



## 1 Insights into exceptional freshening events in the northern Adriatic Sea 2 throughout 2023-2024

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### 11 Abstract

12 The northern Adriatic Sea experienced multiple extreme freshening events in 2023 and 2024,  
13 underscoring the intensifying influence of heavy precipitation, river discharge, and coastal  
14 flooding in the region. This study combines high-frequency *in-situ* observations from two  
15 autonomous meteo-marine monitoring platforms offshore of Fano and Senigallia with river  
16 discharge records, satellite imagery, and Copernicus Marine Service products to examine the  
17 evolution, drivers, and ecological implications of these events.

18 The first freshening event in early summer 2023 was linked to consecutive heavy rainfall  
19 episodes, including Storm Minerva, which triggered catastrophic flooding across the  
20 Emilia-Romagna region. Near-surface salinity declined from  $\sim 36 \text{ g kg}^{-1}$  to below  $24 \text{ g kg}^{-1}$   
21 within two weeks, corresponding to an estimated freshwater input of  $\sim 42.5 \text{ m}^3 \text{ h}^{-1}$ . Events in  
22 late 2023 and 2024 were even more abrupt and intense, culminating in late October 2024  
23 with salinity values dropping to  $\sim 15 \text{ g kg}^{-1}$  following Storm Boris. A key distinction between  
24 the two years was the marked recovery of Po River discharge in 2024 after a prolonged  
25 drought, significantly amplifying freshwater inputs. These events triggered cascading  
26 environmental responses, including stratification, turbidity peaks, and phytoplankton blooms  
27 including summer-time mucilage-forming aggregations, posing risks to aquaculture, water  
28 quality, and coastal tourism.

29 By combining autonomous *in situ* measurements, satellite observations, and Copernicus  
30 reanalysis products, this study demonstrates a robust and cost-effective approach to tracking  
31 extreme hydrological events in coastal zones. The integrated dataset not only captures rapid  
32 thermohaline and biogeochemical changes near-real time but also places them in a broader  
33 environmental context. These findings underscore the value of sustained and interoperable  
34 observing systems in supporting early warning capabilities, scientific research, and climate  
35 adaptation in vulnerable marine regions such as the northern Adriatic Sea.

36

37 **Keywords:** extreme freshening; hydro-meteorological extremes; river discharge; autonomous  
38 monitoring; satellite and reanalysis integration; northern Adriatic Sea; climate-driven coastal  
39 impacts



## 40 Short summary

41 Between 2023 and 2024, the northern Adriatic Sea experienced extreme surface freshening  
42 driven by storms, heavy rainfall and river flooding. Using high-frequency *in-situ* data, satellite  
43 imagery, and Copernicus Marine Service products, this study traces the evolution, causes,  
44 and ecological impacts of these events. Salinity dropped to 15 g/kg, triggering stratification,  
45 turbidity peaks, and algal blooms. Findings stress the need for integrating autonomous  
46 monitoring into operational services.

## 47 1 Introduction

48 Coastal regions like the shallow Northern Adriatic are complex and densely-populated  
49 socio-ecological systems that provide high-value services (Costanza et al., 2021) which are  
50 susceptible to the impacts of climate change and other anthropogenic and natural pressures.

51 Among those, flooding events, triggered by factors such as high tides, storm surges and  
52 precipitation whiplashes can lead to large adverse impacts on human and natural systems  
53 (Atkinson et al., 2013; Wright and Nichols, 2019; Tan et al., 2023). According to the latter,  
54 precipitation whiplashes, including abrupt shifts between dry and wet extremes, favor the  
55 generation of significant surface runoff and flooding, concurrent landslides and erosion that  
56 can also amplify negative trends in water quality. Overall, river discharge plays a crucial role  
57 in coastal ecosystems by providing freshwater and nutrients that impact hydrology,  
58 biogeochemistry, and productivity. Along the Northwestern Adriatic coast, several smaller  
59 rivers and the major Po river discharge nutrients-rich freshwater which is mainly transferred  
60 southward along the Italian coast by the Western Adriatic Current (Goudeau et al., 2013),  
61 while the plume is known to remain close to the coast under stratified conditions (Cozzi and  
62 Giani, 2011). This, in turn, affects nutrient cycling, species growth and survival rates (Ludwig  
63 et al., 2009; Cozzi et al., 2012) as well as water mass formation processes (Falcieri et al.,  
64 2014).

65 The coastal impacts of flooding events extend beyond environmental concerns, affecting  
66 local communities and economies that depend on infrastructure and marine resources (e.g.,  
67 IPCC SROCC, 2020; IPCC AR6, 2023). The need for coastal observations and monitoring efforts  
68 is therefore progressively being recognized in order to guide policy and progress towards  
69 public safety needs. The Copernicus Marine Service plays a key role in this context by offering  
70 a wide range of physical and biogeochemical data near-real time. However, the location,  
71 rarity and complexity of floods and the related coastal events present specific challenges.  
72 Accurate detection and monitoring require an integrated methodology that combines local  
73 high-resolution *in-situ* measurements, satellite data and modeling approaches. This study  
74 leverages the high-resolution data from a coastal meteo-marine buoy and several Copernicus  
75 sources to provide a comprehensive analysis of a series of exceptional freshening events in  
76 the northern Adriatic Sea throughout the last two years.



## 77 **2 Methodology**

78 In order to assess the spatio-temporal characteristics, environmental drivers, and ecological  
79 impact of extreme freshening events in the northwestern Adriatic Sea during 2023 and 2024,  
80 we integrated a set of *in-situ*, satellite-derived, reanalysis, and model-based datasets.

81

### 82 **2.1 Local meteo-marine conditions**

83 High-frequency *in-situ* measurements of thermohaline, atmospheric and biogeochemical  
84 properties were obtained from two autonomous meteo-marine monitoring systems,  
85 positioned ~2 miles offshore of Fano (43° 53'30.0" N, 13° 00'30.0" E) and Senigallia  
86 (43°45'20.9" N, 13°12'32.4" E) on the western coast of the northern Adriatic Sea (product ref.  
87 1 and 2; Table 1).

88 Raw data from these platforms (mentioned as Buoy Fortunae offshore of Fano and Meda  
89 Station offshore of Senigallie henceforth) were first converted with the calibration  
90 coefficients in the configuration file provided by Sea-Bird Electronics and processed  
91 according to the typical SBE data processing sequences. The necessary calculation and  
92 analysis of thermodynamic properties was based on the Gibbs Seawater (GSW)  
93 Oceanographic Toolbox (IOC et al., 2010), which contains the TEOS-10 subroutines  
94 (www.TEOS-10.org) for the evaluation of seawater properties (McDougall and Barker, 2011).  
95 Detailed sensor specifications and processing steps are available in Appendix A1a–A1c.

96

### 97 **2.2 Precipitation and river discharge**

98 Hourly precipitation data were retrieved from the ERA5 reanalysis dataset, produced by the  
99 Copernicus Climate Change Service, which provides gridded atmospheric fields at 0.25°  
100 spatial and 1-hour temporal resolution (product ref. 3; Table 1). In parallel, 6-hourly river  
101 discharge estimates were extracted from the European Flood Awareness System (EFAS)  
102 model, based on the LISFLOOD hydrological model forced with gridded meteorological  
103 observations (product ref. 4; Table 1). Considering the dominant southeastward flow of the  
104 Western Adriatic Current, freshwater input from major (Po, Adige, Reno) and minor regional  
105 rivers (e.g., Lamone, Savio, Metauro, and 14 others) was assessed at their upstream mouths  
106 along the northwestern Adriatic coast (see Figure 3 for river mouth locations and  
107 characteristic circulation patterns).

108

### 109 **2.3 Freshwater rate estimation**

110 To estimate the required freshwater rate that results in a specified decrease in the surface  
111 seawater salinity over a given time period, a simplified salt mass conservation approach was  
112 applied. This method was based on *in-situ* salinity data from the Fortunae buoy (product ref.  
113 1; Table 1) and the estimated area of the affected region, as determined from satellite  
114 observations (product ref. 5 and 6; Table 1). Assuming that salinity and density are conserved  
115 during mixing and proportional to the volumes involved, the following salt mass balance  
116 equation was applied:



$$\rho_1 S_1 V_1 = \rho_2 S_2 V_2 \quad (1)$$

where:

$\rho_1$  and  $\rho_2$  are the initial and final density in  $\text{kg m}^{-3}$

$S_1$  and  $S_2$  are the initial and final salinity in  $\text{g kg}^{-1}$

$V_1$  is the initial considered volume of seawater in  $\text{m}^3$

$V_2$  is the final volume after mixing with the added freshwater in  $\text{m}^3$

And the freshwater flow ( $Q$ ) in  $\text{m}^3/\text{s}$ , required to achieve the observed salinity decrease over the time period  $\Delta t$  is calculated as:  $Q = \frac{\Delta V}{\Delta t}$  (2)

A practical example of this calculation, including measured values from the Fortunae buoy and assumptions on the affected volume based on the buoy's position and local bathymetry, is provided in Appendix A2, along with a schematic diagram illustrating the considered water volume (Figure A1).

#### 2.4 Complementary satellite and model-based datasets

To complement the *in-situ* observations and support the freshwater rate estimation (Section 2.3), we incorporated satellite-derived and model-based datasets (products 5–8; Table 1) providing full spatial coverage of the northwestern Adriatic Sea. These included daily fields of sea surface temperature (SST), chlorophyll-*a* concentration, light attenuation coefficient at 490 nm (KD490), surface salinity, and horizontal current components ( $u$  and  $v$ ).

These datasets served three main purposes:

(1) to delineate the surface extent of freshwater-affected waters and define the horizontal area used in freshwater input calculations (see Appendix A2);

(2) to fill temporal gaps in the buoy and coastal station records, ensuring continuous environmental context during key periods of data loss; and

(3) to extend the analysis beyond the nearshore region, offering insight into the broader evolution of surface thermohaline and biogeochemical properties across the Adriatic Sea.

The satellite products provided gap-free, multi-sensor interpolated surface fields, while the model outputs offered physically consistent estimates of key oceanographic variables across space and time.

#### 2.5 Statistical analysis

Basic statistics were computed following Emery and Thomson (1998). Root Mean Square Difference (RMSD), bias, and cross-correlation were applied to evaluate temporal coherence between thermohaline, biogeochemical and environmental conditions. Detailed equations and assumptions are reported in Appendix A3.



**Table 1:** Products from the Copernicus Service and other complementary datasets used in this study, including the Product User Manual (PUM) and Quality Information Document (QUID). For complementary datasets, the links to the product description, data access and/or references are provided. Last access for all web pages cited in this table: 17 May 2025.

| Product Ref. No. | Product ID & type                                          | Data Access                                  | Documentation                                            |
|------------------|------------------------------------------------------------|----------------------------------------------|----------------------------------------------------------|
| 1                | Fortunae Buoy, <i>in-situ</i> data                         | Fano Marine Center (2025)                    | Penna et al. (2025a)                                     |
| 2                | Senigallia Meda, <i>in-situ</i> data                       | IRBIM-CNR (2025)                             | Penna et al. (2025b)                                     |
| 3                | ERA5, numerical models                                     | Hersbach et al. (2023)                       | Copernicus Climate Change Service (2023)                 |
| 4                | CEMS EFAS, numerical models                                | Mazzetti et al. (2023)                       | Copernicus Emergency Management Service (2025)           |
| 5                | SST_MED_SST_L4_NRT, satellite observations                 | EU Copernicus Marine Service Product (2024a) | QUID: Pisano et al. (2024a); PUM: Pisano et al. (2024b)  |
| 6                | OCEANCOLOUR_MED_BGC_L4_NRT_009_142, satellite observations | EU Copernicus Marine Service Product (2025)  | QUID: Colella et al. (2025); PUM: Colella et al. (2024)  |
| 7                | MEDSEA_ANALYSIS_FORECAST_PHY_006_013, numerical models     | EU Copernicus Marine Service Product (2024b) | QUID: Gualtieri et al. (2024); PUM: Lecci et al. (2024a) |
| 8                | MEDSEA_ANALYSIS_FORECAST_BGC_006_014, numerical models     | EU Copernicus Marine Service Product (2024c) | QUID: Feudale et al. (2024); PUM: Lecci et al. (2024b)   |

159

### 160 3 Results

161 Over the past two years, the northern Adriatic Sea experienced a series of  
162 hydro-meteorological extremes, resulting in rapid and recurrent freshening episodes with  
163 cascading environmental and societal implications.

164

#### 165 3.1 Surface freshening

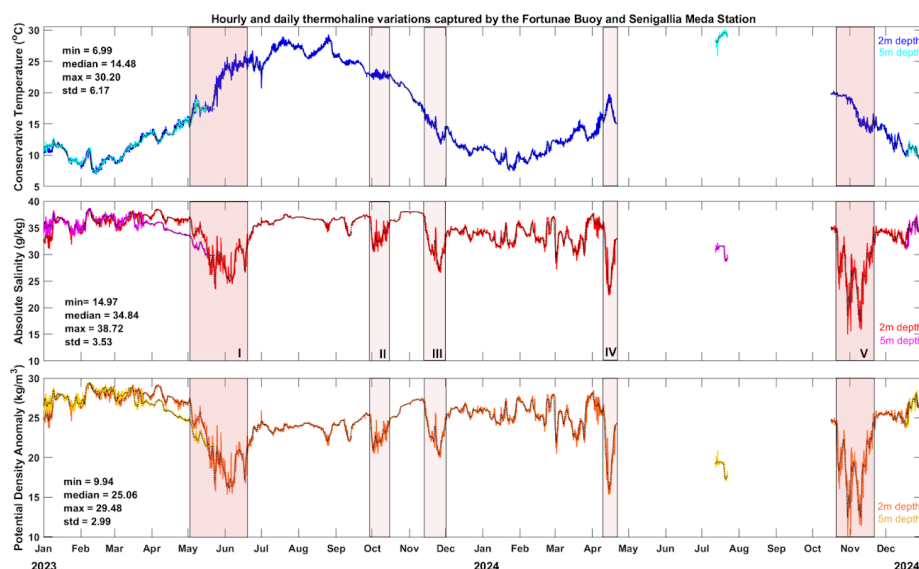
166 Between May 2023 and November 2024, five distinct surface freshening events were  
167 identified in the northern Adriatic Sea from high-frequency salinity observations collected by  
168 the Fortunae buoy and the Senigallia Meda Station. These events varied in duration (12 to 53  
169 days), intensity (6.7 to 20.1 g/kg salinity drop), and temporal structure, shaped both by  
170 prolonged and abrupt freshwater input dynamics (Table A4 and A5).



Event I (2 May – 24 June 2023) was the longest, spanning 53 days. It was characterized by a multi-phase freshening, including an extended period of anomalously low salinity and a gradual recovery. The most pronounced salinity decrease occurred over 13 days (11–24 May), with salinity dropping by  $12.77 \text{ g kg}^{-1}$ , from  $36.19$  to  $23.42 \text{ g kg}^{-1}$ . This prolonged freshening suggests sustained riverine discharge into the northwestern Adriatic. Event II (29 Sep – 16 Oct 2023, 17 days) showed a more abrupt signature. Over just 5 days, salinity fell by  $6.72 \text{ g kg}^{-1}$  (from  $37.17$  to  $30.45 \text{ g kg}^{-1}$ ), indicating a rapid freshwater input followed by a relatively short recovery. Event III (12 Nov – 2 Dec 2023, 20 days) included the highest initial salinity observed ( $37.63 \text{ g kg}^{-1}$ ), followed by a significant 14-day drop to  $26.53 \text{ g kg}^{-1}$ —a total decrease of  $11.10 \text{ g kg}^{-1}$ . Event IV (9–21 Apr 2024, 12 days) was short but intense, featuring a 6-day salinity decrease of  $13.89 \text{ g kg}^{-1}$ , from  $36.16$  to  $22.27 \text{ g kg}^{-1}$ —among the steepest gradients recorded. Event V (20 Oct – 22 Nov 2024, 33 days) was the most extreme in terms of salinity reduction. A 10-day drop of  $20.12 \text{ g kg}^{-1}$  brought surface salinity from  $35.09$  to  $14.97 \text{ g kg}^{-1}$ , making this the most intense freshening event of the record.

These events illustrate the basin's dual sensitivity to sustained meteorological forcing and intense short-term hydrological extremes. Cross-event comparisons emphasize differing recovery behaviors and highlight the coupling between catchment saturation and downstream marine responses (Figures A2-A6).

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190

**Figure 1:** Hourly (colored lines) and daily-averaged (black dotted lines) time series of (a) conservative temperature, (b) absolute salinity, and (c) potential density anomaly recorded at 2 m and 5 m depth offshore of Fano and Senigallia, respectively (product ref. 1 and 2; table 1). Basic statistical descriptors (minimum, maximum, median, standard deviation) for each thermohaline property are reported in the top left corner of each panel. Light red shaded areas (I–V) indicate the timing of the five most significant surface freshening events identified between 2023 and 2024.

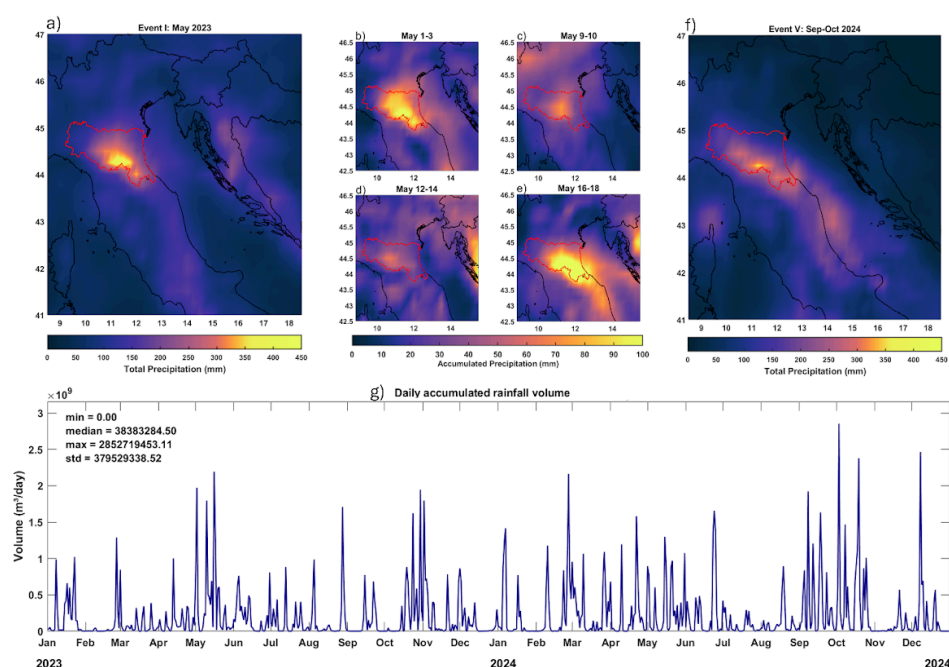


### 3.2 Environmental connections

Hydrological analysis revealed that major freshening events coincided with intense precipitation and river discharge anomalies in the Emilia-Romagna region, with events driven by both catchment saturation and localized convective storms.

A sequence of five rainfall episodes culminated in catastrophic flooding from 1–24 May 2023 (Figure 2 b). The first rainstorm (1–3 May) brought over 200 mm of precipitation to central-eastern Emilia-Romagna. Initial flooding affected the Reno and Lamone basins. Two subsequent moderate episodes (9–10 May and 12–14 May) further saturated soils. The most severe storm, associated with Storm Minerva (16–18 May), delivered over 300 mm in areas such as Forlì, with cumulative precipitation more than 5 times the monthly climatological average.

During this period, the Po River remained well below the climatological average discharge with values around 2000 m<sup>3</sup>/s, whereas local rivers like the Lamone, Savio, and Reno exceeded historical flood levels (Figure 3c). Cross-correlation analysis between accumulated precipitation and river discharge (Figure A5) confirmed statistically significant relationships ( $p < 0.05$ ), with time lags ranging from -6 to -120 hours. Rapid response was observed in local rivers with short catchments, such as Rubicone ( $r = 0.74$ , lag = -6 h), while larger basins like the Adige exhibited longer delays ( $r = 0.71$ , lag = -36 h).



**Figure 2:** Spatial distribution of accumulated precipitation (product ref. 2; table 1) over Emilia-Romagna and surrounding areas during key extreme rainfall events associated with surface freshening Event I and Event V (see Figure 1). (a) Total precipitation during the combined May 2023 period (Event I). Accumulated precipitation during individual May 2023 storm episodes: (b) 1-3 May,



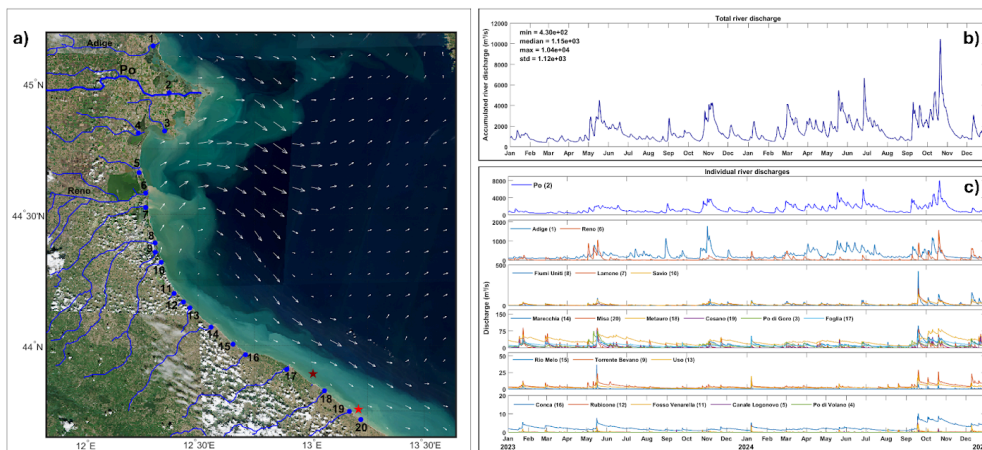
(c) 9–10 May, (d) 12–14 May, and (e) 16–18 May. (f) Total precipitation during the two September–October 2024 events (Event V). The Emilia-Romagna region is outlined in red in each panel. (g) Time series of daily accumulated rainfall volume ( $\text{m}^3 \text{ day}^{-1}$ ) over the domain, highlighting the timing and intensity of individual rainfall peaks between January 2023 and December 2024. Basic statistical descriptors (minimum, maximum, median, standard deviation) are reported in the upper left corner.

No widespread heavy precipitation was recorded in correspondence with Event II in late September 2023, but localized convective storms likely impacted the Marche region between 25–29 September. Discharges increase of the Adige and Po was reported and the freshening signal suggests a short-lived but intense localized input (Figure 1). In accordance, two prolonged rainfall episodes occurred later during 2–5 November and 30 November–2 December (Event III). The latter was the most severe, with up to 383 mm of rainfall recorded in the Parma Apennines. A third, minor event on 4–5 December followed the main storm.

During spring 2024, an unseasonable storm system between 20–24 April brought 70–80 mm of weak but steady rainfall and rivers with short response times reacted quickly to the precipitation input, leading to the abrupt salinity drop during Event IV (Figure 1).

Autumn 2024 saw the return of exceptional rains. Between 17–20 September, Storm Boris delivered ~300 mm of rainfall in eastern Emilia-Romagna, causing major river discharges in local rivers like the Savio, Fiumi Uniti and Lamone River (Figure 3c). Less than a month later (18–19 October), another storm triggered river discharge records for all major rivers, especially for the Po River (record value=7880  $\text{m}^3/\text{s}$ ), reflecting a marked hydrological recovery after prolonged drought.

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**Figure 3:** (a) Overview of (a) the study area with the location of the 20 assessed river mouths (blue dots) and the positions of the autonomous monitoring platforms offshore of Fano and Senigallia (dark and light red star, respectively). The background corresponds to a Sentinel-2 Level 2A true-color image (<https://dataspace.copernicus.eu/browser>) acquired on 31 October 2024, overlaid with surface current vectors derived from the numerical circulation model (product ref. 8; table 1) for the same date. (b) Daily time series of the total accumulated river discharge ( $\text{m}^3 \text{ s}^{-1}$ ) from all 20 rivers for the

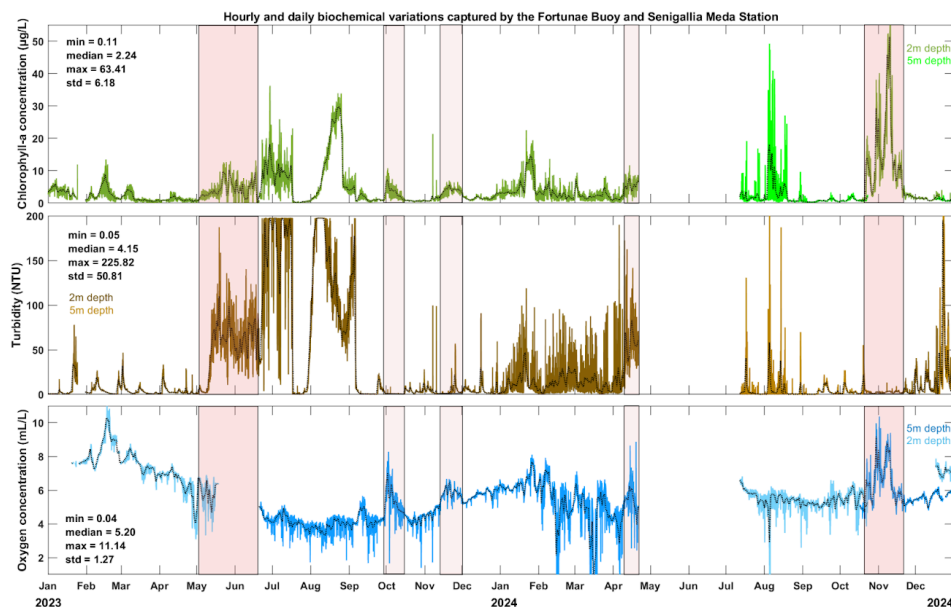


period January 2023–December 2024 (product ref.3; table 1). Key descriptive statistics (minimum, median, maximum, standard deviation) are indicated. (c) Individual river discharge time series, grouped by magnitude, with numeric labels corresponding to the river mouth positions indicated in panel (a).

This analysis affirms that both large-scale catchment saturation and localized storm activity contributed significantly to the observed salinity anomalies. Rivers with differing catchment sizes showed distinct response times, with immediate peaks in small rivers and delayed responses in larger ones. Figures 2 and 3, along with Appendix Figures A2–A6, provide spatial and temporal context for precipitation and discharge patterns associated with each event.

### 3.3 Ecological implications

Each freshening event identified in this study (Figure 1) triggered a marked biogeochemical response in the northern Adriatic Sea, as captured by the high-frequency *in-situ* measurements of chlorophyll-a, turbidity, and dissolved oxygen collected by the Fortunae Buoy and the Senigallia Meda Station (Figure 4). These parameters serve as proxies for primary productivity, sediment transport, and oxygen dynamics, offering direct evidence of ecosystem perturbations following extreme hydro-meteorological events.



**Figure 4:** Hourly (colored lines) and daily-averaged (black dotted lines) time series of (a) chlorophyll-a concentration, (b) turbidity, and (c) dissolved oxygen concentration measured at 2 m and 5 m depths by the Fortunae buoy (offshore of Fano) and the Senigallia Meda station, respectively (product ref. 1 and 2; table 1). Basic statistical descriptors (minimum, maximum, median, standard deviation) are reported in the left corner of each panel. Red shaded areas (I–V) denote the timing of the five most pronounced surface freshening events as identified in Figure 1. Biogeochemical responses, including



sharp increases in turbidity and chlorophyll-a, coincide with or follow these events, reflecting ecosystem perturbations.

Following Event I (May 2023), which was preceded by a sequence of five intense rainfall episodes in the Emilia-Romagna region and culminated in catastrophic flooding (Figure 2b–e), an extreme turbidity increase ( $\sim 100$  NTU average) was recorded for more than a month, along with chlorophyll-a concentrations exceeding  $10 \mu\text{g/L}$ . These responses reflect the combined influence of excess sediment transport and nutrient enrichment, especially from local rivers like the Lamone, Reno, and Savio, which exceeded historical discharge levels (Figure 3c). The sustained rainfall and resulting prolonged runoff seems to have led to a persistent stratified surface layer that confined biological activity and promoted bloom formation.

After the record May flood period, a particularly notable anomaly was observed in June–July 2023, with sustained extreme turbidity ( $>200$  NTU) and following chlorophyll-a values ( $>30 \mu\text{g/L}$ ). Subsequent visual inspections of the buoy infrastructure revealed the presence of mucilage-forming macroaggregates, consistent with recurring gelatinous algal blooms historically observed in the Adriatic under warm, stratified, and nutrient-enriched conditions (Arrighi and Domeneghetti, 2023). These mucilage events have well-documented impacts on marine ecosystems, coastal water quality, and economic sectors such as aquaculture and tourism.

The response to Event II (late September–October 2023) presented a contrasting case. While no widespread heavy precipitation and flooding occurred in Emilia-Romagna, localized convective storms over the Marche region and rising discharges in the Adige and Po rivers triggered a short-lived but intense freshening. Although turbidity remained low, the biogeochemical response included a marked chlorophyll-a increase and oxygen supersaturation, indicating a nutrient-rich but low-sediment freshwater input. Moreover, dissolved oxygen rose near-synchronously with chlorophyll-a concentrations ( $r=0.77$ ,  $\text{lag}=0$  h), consistent with well-lit bloom conditions. This event exemplifies how smaller, convective systems can fuel biological productivity without large sediment loads—favorable light conditions likely allowed rapid phytoplankton growth.

The prolonged rainfall in early and late November 2023 preceded Event III, which produced another strong bloom and variable oxygen patterns. This response suggests that delayed runoff from larger, saturated catchments delivered substantial nutrient loads, with peak phytoplankton activity followed by oxygen variability related to organic matter remineralization and light attenuation during turbid phases.

The corresponding biogeochemical response to event IV followed an unseasonable storm system in April 2024. Rapid response from short catchment rivers like the Rubicone and Uso led to an abrupt salinity drop (Figure 1) and sharp turbidity and chlorophyll peaks, consistent with the fast land-sea transfer typical of springtime storms over saturated terrain. These



316 dynamics emphasize the system's sensitivity even to moderate precipitation when  
317 antecedent soil conditions favor immediate runoff.

318 Finally, Event V in autumn 2024 was preceded by two major storm systems: Storm Boris  
319 (17–20 September) and an intense October storm (18–19 October), the latter driving the Po  
320 River to record discharge levels (Figure 3c). This sequence produced the most intense surface  
321 freshening and the highest chlorophyll-a concentration observed during the study period,  
322 exceeding 60  $\mu\text{g/L}$ . Interestingly, these extremely high chlorophyll-a levels occurred in  
323 conjunction with notably low turbidity, suggesting that sediment-laden runoff from the Po  
324 River may have settled or dispersed before reaching the offshore monitoring sites at Fano  
325 and Senigallia. This decoupling implies that nutrient transport remained effective despite  
326 reduced suspended particulate matter, allowing for favorable light conditions and enhanced  
327 primary productivity—consistent with a multi-day negative turbidity–chlorophyll relationship  
328 ( $r=-0.32$  at  $-144\text{h}$  lag) and near-synchronous, positive chlorophyll–oxygen coupling ( $r=0.86$  at  
329  $0\text{h}$  lag), together indicating strong photosynthetic control under clear conditions.

330 Across all events, dissolved oxygen dynamics reflected a combination of photosynthetic  
331 production during bloom conditions and oxygen depletion during periods of high turbidity  
332 and organic matter degradation. Event-scale lead–lag patterns showed a biphasic  
333 turbidity–chlorophyll response with a short-lag negative branch when high turbidity limits  
334 light, and a positive branch at multi-day delays when nutrient delivery and stratification  
335 promote blooms. The chlorophyll–oxygen coupling is typically positive and  
336 near-synchronous, with longer-lag negatives appearing during potential bloom decay and  
337 post-bloom respiration.

338

339 These findings confirm that hydro-meteorological forcing, whether through widespread  
340 rainfall, localized storms, or antecedent soil saturation, directly drive ecosystem-level  
341 responses in the northern Adriatic Sea. The magnitude and timing of these responses  
342 depend not only on precipitation intensity and discharge volume, but also on the sediment  
343 load, nutrient delivery, and seasonal conditions governing stratification and light availability.  
344

#### 345 **4 Discussion and conclusions**

346 The northern Adriatic experienced a series of extreme freshening events between 2023 and  
347 2024, underscoring its vulnerability to compound hydro-meteorological extremes. Events  
348 such as Storm Minerva and Storm Boris were marked by intense precipitation and  
349 widespread flooding, with significant hydrological and ecological repercussions. These cases  
350 highlight the increasing role of precipitation whiplash and flood-drought cycles in modulating  
351 coastal hydrography.

352 According to the IPCC's Sixth Assessment Report, heavy rainfall events and the corresponding  
353 overflow are projected to increase in frequency and intensity as global temperatures rise  
354 beyond  $1.5^\circ\text{C}$  (IPCC, 2023). River floods in central and western Europe are already increasing,  
355 and small catchments, like those affected along the northwestern Adriatic coast, are



356 especially vulnerable. Future storms may more frequently exceed their coping capacities,  
357 reinforcing the urgency of adaptive monitoring systems.

358 In the Northern Adriatic, where the Po River and smaller local rivers drive salinity and  
359 biogeochemical patterns, such shifts have significant implications. As the shallowest and  
360 northernmost basin of the Mediterranean is particularly vulnerable to such perturbations  
361 due to its limited flushing, strong land-sea coupling, and intensive human pressure (Coll et  
362 al., 2010). Its physical and ecological sensitivity to episodic freshwater pulses, such as those  
363 examined here, underscores the growing importance of continuous monitoring in the  
364 context of climate change.

365 Surface freshening alters water column structure, promotes stratification, and modulates  
366 ecological responses. In summer 2023 and 2024, sea surface temperatures exceeded 30°C,  
367 accompanied by extensive mucilage-forming algal aggregations. These events compromise  
368 water quality, threaten aquaculture viability, and impact tourism, posing socio-ecological  
369 risks.

370 High-resolution *in-situ* observations play a critical role in capturing such rapid and localized  
371 phenomena. Coastal meteo-marine platforms, such as the utilized Fortunae buoy and  
372 Senigallia Meda station, offer a cost-effective, automated system capable of operating under  
373 harsh conditions and at high sampling rates in complex nearshore zones.

374 We therefore recommend a collective effort that incorporates such observational datasets  
375 into Copernicus and broader databases. Such integration would bridge existing gaps in  
376 coastal coverage, complementing the basin-wide scope of satellite and reanalysis products  
377 with finer-scale, real-time data. As climate-induced extremes accelerate, safeguarding  
378 ecological and societal resilience in shallow semi-enclosed seas, such as the Adriatic Sea,  
379 requires sustained, integrated, and transdisciplinary efforts—anchored in robust, real-time  
380 observations and openly accessible data.

381

## 382 **Appendix**

383

### 384 **A1) Overview of the meteo-marine buoy Fortunae**

385 The multidisciplinary buoy is equipped with a series of sensors that measure atmospheric  
386 parameters at 2m height; wave parameters at sea level; as well as current, thermohaline and  
387 biochemical parameters at ~2m depth below the sea level.

388

#### 389 **a) Atmospheric conditions at 2m height**

390 More precisely, the following atmospheric parameters are systematically sampled every 30  
391 minutes at 2 meters above sea level using a GILL MaxiMet GMX500 Compact Weather

392 Station equipped with GPS (<https://gillinstruments.com/>):

393



**Table A1)** Overview of the observed atmospheric parameters with the corresponding technical details and characteristics. Additional information are available under the feature specification of the GMX500 Model: <https://gillinstruments.com/wp-content/uploads/2022/08/1957-008-Maximet-gmx500-lss-9.pdf>

| Measured Parameters                     |                  |             |            |                      |
|-----------------------------------------|------------------|-------------|------------|----------------------|
| Parameter                               | Unit             | Range       | Resolution | Accuracy             |
| Air pressure ( $P_{air}$ )              | hPa              | 300 to 1100 | 0.1        | $\pm 0.5$ hPa @ 25°C |
| Air temperature ( $T_{air}$ )           | °C               | -40 to +70  | 0.1        | $\pm 0.3$ °C @ 20°C  |
| Dew point ( $T_{dew}$ )                 | °C               | -40 to +70  | 0.1        | $\pm 0.3$ °C @ 20°C  |
| Relative Humidity (RH)                  | %                | 0 to 100    | 1          | $\pm 2$ % @ 20°C     |
| Wind direction ( $D_w$ )                | deg              | 0 to 359    | 1          | $\pm 3$ ° to 40 m/s  |
| Wind speed ( $U_w$ ) and gust ( $U_g$ ) | ms <sup>-1</sup> | 0.1 to 60   | 0.01       | $\pm 3$ % to 40 m/s  |

398

#### 399 b) Wave conditions at sea level

400 Accordingly, the following wave parameters are systematically sampled every 60 minutes at  
 401 sea level utilizing a Brizo-X Directional Wave Height Sensor with an integrated Global  
 402 Navigation Satellite System (GNSS) from Xeos Technologies (<https://xeostech.com/brizo-x>):

403 **Table A2)** Overview of the observed waves characteristic with the corresponding technical details.  
 404 Wave height range information stem from Wang et al. (2016). Additional information are available  
 405 under the feature specification of the Brizo-X Model:  
 406 <https://xeostech.com/sites/default/files/2019-08/BrizoX%20Brochure%20WEB.pdf>

| Measured Parameters                 |      |               |                            |
|-------------------------------------|------|---------------|----------------------------|
| Parameter                           | Unit | Range         | Accuracy                   |
| Significant wave height ( $H_s$ )   | m    | 0.2-20        | $\pm 1$ % @ -40°C to +60°C |
| Maximum wave height ( $H_{max}$ )   | m    | 0.2-20        | $\pm 1$ % @ -40°C to +60°C |
| Waves mean period ( $T_z$ )         | sec  | 1.56 to 33.33 | $\pm 1$ % @ -40°C to +60°C |
| Waves maximum period ( $T_{Hmax}$ ) | sec  | 1.56 to 33.33 | $\pm 1$ % @ -40°C to +60°C |
| Wave direction ( $D_p$ )            | deg  | 0 to 359      | $\pm 3$ ° @ -40°C to +60°C |
| Directional spread ( $B_m$ )        | deg  | 0 to 359      | $\pm 3$ ° @ -40°C to +60°C |

407

408 The Brizo-X Directional Wave Height Sensor utilizes standard spectral analysis techniques and  
 409 formulas to calculate wave parameters for waves of periods from 1.6 s to 33 seconds (Earle,  
 410 1996). The energy density spectrum of a sea state is generally designated by  $E(f)$  and the  
 411 total energy is given by

$$\overline{E} = \int_0^{\infty} E(f) df \quad (3)$$

413 The wave frequency spectrum can, therefore, be determined from a wave record  $\eta(t)$  by  
 414 using a Fourier transform as follows: The wave energy averaged over a period

415  $\left[ -T/2 < (t - t_0) < T/2 \right]$  is given by

416

$$\overline{E} = \frac{g\rho}{T} \int_{-T/2}^{T/2} \left( \eta(t - t_0) - \langle \eta \rangle \right)^2 dt \quad (4)$$

418 where  $\langle \eta \rangle$  is the mean value.

419 Inserting in this expression the Fourier development of  $\left( \eta(t - t_0) - \langle \eta \rangle \right)$ , gives

420



$$\bar{E} = \sum_{k=1}^{\infty} E(f_k) \Delta f, \quad f_k = k \Delta f, \quad \Delta f = \frac{1}{T}, \quad E(f_k) \Delta f = \frac{g\rho}{8} |H_k|^2, \quad H_k = \frac{4}{T} \int_{-T/2}^{T/2} (\eta(t - t_0) - \langle \eta \rangle) e^{-2\pi i f_k t} dt \quad (5)$$

Where  $g$  is the gravitational acceleration,  $\rho$  is the seawater density.

#### c) Thermohaline and biochemical conditions at 2m depth

Additionally, the following oceanographic parameters are systematically sampled every 30 minutes at ~2m depth below the sea level by a submerged MicroCAT SBE-37 SIP (Serial Interface Pumped) CTD (Conductivity-Temperature-Depth) and a WET Labs ECO-FLNTU fluorescence sensor with Bio-Wiper option from Sea-Bird (<https://www.seabird.com/>) :

**Table A3)** Overview of the observed oceanographic parameters\* with the corresponding technical details and characteristics. Additional information are available under the SBE feature specifications: <https://www.seabird.com/moored/sbe-37-si-and-sip-microcat/>

| Measured Parameters   |                    |             |                      |
|-----------------------|--------------------|-------------|----------------------|
| Parameter             | Unit               | Range       | Accuracy/Sensitivity |
| Pressure (P)          | Pa                 | to ~6022000 | ± 0.1%               |
| Temperature (T)       | °C                 | -5 to +45   | ± 0.002              |
| Conductivity (Cond)   | Sm <sup>-1</sup>   | 0 to 7      | ± 0.0003             |
| Turbidity (turb)      | NTU                | 0.01 to 25  | 0.01                 |
| Chlorophyll-a (chl-a) | µg L <sup>-1</sup> | 0.01 to 50  | 0.025                |

\* Though not included in this study, additional parameters are available from an SBE optical oxygen sensor and a Nortek Aquadopp current meter from July 14th 2023 onwards.

The TEOS-10 GSW Matlab routines (version 3.05.5) were applied to derive Absolute Salinity ( $S_A$ ) (mass fraction of dissolved material, in gkg<sup>-1</sup>) and of Conservative Temperature (CT, in °C) from of Practical Salinity ( $S$ , unitless) and Potential Temperature ( $\theta$ , in °C), respectively. According to McDougall and Barker (2011) these properties are calculated as follows:

$$S_A = \left( \frac{35.16504}{35} \right) S + \delta S_A(x, y, p) \quad (6)$$

where  $\delta S_A = S_A - S_R$  is the difference between the Absolute Salinity and Reference Salinity ( $S_R$ ) based on the location, with  $x$  and  $y$  being the longitude and latitude in decimal degrees and  $p$  the pressure in dbar

$$CT = \frac{h^0}{C_p^0} \quad (7)$$

where  $C_p^0 = 3991.86795711963 \text{ J kg}^{-1} \text{ K}^{-1}$  is a reference value of the specific heat capacity, chosen to be as close as possible to the spatial average of the heat capacity over the ocean surface and  $h^0$  is the potential enthalpy which corresponds to the enthalpy ( $h$ , in J kg<sup>-1</sup>) at a reference pressure:

$$h^0(S, \theta, p_r) = h(S, \theta, p) - \int_{p_r}^p \frac{1}{\rho(S, \theta, p)} dp \quad (8)$$



#### 454 **A2) Freshwater flow rate calculation**

455 Following the salt mass balance equation (1) and based on the *in-situ* data from the Fortuna  
 456 buoy (Product Ref. No. 1) and the estimated impacted area from the satellite observations  
 457 (Product Ref. No. 5 and 6), the freshwater input leading to the first extreme freshening can  
 458 be calculated as follows:

459 Taking into account that

460  $\rho_1 = 1026.212 \text{ kg m}^{-3}$  is the initial seawater density measured by the buoy

461  $\rho_2 = 1015.725 \text{ kg m}^{-3}$  is the final seawater density measured by the buoy

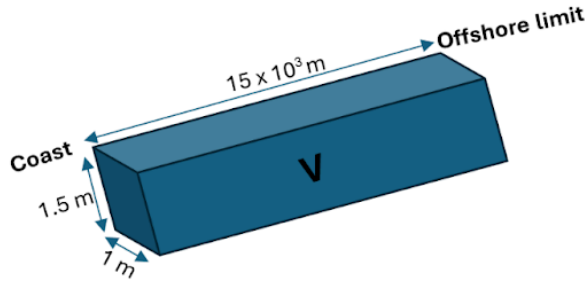
462  $S_1 = 36.194 \text{ g kg}^{-1}$  is the initial seawater salinity measured by the buoy

463  $S_2 = 23.424 \text{ g kg}^{-1}$  is the final seawater salinity measured by the buoy

464  $V_1 = 22.5 \times 10^3 \text{ m}^3$  is the initial volume of seawater confined by the distance from the shore

465 ( $15 \times 10^3 \text{ m}$ ), the width (1 m) and depth (1.5 m) considering the position of the buoy sensors

466  $V_2$  is the final volume



467  
 468 **Figure A1:** Indication of the considered volume of seawater.  
 469

470 Equation  $\rho_1 S_1 V_1 = \rho_2 S_2 V_2$  can be solved for  $V_2 = V_1 \rho_1 S_1 / \rho_2 S_2 = 35.762 \times 10^3 \text{ m}^3$  and the  
 471 corresponding volume change  $\Delta V = V_2 - V_1 = 13.262 \times 10^3 \text{ m}^3$  provides the freshwater volume  
 472 and the flow rate ( $Q_f$ ) required to achieve the average salinity change of  $0.982 \text{ g kg}^{-1} \text{ d}^{-1}$   
 473 (from  $36.194 \text{ g kg}^{-1}$  to  $23.424 \text{ g kg}^{-1}$ ) over the first specified 13-day period as follows:  
 474  $Q_f = \Delta V / \Delta t = 1020.222 \text{ m}^3 \text{ d}^{-1}$  or  $42.509 \text{ m}^3 \text{ h}^{-1}$ .

475

#### 476 **A3) Statistical analysis**

477 Following Emery and Thomson (1998), the standard deviation ( $\sigma$ ) and the corresponding  
 478 standard error ( $S_\varepsilon$ ) were calculated from the variance ( $\sigma^2$ ) as follows:

$$479 \quad \sigma^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2 \quad (9)$$

480

$$481 \quad S_\varepsilon = \frac{\sigma}{\sqrt{N}} \quad (10)$$

482

483 where  $x_i$ :  $i^{\text{th}}$  data point in the dataset and  $N$ : the number of data points

484

485



Correspondingly, the Root Mean Square Difference (RMSD) and bias of the different datasets (x, y) were calculated based on the following equations:

$$RMSD = \sqrt{\frac{\sum_{i=1}^N (y_i - x_i)^2}{N}} \quad (11)$$

$$bias = \frac{\sum_{i=1}^N (y_i - x_i)}{N} \quad (12)$$

In addition, the cross-covariance ( $C_{xy}$ ) and cross-correlation ( $r_{xy}$ ) function was used to assess the relationship between two time series (Emery and Thomson, 1998). Assuming x and y are the relative variables, the function were calculated as follows:

$$C_{xy}(\tau) = \frac{1}{N-k} \sum_{i=1}^{N-k} [y_i - \bar{y}] [x_{i+k} - \bar{x}] \quad (13)$$

where  $\tau=k\Delta t$  is the lag time for k sampling time increments of duration  $\Delta t$

$$r_{xy}(\tau) = \frac{C_{xy}(\tau)}{\sigma_x \sigma_y} \quad (14)$$

where  $\sigma_x$  and  $\sigma_y$  are the standard deviations for each time series.

#### A4) Summary of the freshening events

**Table A4)** Overview of the 5 defined freshening events, representing the start and end date, the duration (in days) and the highest and lowest measured absolute salinity during each corresponding event (in g/kg).

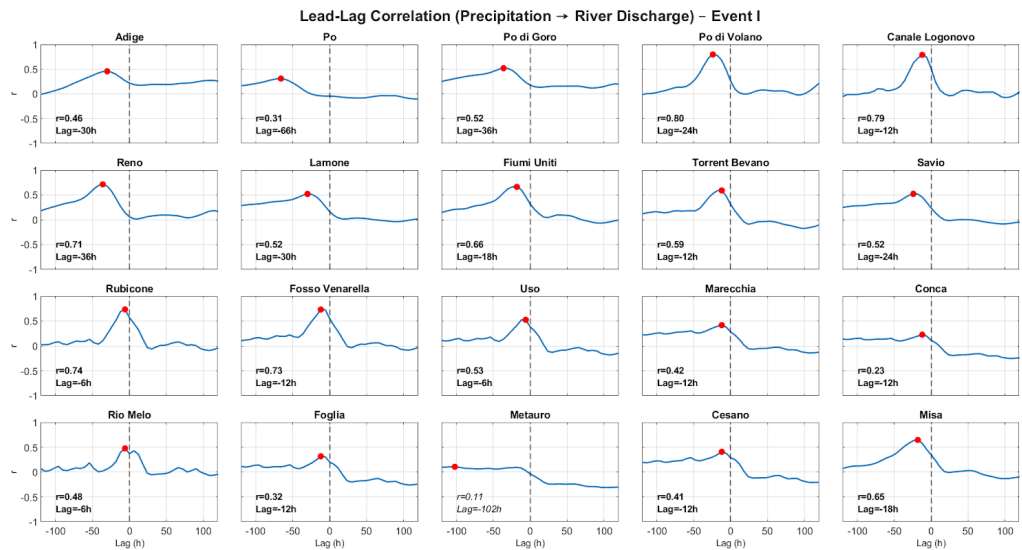
| Freshening event | Start       | End         | Duration | Highest Salinity | Lowest Salinity   |
|------------------|-------------|-------------|----------|------------------|-------------------|
| I                | 02-May-2023 | 24-Jun-2023 | 53       | 37.17            | 23.42 (on 24-May) |
| II               | 29-Sep-2023 | 16-Oct-2023 | 17       | 37.16            | 30.45 (on 02-Oct) |
| III              | 12-Nov-2023 | 02-Dec-2023 | 20       | 37.63            | 26.53 (on 26-Nov) |
| IV               | 09-Apr-2024 | 21-Apr-2024 | 12       | 36.16            | 22.27 (on 15-Apr) |
| V                | 20-Oct-2024 | 22-Nov-2024 | 33       | 35.19            | 14.97 (on 30-Oct) |

**Table A5)** Overview of the most pronounced freshening period during each event, representing the duration (in days) during which the largest total decrease in surface salinity (in g/kg) was observed. The corresponding maximum and minimum salinity values and the respective timestamps are reported.

| Freshening event | Length | Maximum salinity drop | Highest salinity | Lowest salinity | Drop start  | Drop end    |
|------------------|--------|-----------------------|------------------|-----------------|-------------|-------------|
| I                | 13     | 12.769                | 36.194           | 23.424          | 11-May-2023 | 24-May-2023 |
| II               | 5      | 6.716                 | 37.165           | 30.450          | 29-Sep-2023 | 02-Oct-2023 |
| III              | 14     | 11.099                | 37.633           | 26.534          | 12-Nov-2023 | 26-Nov-2023 |
| IV               | 6      | 13.893                | 36.164           | 22.271          | 10-Apr-2024 | 15-Apr-2024 |
| V                | 10     | 20.124                | 35.091           | 14.966          | 20-Oct-2024 | 30-Oct-2024 |



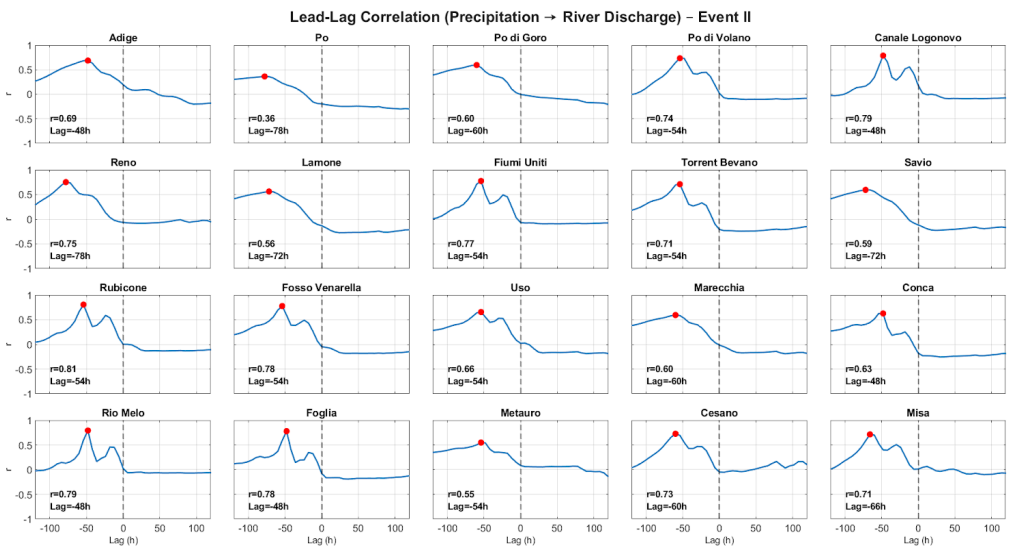
511 A5) Lead-lag correlations between accumulated precipitation and river discharge responses



512

513 **Figure A2:** Lead-lag correlation plots between accumulated precipitation over the Emilia-Romagna  
514 region and the discharge of 20 rivers during the first major flooding periods that lead to the  
515 previously-defined freshening event I. Each subplot shows the Pearson correlation coefficient ( $r$ ) as a  
516 function of lag time (in hours), where negative lags indicate that precipitation leads river discharge.  
517 The maximum correlation point for each river is marked with a red dot. Corresponding correlation  
518 values and lags are annotated in bold if statistically significant ( $p < 0.05$ ), and in italics otherwise.

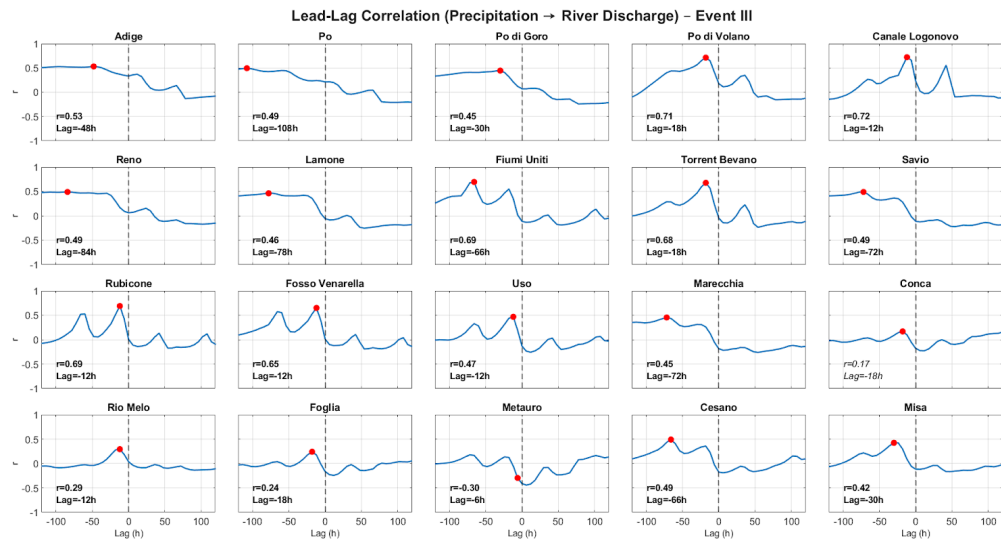
519



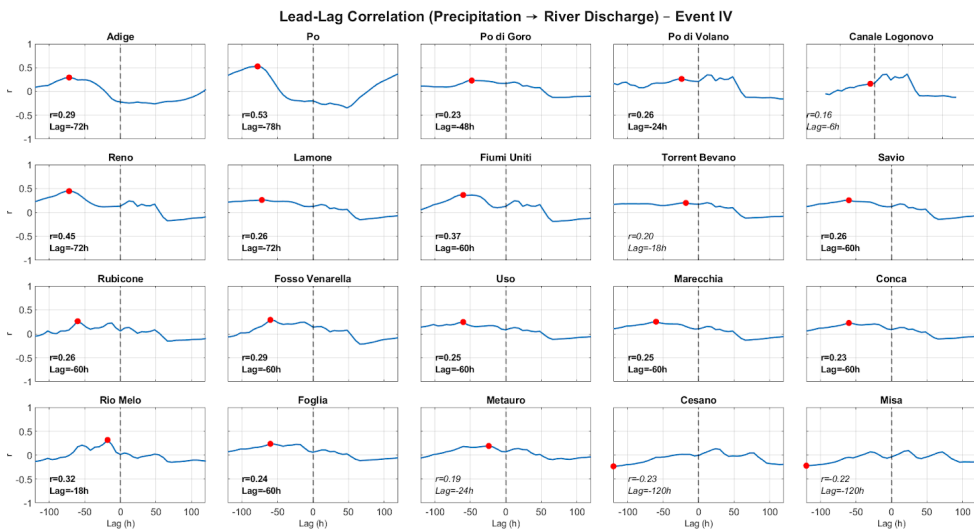
520

521 **Figure A3:** Same as Figure A2 but for the second event.

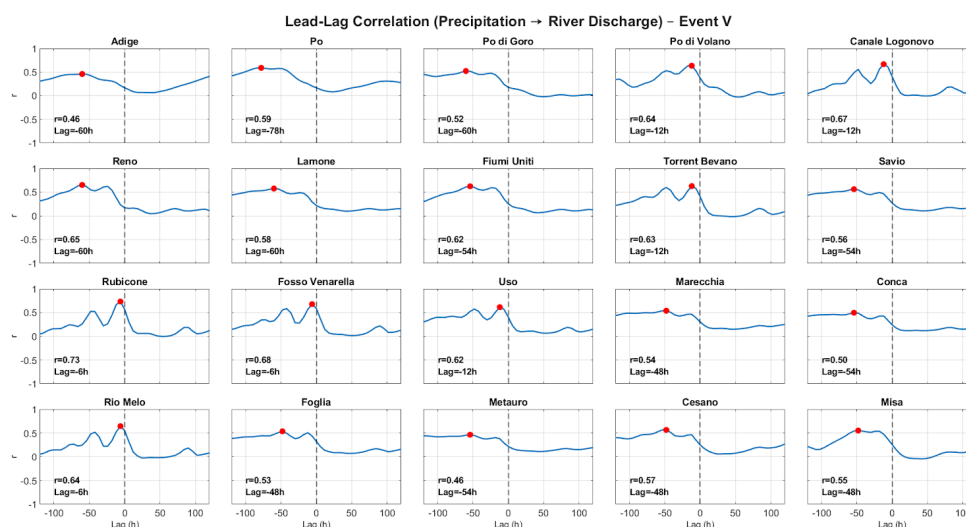
522



523  
524 **Figure A4:** Same as Figure A2 but for the third event.  
525



526  
527 **Figure A5:** Same as Figure A2 but for the fourth event.  
528



529

530 **Figure A6:** Same as Figure A2 but for the fifth event.

531

532

### 533 Data and code availability

534 Utilized datasets as well as their availability and documentations are summarized in Table 1.

535 MATLAB scripts used for the analyses described in this study can be obtained from the  
 536 corresponding author upon reasonable request. The country and regional boundaries shown  
 537 in the maps are based on GADM shapefiles (version 4.1) which are available at  
 538 [https://gadm.org/download\\_country.html](https://gadm.org/download_country.html). The utilized colormaps are freely available in the  
 539 cmocean package by Thyng et al. (2016) which contains colormaps for commonly-used  
 540 oceanographic variables.

### 541 Author contributions

542 N.K. analyzed the data, prepared the figures and wrote the manuscript. P.F., E.Z., F.M.,  
 543 contributed to the paper organization and to the analysis of the results. P.F., E.Z. were  
 544 responsible for the project management of the meteo-oceanographic buoy. F.M. enabled the  
 545 near real-time transfer and the visualization of the corresponding data. P.P., A.C., F.M., P.F.,  
 546 F.M., N.K. were involved in the maintenance and the quality assurance of the  
 547 meteo-oceanographic buoy instruments. All authors reviewed and edited the manuscript.

548

### 549 Competing interests

550 The authors declare that they have no known conflict of interest.

551

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 555 offshore of Fano.

556



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