex river systems.

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Author contributions

Conceptualisation, F.Y., M.B. and C.G.; Data curation, D.N. and E.C.; Formal analysis, F.Y. and N.G.; Funding acquisition, M.B., C.G. and M.P.; Investigation, M.B., C.G. and M.P.; Methodology, F.Y. and N.G.; Project administration, M.B., C.G. and M.P.; Resources, M.B., C.G. and M.P.; Software, F.Y. and N.G.; Supervision, M.B., C.G., B.H. and Q.F.; Validation, F.Y., N.G., B.H. and Q.F.; Visualisation, F.Y.; Writing—original draft, F.Y. and N.G.; Writing—review and editing, M.B., C.G., N.G., D.N. and E.C. All authors have read and agreed to the published version of the manuscript.

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ORCID

Mariano Bresciani 0000-0002-7185-8464

Data availability statement

The Landsat data used in this study were downloaded from the United States Geological Survey (https://earthexplorer.usgs.gov/). The water quality data used in this study is provided by the Regional Agencies for Environmental Protection (ARPA) of the Piemonte, Lombardia and Emilia-Romagna regions.

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