

Short-term recovery of inland and marine environments after the 2023 Emilia-Romagna flood

Corresponding Author: Dr Riccardo Bentivogli

This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Communications Earth & Environment.

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Dr Bentivogli,

Your manuscript titled "How resilient are inland and marine environments to extreme events? 2023 Emilia-Romagna flood insights" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, extensive revisions will be required before we can further consider the manuscript for publication. We would, however, be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Additionally, the following editorial thresholds should be addressed in the revised manuscript for further consideration in the Communications Earth & Environment:

- * Focus the paper's narrative by concentrating the analysis on the most significant findings, rather than presenting an overwhelming array of parameters.
- * The methodological rigor needs to be strengthened by providing a clear justification for the sampling strategy, explicitly acknowledging its limitations, and recalculating nutrient data to present fluxes instead of mere concentrations in order to better capture the impact of the flood event.
- * Contextual evidence needs to be provided to firmly establish the extremity of the event.

If additional work allows you to either incorporate or refute these criticisms, we will be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Theodora Nah, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-8755-6153

Somaparna Ghosh, PhD
Associate Editor - Communications Earth & Environment
Consulting Editor - Communications Sustainability

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Due to what seems to be an increasing frequency in the occurrence of intense/extreme precipitation events, more data which aids in a better understanding of the importance of these pulse events on inland and coastal water quality is timely and important. Unfortunately data collected immediately after an extreme event is rare, and, therefore, this manuscript provides an important contribution to the library of data available in regards to such events. In particular the authors examination of protist community DNA barcoding is quite novel and an important addition to water quality assessment in streams. The data presented within this manuscript is novel and the work, with significant revisions, will prevent an important contribution to the field of watershed science.

The manuscript describes a wide variety of parameters, all of which are important to understanding the impact of these extreme events on inland and coastal systems. Unfortunately the sheer number of parameters lead to a lack of individual depth in discussion of the parameters, as well as make the manuscript a bit difficult to follow, becoming more of a 'data dump' rather than a well-written scientific article. It is however, in respect to the authors, difficult to present so much data in a short article. In addition to the difficulty in describing all the parameters, it is also difficult to develop clear and easy-to-read figures to display the data, and therefore the figures leave much to be desired (this will be described in more detail in the attached manuscript).

In general, the manuscript would be improved by focusing on specific parameters of high relevance and developing both the description of the methods for the measurement of those parameters and the discussion of their inputs in light of such an extreme event.

All minor comments will be annotated in the attached manuscript.

Major comments:

Introduction: The introduction is well written and contains the requisite information and references. The introduction, however, focuses on pharmaceuticals and emerging contaminants, and this is only a small part of the data described later in the article. Perhaps the article should then focus on these data and develop further the discussion of the findings, rather than bringing in many other variables.

Results: This section is hard to follow as there is so many data being presented and many are attached to acronyms for study site locations and require the reader to continuously return to the initial map (see attached manuscript). The figures (see attached manuscript) are often hard to read.

Nutrient and chemical data is reported in concentrations in the stream, but in the case of discharge, flux is a more important parameter, as the flux of nutrients (etc.) may be much higher even if concentration is lower due to dilution effects. A summary table of all data may improve understanding for the reader.

Discussion: Would benefit from being broken up into sections which correspond to the methods and results. If this is not possible, the discussion should at least follow the order of the results. Some comments in the discussion are not clear from the results (see attached manuscript) and this may be due to a reporting of concentrations instead of fluxes.

Conclusion: Is fine, but brings up an important point, which should be discussed in detail. There is a lack of antecedent data from right before the events so it is difficult to say what for example the Chl A situation was before the event, one could make the case that there was already a bloom event occurring.

Methods: Here is where the biggest concern lies. Many questions are not answered in the methods description.

1. How were all of these samples collected in one day?
2. Was only one sample collected in each location? If so, how can we be sure this is representative of the situation?
3. Surface samples are often not representative of the true concentration of many constituents in rivers, was there any analysis done to check this, if not this caveat must be stated.
4. Is there any discharge information from the channels?
5. Is there any information about LULC? As this comment was made in the introduction.

It is clear that some of these points cannot be changed (samples already collected), but then clear caveats should be made.

Please see additional comments in annotated manuscript.

Reviewer #3 (Remarks to the Author):

Dear authors.

this was an interesting paper, and reiterates the importance of understanding the impact of extreme flood events on the marine environment.

I have made some comments through the manuscript and have attached as a word document.

My main concerns are the lack of data that you present - there are only two figures, and it is difficult to get an understanding of what happened during and after the event. YOU present a heat map, but I also think you need a table of statistical measurements. This can be then used to put your comparison of long term means against the event. The boxplots and mean event values do not provide enough information on how important this event was in terms of extreme or prolonged values. I would like to see more use of temporal information - the event data presented against long term data over time (months - years). In absence of long term data, you could use the remote sensing data to provide background water quality information. YOU need to present information on how extreme this event was - which can be done through the use of rainfall or flow information. put the event in context.

Be careful of how you frame the event as being human caused - there are always flood events, and you are trying to show what part of that extreme natural variability is now being caused by longer, and more extreme events. To do this, you must put this current one in context. Again, rainfall or flow data may really help build this case.

Your remote sensing data could be used better - there are many papers that show how remote sensed data can map and track flood plumes to give an estimate of overall extent and duration - this would also be useful to show how "extreme" this event was. (refer to references provided in comments).

Finally, you need a overall figure to bring all of your data together, a timeline showing the rise and fall of your different measurements along with your protist information. Show how the system works together - then you will really add value to this paper.

I have put other comments directly into the word document.

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Version 1:

Decision Letter:

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Dear Dr Bentivogli,

Your manuscript titled "How resilient are inland and marine environments to extreme events? 2023 Emilia-Romagna flood insights" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Theodora Nah, PhD
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Somaparna Ghosh, PhD
Associate Editor - Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

General comments:

The authors were able to address many of the suggestions of both reviewers, and, therefore the new manuscript provides a more coherent description of the impact of two major rainwater pulse events on both the local river system and the corresponding coastal area. This manuscript presents an important contribution to our understanding of coastal hydrology in the face of climate change.

I still have reservations about the conclusions drawn from some of the data, particularly in the marine system as samples

collected at 50 cm depth are unlikely to be representative of the whole water column, particularly when the waters are not well-mixed. There is no mention of tide level for the marine water samples (were they collected at similar points in the tidal cycle across the three time periods?) There could be large differences in water quality between flood and ebb tides in coastal area. Indeed, although I agree that the rivers and channels were likely well-mixed soon after the flood event, what evidence is there to suggest that this is the case in sample periods T2, and T3? I think more needs to be stated about the limitations of the data, and/or, perhaps what could be improved upon for future studies. Finally, the T1 period is described as peak turbidity, but the sampling likely occurred after the rivers were safe to navigate, hence, it is likely after peak turbidity, maybe a statement should be made, that some of the parameters are likely underestimates in T1.

In addition, I agree with reviewer 3's comments about there being a significant amount of data, some of which gets lost in the manuscript. Perhaps the section about emerging contaminants could be discussed separately in another article, as the picture is a bit muddled with what is happening in some of the stations, and maybe the story is too complex to discuss herein, but I would leave this up to the authors to decide.

Some specific comments:

- All new sections should be edited for grammar and punctuation, there are some mistakes.
- It seems like there are now two figure 1s, a. the maps and b. the figure with concentrations on a heatmap, also the heatmap figure would benefit from a legend of the parameters.
- Figure 5 would benefit from spacing between stations
- Figure 6 is beyond my understanding
- Figure 7 needs better alignment so the stations can be compared for BPAs and Pharmaceuticals
- Table 1 might benefit from clearer spacing
- Figure 9 would be better without the station locations in all images, maybe this could just be in the first image and a box could be in the other images?

Reviewer #3 (Remarks to the Author):

The authors have considered and answer all the reviewers concerns. I am happy to recommend publication

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Dear Dr Bentivogli,

Your manuscript titled "How resilient are inland and marine environments to extreme events? 2023 Emilia-Romagna flood insights" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Somaparna Ghosh, PhD
Associate Editor,
Communications Earth & Environment
Consulting Editor,
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have sufficiently addressed all comments from both rounds of review, I have no further comments

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We thank the Editor and the Reviewers for their careful evaluation of our manuscript and for their constructive and insightful comments. We have substantially revised the manuscript in response to these suggestions. All changes have been incorporated into the revised version and are highlighted in the tracked-changes manuscript. Below, we provide a point-by-point response to each comment.

Reviewer #1

Comment

The manuscript describes a wide variety of parameters, all of which are important to understanding the impact of these extreme events on inland and coastal systems. Unfortunately the sheer number of parameters lead to a lack of individual depth in discussion of the parameters, as well as make the manuscript a bit difficult to follow, becoming more of a 'data dump' rather than a well-written scientific article. It is however, in respect to the authors, difficult to present so much data in a short article. In addition to the difficulty in describing all the parameters, it is also difficult to develop clear and easy-to-read figures to display the data, and therefore the figures leave much to be desired (this will be described in more detail in the attached manuscript).

Response

We thank the reviewer for these comments that were addressed in the revised version of the manuscript: the number of parameters has been reduced, keeping only the most relevant ones in order to avoid a data dump. By doing so, the discussion has been revised resulting in a more focused and coherent discussion.

Some of the figures have been redone according to the reviewers' comments (i.e., Fig. 1,2, 5, 6,7,9) and new ones have been added (Fig. 4, 8).

We also prepared an integrative summary figure that synthesizes the main outcomes of the study. As the journal figure limit has been reached, this figure is proposed for inclusion in the Supplementary Materials, should the Editor and Reviewers consider it appropriate. All minor comments, editorial suggestions, and clarifications provided in the annotated manuscript have been carefully addressed in the revised version.

Comment

In general, the manuscript would be improved by focusing on specific parameters of high relevance and developing both the description of the methods for the measurement of those parameters and the discussion of their inputs in light of such an extreme event.

Response

We thank the reviewer for this important comment. In response, we streamlined the manuscript by focusing on the parameters most relevant to flood-induced alterations. Accordingly, in Figure 2 we removed variables (temperature, pH, and CDOM) that were not discussed in depth. These measurements are nevertheless provided in Supplementary Table S2 to ensure full transparency and because they are required later in the manuscript for comparison with historical datasets.

In Figure 4, which presents the long-term seasonal baseline (2010–2022) versus the 2023 post-flood conditions, temperature and pH were retained because these parameters are available in the ARPAE historical dataset and are essential to provide a complete and coherent comparison. Excluding them would have reduced the interpretability of the historical context and weakened the discussion regarding ecosystem responses.

Overall, the parameter set has been refined, and the Methods section was revised to better describe the measurement and relevance of the variables retained in the main text.

Comment

Introduction: The introduction is well written and contains the requisite information and references. The introduction, however, focuses on pharmaceuticals and emerging contaminants, and this is only a small part of the data described later in the article. Perhaps the article should then focus on these data and develop further the discussion of the findings, rather than bringing in many other variables.

Response

The introduction and Material and Methods section were improved by including additional details about the event and the characterization of the study area, respectively. This allowed for a better contextualization of the territory, highlighting its specific characteristics as well as vulnerabilities. Such context is essential to understanding why the event, although already extreme in meteorological terms, had such profound impacts on the local territory.

In the revised version of the manuscript, we focused on the most relevant parameters, but we believe that the strength of this work lies in the integration of environmental monitoring approaches that allow us to outline a more comprehensive picture and to better understand processes that are interconnected. The study area is particularly complex in terms of water management, relying on a delicate balance that an event like this can easily disrupt, leading to sudden changes in conditions and potential medium- and long-term impacts that are still not fully understood.

Comment

Results: This section is hard to follow as there is so many data being presented and many are attached to acronyms for study site locations and require the reader to continuously return to the initial map (see attached manuscript). The figures (see attached manuscript) are often hard to read.

Response

We thank the reviewer for this valuable comment. In response, we have substantially revised the Results section to improve clarity, structure, and readability. The section now follows a more coherent narrative

flow, first describing the measured environmental parameters and then contextualising them through historical comparisons for both inland and marine waters, using only the parameters for which long-term datasets are available. Acronyms have been streamlined and the text now provides clearer guidance on site locations without requiring continuous reference to the map.

Figure revisions:

- Figure 1: The figure has been redesigned following the reviewer's suggestions. In Fig. 1a, the river catchments involved in the Ravenna flood are now clearly highlighted. In Fig. 1b, sampling-site labels were simplified, marine stations are now uniformly indicated by "*", the basemap has been replaced with CORINE Land Cover, and legends and labels have been enhanced for readability.
- Figure 2 (heatmap): We improved the figure's readability by replacing the previous legend term "Intensity" with "min-max", which more accurately reflects the normalised range of each parameter (as correctly pointed out by the reviewer). Absolute minimum and maximum values for each variable are now displayed above the heatmap to aid interpretation. Axis labels were refined and non-essential parameters removed to simplify the visualisation.
- Figure 3: Now presents historical comparisons for inland-water parameters that correspond to the stations sampled in this study.
- Figure 4: Now presents historical comparisons for marine-water parameters for which long-term baseline data are available, ensuring consistency with the discussion and improving contextualisation.

- Figure 7 (emerging contaminants): Axis labels, tick marks, and annotations were enlarged and reformatted, and the overall layout was simplified. The figure was regenerated at high resolution to meet publication standards.
- Figure 8: Presents the satellite-derived long-term climatology of Chl-a for 2010–2022, allowing 2023 anomalies to be contextualised relative to historical variability.
- Figure 9 (satellite imagery): The image was completely revised to resolve previous resolution issues and improve interpretability.

These revisions substantially improve the readability of the Results section and the clarity of the figures, addressing the reviewer's concerns.

Comment

Nutrient and chemical data is reported in concentrations in the stream, but in the case of discharge, flux is a more important parameter, as the flux of nutrients (etc.) may be much higher even if concentration is lower due to dilution effects. A summary table of all data may improve understanding for the reader.

Response

We thank the reviewer for this important point. We agree that, in principle, nutrient and contaminant fluxes are more informative than concentrations when discharge data are reliable. However, for the May 2023 flood event it was not possible to derive robust flux estimates.

Several rivers and drainage channels overtopped their banks before reaching the sea, while multiple pumping stations operated continuously at full capacity and were supplemented by temporary external pumps to accelerate floodwater removal. As a result, discharge measurements for both rivers and pumping stations during and immediately after the event were either unavailable or not representative of the actual transport pathways. Under these conditions, flux calculations would have introduced substantial uncertainty and potentially misleading estimates.

For this reason, nutrient and chemical concentrations were retained as the most robust and internally consistent metric to compare enrichment patterns across sites and sampling periods. This limitation is now clearly acknowledged in the Methods section of the revised manuscript.

To further contextualise the hydrological setting and the extremity of the event, we integrated additional information on the main rivers and drainage channels, including their standard discharge values, in Table S1 (Supplementary Materials). These aspects are now also explicitly addressed in the Introduction and further expanded in the Materials and Methods section to provide clearer context for the flood dynamics affecting the study area.

Comment

Discussion: Would benefit from being broken up into sections which correspond to the methods and results. If this is not possible, the discussion should at least follow the order of the results. Some comments in the discussion are not clear from the results (see attached manuscript) and this may be due to a reporting of concentrations instead of fluxes

Response

We thank the reviewer for this useful suggestion. As noted in our response above regarding nutrient fluxes, we have now clarified the distinction between concentrations and flux-related interpretations, ensuring that all arguments presented in the Discussion are fully supported by the reported Results. The Discussion section has been thoroughly revised to improve clarity and logical flow. We explored the possibility of reorganizing the Discussion into subsections aligned with the Methods and Results; however, given the number of parameters analysed and their interdependence along the river-to-sea continuum, this structure tended to fragment the narrative and weaken the overarching synthesis.

Instead, we reorganized the text to follow a clear temporal and process-based progression, closely mirroring the order of the Results while maintaining a coherent storyline. The revised version now presents the observations in a more linear, concrete, and interpretable manner, ensuring that each point raised in the Discussion is directly traceable to the corresponding findings.

We believe these revisions significantly improve the readability and interpretability of the Discussion.

Comment

Conclusion: Is fine, but brings up an important point, which should be discussed in detail. There is a lack of antecedent data from right before the events so it is difficult to say what for example the Chl A situation was before the event, one could make the case that there was already a bloom event occurring

Response

We thank the reviewer for highlighting this important point. We agree that the lack of site-specific antecedent data immediately prior to the flood represents a key limitation in interpreting the magnitude of the observed ecological changes. This limitation is now explicitly discussed in the Conclusions as well as in the Results and Discussion, where we clarify how the absence of high-frequency, pre-event measurements constrains our ability to determine whether, for example, a phytoplankton bloom might have already been developing before the flood.

To address this issue as thoroughly as possible, we strengthened our contextual framework throughout the manuscript. Specifically:

- We provide a detailed discussion on the scarcity of local, high-resolution historical datasets, which limits robust pre-event baselines for many parameters.
- For chlorophyll-a, we incorporated all available historical in-situ records from ARPAE (Fig. 4) and extended the analysis by including a long-term satellite-derived climatology (Fig. 8), allowing us to contextualise 2023 conditions relative to more than a decade of regional variability.
- We now state more clearly that, despite these efforts, uncertainty remains regarding the precise antecedent state of the system immediately before the flood.

These additions ensure that the limitation is fully acknowledged and transparently integrated into the interpretation of our findings.

Comment

Methods: Here is where the biggest concern lies. Many questions are not answered in the methods description.

1. How were all of these samples collected in one day?

Response

Fieldwork was organized into specialized groups operating simultaneously across inland and marine environments to minimize the duration of sampling. Each team focused on a specific set of sites and analytical targets, allowing all samples to be collected within the same day (or two consecutive days) and promptly delivered to the respective laboratories for processing.

This coordinated design ensured temporal coherence between compartments and minimized short-term variability. We have clarified these aspects in the revised Material and Methods section.

Comment

2. Was only one sample collected in each location? If so, how can we be sure this is representative of the situation?

Response

We thank the reviewer for this important observation. At each station and for each sampling period, replicate samples were collected to ensure the representativeness and reproducibility of the measurements. This approach allowed us to account for small-scale spatial variability and to obtain robust average values for each site.

We have now made this aspect explicit in the revised Materials and Methods section, clarifying that replicate water samples were collected and processed independently for all measured parameters.

Comment

3. Surface samples are often not representative of the true concentration of many constituents in rivers, was there any analysis done to check this, if not this caveat must be stated.

Response

We thank the reviewer for this pertinent observation. In this study, only surface water samples were collected. Water samples from both inland and marine stations were taken within the upper 50 cm of the water column. Under the highly dynamic hydrological conditions that followed the flood, the water column was well mixed and therefore broadly representative of the overall system. Nonetheless, we acknowledge that vertical variability may occur and that different concentrations could be observed at greater depths under more stable conditions. This limitation has now been clearly stated in the revised Materials and Methods.

Comment

4. Is there any discharge information from the channels?

Response

Yes. We added a new table in the Supplementary Materials (Table S1) providing detailed discharge-related information for the main rivers and drainage channels included in the study. The table reports basin area, long-term pre-event average discharge (1992–2022), available discharge estimates for May 2023, and the corresponding data sources.

These data are used to contextualize the hydrological magnitude of the flood and to highlight the exceptional nature of the event relative to typical conditions, while acknowledging the limitations associated with discharge measurements during extreme flooding and emergency pumping operations.

Comment

5. Is there any information about LULC? As this comment was made in the introduction

Response

Land Use and Land Cover (LULC) information was added in the current Fig. 1 and discussed in the introduction and study area sections.

Although the 2023 flood event affected a large portion of the Emilia-Romagna region, including several Apennine River catchments, the local coastal LULC did not play a significant role in triggering or amplifying the flooding. Here the event was primarily driven by the geomorphological configuration of the plain, characterized by low topography and a complex network of primary and secondary watercourses and by the exceptional water volume from rainfall and river overflows, which exceeded the system drainage capacity. In some areas, water remained stagnant over agricultural fields and urban zones for several days following the event

Comment

It is clear that some of these points cannot be changed (samples already collected), but then clear caveats should be made

Response

We agree with the reviewer that certain aspects of the study design cannot be changed retrospectively, as sampling was necessarily constrained by the timing and nature of the flood event. However, in revising the manuscript we have taken care to clearly acknowledge these limitations and to explicitly state the caveats associated with data availability, sampling frequency, and spatial coverage.

In particular, we now highlight that:

- event-driven, short-term sampling captures only transient conditions and may not fully represent longer-term water-quality dynamics;
- short sampling windows may overemphasize short-lived peaks in pollutant concentrations while underestimating recovery trajectories;
- medium-term monitoring (as performed here) provides key insights into immediate system responses, but remains insufficient to fully describe ecosystem resilience over longer temporal scales.

As detailed in our responses above, we have improved the contextualization of the event, clarified the implications of limited antecedent data and strengthened the interpretation of our findings in light of these constraints. The revised manuscript now provides a more transparent and nuanced discussion of the limitations inherent to opportunistic sampling during extreme events.

Comment

Please see additional comments in annotated manuscript.

Response

All additional comments and editorial suggestions provided in the annotated manuscript have been carefully addressed in the revised version of the manuscript.

Reviewer #3

Comment

Dear authors.

this was an interesting paper, and reiterates the importance of understanding the impact of extreme flood events on the marine environment.

I have made some comments through the manuscript and have attached as a word document.

My main concerns are the lack of data that you present - there are only two figures, and it is difficult to get an understanding of what happened during and after the event.

Response

We thank the reviewer for this comment. In the revised manuscript, we substantially expanded the presentation of the data to provide a clearer and more comprehensive picture of the hydrological and ecological dynamics during and after the event. Following the restructuring described in our responses to Reviewer 1, we reorganised the Results and Discussion sections and added several new figures to improve interpretability.

In particular:

- Figure 1 has been redesigned to clarify the study area and the hydrological context of the event.
- Figure 2 (heatmap) has been improved for readability, with clearer labelling and reduced parameter redundancy.
- Figures 3 and 4 now present historical baselines for inland and marine waters, allowing direct comparison with 2023 post-flood conditions.
- Figure 7 (emerging contaminants) has been reformatted with clearer axes, improved annotations, and high-resolution output.
- Figure 8 now provides a satellite-derived climatology of Chl-a for 2010–2022 to contextualise the 2023 anomalies.

Together, these additions enhance the manuscript's clarity and allow the reader to follow the sequence of environmental responses from the onset of the flood through the subsequent months. We believe the expanded figure set now provides a comprehensive and accessible overview of the event and its short-term impacts.

Comment

YOu present a heat map, but I also think you need a table of statistical measurements. This can be then used to put your comparison of long term means against the event. The boxplots and mean event values do not provide enough information on how important this event was in terms of extreme or prolonged values.

Response

We thank the reviewer for this constructive suggestion. In response, we have expanded the statistical characterization of the event and strengthened the comparison with historical conditions.

- We added a new table in the Supplementary Materials (Table S2) reporting the measured values of all parameters included in the heatmap. This provides the quantitative detail requested by the reviewer and complements the visual representation of the heatmap.
- To better contextualize the extremity of the event, we incorporated additional comparisons with historical datasets, both for inland waters (rivers and drainage canals) and marine stations. Figures 3 and 4 now present long-term seasonal distributions (2010–2022) for the parameters available in the ARPAE historical records, enabling direct comparison with the 2023 post-flood measurements.
- We also added new contextual information on river discharges and drainage volumes where available. These data are summarized in Table S1, which details standard discharge values for the main rivers and drainage channels, highlighting the exceptional hydrological conditions during the 2023 event.
- For chlorophyll-a, we expanded the analysis by combining in-situ historical records with satellite-derived long-term climatologies (new Fig. 8), which allow for quantification of the degree of anomaly observed in 2023.

We acknowledge that complete baselines are not available for all parameters (i.e. eDNA, CECs), and this limitation is now clearly stated in the Conclusions. Nevertheless, we have made considerable efforts to incorporate all existing historical information to provide a robust contextualization of how extreme and prolonged this event was.

Comment

I would like to see more use of temporal information - the event data presented against long term data over time (months - years). In absence of long term data, you could use the remote sensing data to provide background water quality information.

Response

We thank the reviewer for this additional observation. As noted above, both the temporal context and the lack of long-term local datasets represent important limitations when interpreting the 2023 event. In the revised manuscript, we have substantially strengthened the temporal dimension of the analysis by integrating all available long-term data and by incorporating remote-sensing products where in-situ records were limited or unavailable.

Specifically:

- Inland and marine historical datasets (2010–2022) were analysed to provide seasonal baselines for key physical and chemical parameters. These comparisons are now presented in Figures 3 and 4, which place the 2023 post-flood observations in the context of more than a decade of routine monitoring.
- For chlorophyll-a we followed the reviewer's recommendation and developed a satellite-derived climatology based remote sensing data (new Figure 8). This dataset captures multi-year variability (2010–2022) and allows a temporal comparison between the 2023 event and typical seasonal-to-interannual conditions.

- Additional hydrological information (river discharges, drainage-channel flow volumes) has been compiled in Table S1, further contextualising the magnitude and timing of the event relative to standard conditions.

Together, these additions provide the temporal framework requested by the reviewer and allow for a clearer assessment of how unusual or extreme the observed 2023 conditions were compared with the preceding decade.

Comment

YYou need to present information on how extreme this event was - which can be done through the use of rainfall or flow information. put the event in context

Response

We thank the reviewer for this important comment. In the revised manuscript, we strengthened the contextualisation of the 2023 flood by explicitly presenting hydrological and meteorological evidence of its extremity.

The Introduction has been expanded to include quantitative information on rainfall intensity, storm duration, and the hydrological setting of the Ravenna coastal plain, providing clearer context for why this event was exceptional (Lines 128-155).

We added Table S1 (Supplementary Materials), which reports standard discharge values for the main rivers and drainage channels and compares them with the available measurements during the 2023 event. This table allows readers to directly evaluate the magnitude of the flood relative to typical hydrological conditions.

Comment

Be careful of how you frame the event as being human caused - there are always flood events, and you are trying to show what part of that extreme natural variability is now being caused by longer, and more extreme events. To do this, you must put this current one in context. Again, rainfall or flow data may really help build this case

Response

We thank the reviewer for this important remark regarding how the event is framed. In the revised manuscript, we carefully revised the text to avoid implying direct human causation and to more clearly distinguish between natural hydrological variability and potential climate-related intensification of extreme events.

To contextualise the 2023 flood within the broader range of historical variability, we strengthened the manuscript in several ways:

The Introduction now includes a clearer description of the meteorological and hydrological setting, including rainfall intensity, storm duration, and the characteristics of the local drainage system.

We incorporated quantitative information on river discharge and drainage-channel flow volumes into Table S1 (Supplementary Materials), allowing readers to compare typical hydrological conditions with those observed during the event.

Additional contextualisation is provided in the Results and Discussion, where we clarify that interpreting human-driven contributions requires situating the 2023 flood within its long-term climatic and hydrological background rather than attributing causation to a single mechanism. These additions directly address the reviewer's comment by ensuring that the event is placed within an appropriate natural and hydrological context, supported by rainfall and flow information where available.

Comment

Your remote sensing data could be used better - there are many papers that show how remote sensed data can map and track flood plumes to give an estimate of overall extent and duration - this would also be useful to show how "extreme" this event was. (refer to references provided in comments)

Response

We thank the reviewer for this insightful comment and agree that remote-sensing products can provide powerful tools for characterising flood-plume extent, duration, and dynamics. We have now incorporated the key references suggested by the reviewer (e.g., Petus et al., 2016; Devlin et al., 2012), and complemented them with additional recent studies relevant to flood plume mapping (e.g., Abhishek et al., 2025) into the Introduction to acknowledge the extensive body of work on satellite-based plume mapping and its relevance to coastal water-quality assessments.

In the context of the present study, our remote-sensing analysis was designed primarily to support the interpretation of biogeochemical responses rather than to perform a full plume-mapping assessment, which would require a dedicated methodological framework and a substantially expanded dataset. Such a comprehensive analysis, including hydrodynamic metrics, plume extent modelling, and multi-sensor integration, would extend beyond the scope and objectives of the current manuscript and, in our view, would be better suited to a standalone study.

Accordingly, statements in the Discussion referring to algorithm performance under post-flood conditions (e.g. during T3) are intended to reflect changes in optical water quality rather than plume-scale dynamics.

Nevertheless, in line with the reviewer's suggestion, we expanded the temporal context provided by the remote-sensing products. Specifically, we added a satellite-derived climatology of chlorophyll-a (2010–2022) (now presented in Fig. 8) that highlights how anomalous the 2023 conditions were relative to a multi-year baseline.

Comment

Finally, you need a overall figure to bring all of your data together, a timeline showing the rise and fall of your different measurements along with your protist information. Show how the system works together - then you will really add value to this paper

Response

We thank the reviewer for this valuable suggestion. We agree that a synthesis figure integrating the hydrological, physicochemical, and biological responses over time would provide an informative overview of system dynamics.

In the revised manuscript, we explored the possibility of constructing such a figure. However, given the wide range of parameters measured, their differing temporal resolutions, and the spatial heterogeneity of the sampling stations, creating a single, quantitative integrative figure that remained scientifically robust and visually interpretable proved extremely challenging. For these reasons, a comprehensive multi-parameter timeline could not be incorporated into the main text without risking oversimplification or loss of clarity.

Nevertheless, we prepared a qualitative summary figure, in which symbol size reflects the relative magnitude of the key parameters through time, to illustrate the overarching patterns observed across datasets. Because the journal's figure limit has been reached, we have included this figure as an attachment and would be pleased to incorporate it into the Supplementary Material should the reviewers or editor consider it useful.

We believe that this approach offers a balanced compromise, providing readers with an integrated visual summary while maintaining clarity and accuracy in the interpretation of the individual datasets.

Comment

I have put other comments directly into the word document

Response

All additional comments and notes in the annotated manuscript were addressed and required answers given either in the text or in the comments.

How resilient are inland and marine environments to extreme events? 2023 Emilia-Romagna flood insights

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Abstract

This study uses an integrated and multidisciplinary approach to assess the short- and medium-term effects of 2023 Emilia-Romagna (Italy) flood on inland and marine environments and their recovery capability. To capture the evolution of post-flood conditions, three monitoring campaigns were conducted: (i) immediately after the flood (late May), (ii) approximately after one month (mid-June), and (iii) after five months (early October). During each campaign, we characterized rivers and coastal marine waters by combining in-situ measurements of abiotic and biotic parameters with eDNA-based community assessment, emerging contaminant analyses, and satellite-derived data. Despite the large spatial extent and intensity of the disturbance affecting the entire river-to-coast continuum, most parameters showed partial to near-complete recovery within five months, evidencing strong system resilience. The lack of pre-event baselines constrains precise impact assessment, underscoring the need for long-term, standardized monitoring frameworks that integrate innovative tools to capture environmental consequences of extreme events and evaluate coastal vulnerability.

1 Introduction

Extreme weather events are becoming increasingly frequent and severe, driven by the accelerating effects of climate change. Among these events, flooding is one of the most devastating¹. Floods, categorized into riverine, coastal, urban, and flash types, are caused by prolonged rainfall, rapid storm surges, or the overflow of rivers and streams beyond their banks^{2,3}. Urbanization and land-use changes in inland areas significantly contribute to coastal vulnerability by increasing sediment transport, altering water quality, and disrupting hydrological cycles⁴. These events not only disturb terrestrial and aquatic environments but also mobilize pollutants toward downstream areas, altering biogeochemical dynamics and amplifying stress on coastal ecosystems^{5,6}. Excessive nutrient concentrations and terrestrial organic matter from river inputs often lead to harmful algal blooms⁷, hypoxia, and eutrophication, particularly in semi-enclosed seas^{8,9}. These nutrients enhance primary production in surface waters, increasing the deposition of organic matter to sediments, where its decomposition further depletes oxygen levels^{10,11}. Floodwaters also act as vectors for anthropogenic contaminants, including pesticides, heavy metals, and contaminants of emerging concern (CECs) which include perfluorinated compounds, plasticizers, additives (e.g., bisphenol A) and pharmaceuticals. The altered redox conditions during flood-induced deoxygenation events can increase the mobility and toxicity of these pollutants, with profound implications for aquatic ecosystems, water quality, and human health^{12–14}. Among CECs, pharmaceuticals are of increasing relevance, particularly considering their potential mobilization during extreme hydrological events. Recent studies suggest that

intense rainfall and associated sewer overflows may exacerbate pharmaceutical inputs into sensitive coastal environments, raising concern for the health of aquatic ecosystems under climate change scenarios¹⁵. The monitoring after extreme events generally involves the assessment of the immediate and direct impacts on urban infrastructures, ecosystems, and human health. However, understanding the complex interplay between extreme flood events and their visible and unseen cascading effects on coastal and marine ecosystems is crucial but understudied. The short- and long- term monitoring of unseen impacts such as shifts in biological communities, the spread of contaminants (such as CECs), or delayed biological responses often go undetected by routine monitoring but it can be significant for predicting ecosystem resilience, informing coastal management strategies, protecting biodiversity, preventing ecological degradation, economic losses (e.g., fisheries, tourism), and health risks related to water quality.

Between early May (1st – 4th) and mid-May (16th – 17th) 2023, the Emilia-Romagna region in northern Italy, experienced two extreme meteorological events that led to catastrophic flooding, landslides, and widespread destruction^{16–18}. The May 2023 events, described as "unprecedented" in the region's hydrological history, resulted from the convergence of extreme meteorological and hydrological conditions¹⁹. Rainfall return' periods exceeded 100 years in many areas, reaching over 500 years in the most affected zones. The first event was caused by a polar low-pressure system that stalled over central Italy, resulting from the convergence of moist air masses from the Adriatic Sea and cold bora winds from the north. This interaction, intensified by orographic effects from the Apennine Mountains, led to over 200 mm of rainfall in 48 hours in some areas. Two weeks later, a second low-

pressure system exacerbated the crisis, producing even more intense rainfall, up to 240 mm in localized areas, exceeding historical records. Together, these events brought an estimated $350 \times 10^6 \text{ m}^3$ of water, equivalent to six months of average rainfall within a remarkably short period²⁰. Rivers across Emilia-Romagna experienced record-breaking floods that breached embankments at 23 locations and flooded over 540 km² of lowlands. Among the most impacted areas were the city of Ravenna and its surrounding, the catchments of the Lamone, Montone, Ronco, Savio rivers, and the tributaries of the Destra Reno canal (**Error! Reference source not found.**). Along the Adriatic coastal areas, storm surges further worsen the flooding by slowing the drainage of floodwaters. The drainage infrastructure, with its narrow embankments not designed to handle this excess water, failed to discharge water to the sea efficiently and, in some cases, water stagnated on crops and cities for several days after the event. In the Apennine region, prolonged saturation triggered nearly 66,000 landslides, disrupting critical infrastructure and isolating several communities. The impacts of this extreme event are well documented. Entire communities were forced to evacuate; there were 17 deaths and 36,600 evacuees; farmlands were flooded, leading to the destruction and contamination of crops²¹ and death of livestock, while urban areas suffered significant structural damage²². The floods also caused significant environmental impacts²³. Floodwater transported large quantities of sediments, organic matter, and pollutants into the surface water bodies (rivers and drainage networks), eventually reaching the Adriatic Sea. This led to algal blooms, the death of aquatic organisms²⁴, and severe impacts on the local economy.

103 Beyond these impacts, the study aims to assess additional direct and indirect effects on
104 inland and marine waters that were not captured by standard routine monitoring
105 conducted according to major legislative protocols following the May 2023 flood event.
106 Here, a multidisciplinary and integrated protocol is applied to analyze geochemical,
107 environmental, and biological factors, providing a comprehensive understanding of the
108 flood short- and medium- term impacts, and assessing the intrinsic recovery capacity of
109 the system. The approach includes analyses to assess abiotic and biotic parameters,
110 analyzing also protist communities using environmental DNA (eDNA) metabarcoding, and
111 estimating emerging contaminants, along with evaluating remote sensing capacity to
112 assess the marine water quality. The study offers a holistic understanding of complex
113 environmental phenomena and bridges a significant knowledge gap by providing new
114 insights into the interconnected impacts of human-driven disasters on the environment.
115 Our findings show how key physical, chemical, and biological parameters respond to
116 system perturbation caused by the flood event, and underscore the importance of high-
117 resolution, integrated monitoring across terrestrial and marine environments to effectively
118 assess the dynamics and impacts of extreme hydrological events.

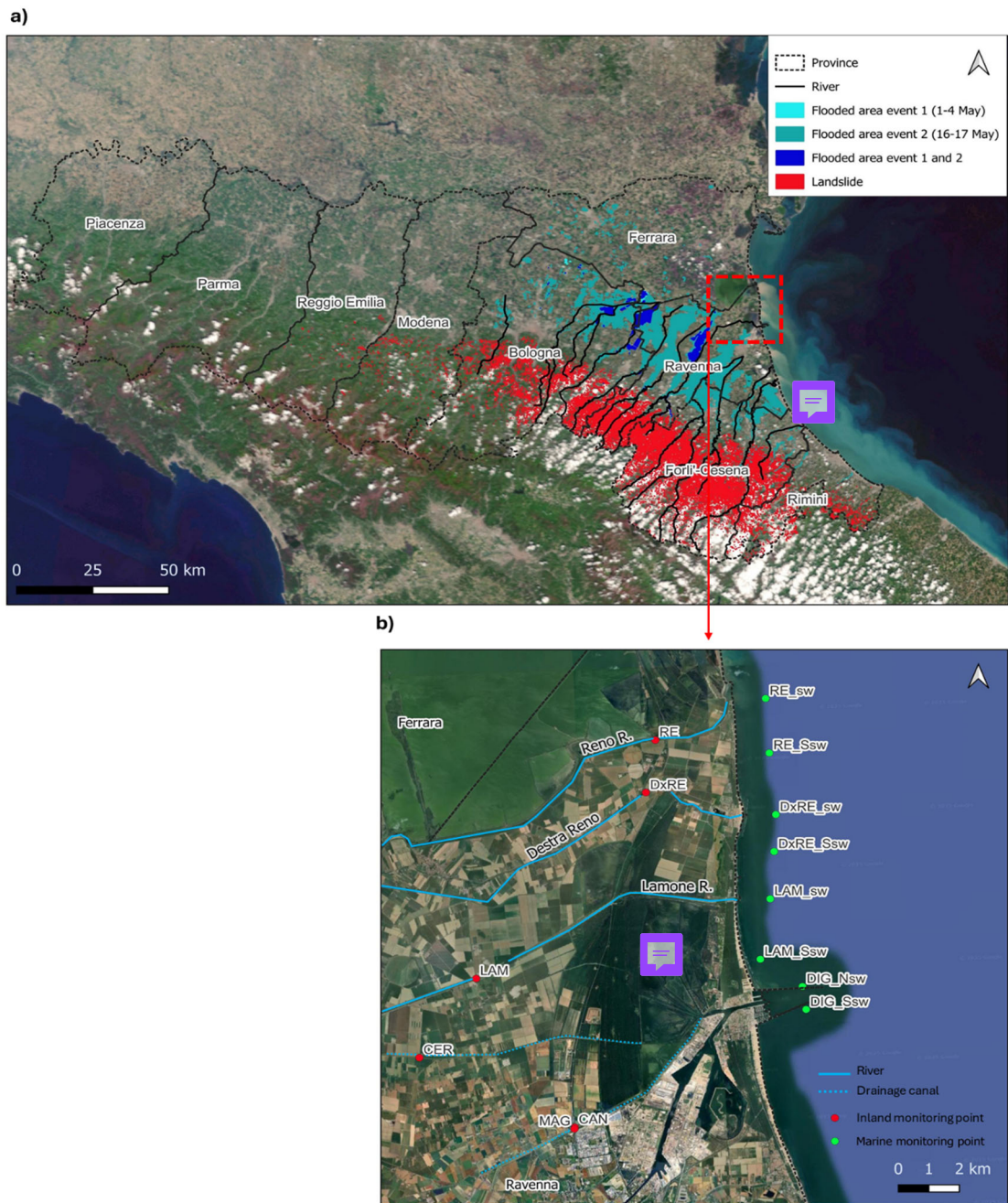


Figure 1 | Areas affected by floods and landslides in May 2023 and location of the study area. a | Rivers (black) and areas of the Emilia Romagna region affected by landslides (red), and floods during the first (light blue), second (green), or both (dark blue) floods. (Data source: Emilia-Romagna data geoportal; base map: European Union, Copernicus Sentinel-2 imagery, date 05/05/2023); **b |** Inland (red) and marine (green) monitoring points selected along the main rivers and drainage channels involved in the flood.

2 Results

Following the flood event in May 2023, significant variations were recorded across all measured environmental parameters (Figure 2).

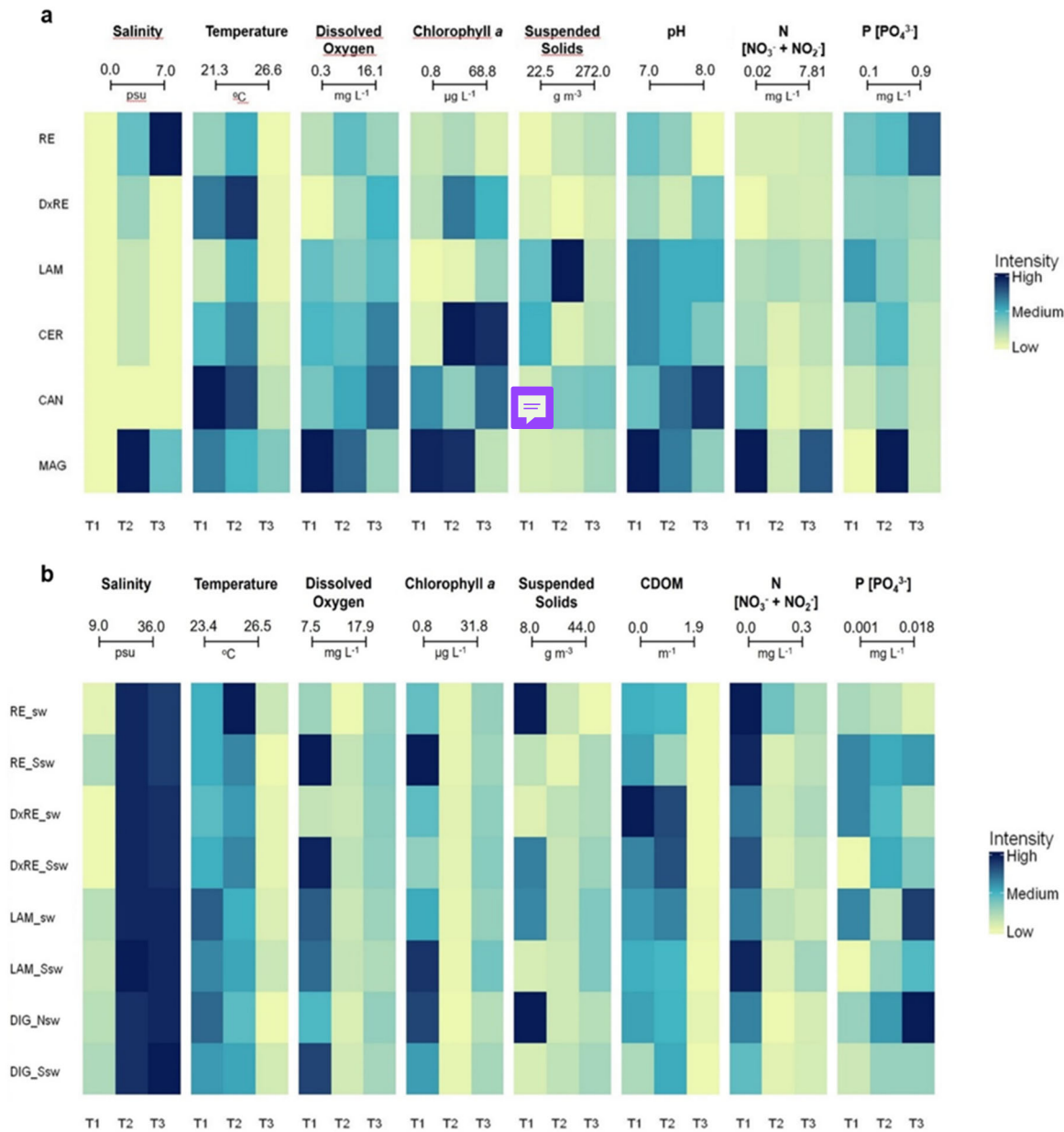


Figure 2 | Heatmap of environmental parameters of inland and marine monitoring points. a | River and canal sampling stations; b | marine sampling stations. Data were normalized per parameter to allow for consistent comparison.

129 Water temperature (T) followed a typical seasonal trend, with maximum value in summer
130 (26.6 °C in June) and minimum with the start of the fall season (21.3 °C in October). Sea
131 salinity (S) dropped markedly due to the freshwater influx from the flood, with a minimum
132 of 9.0 psu at RE_sw and DxRE_sw in May. By October, salinity had returned to typical
133 marine values (~35 psu; Figure 2b). Dissolved oxygen (DO) showed anoxic conditions
134 following the flood (May) in DxRE and reached post-flood minima in June, both at inland
135 (0.3 mg L⁻¹ at DxRE) and marine station (5 mg L⁻¹ RE_sw), reflecting elevated biological
136 oxygen demand.

137 Microalgal pigment concentrations revealed distinct spatial dynamics. Marine stations
138 showed an immediate post-flood chlorophyll-a (CHL) peak in May (up to 31.8 µg L⁻¹ at
139 RE_Ssw), followed by a sharp decline in June and partial recovery by October. This
140 recovery aligns with historical monthly and annual averages observed during Arpae inland
141 monitoring data^{25,26}. Phaeopigments mirrored this trend, with the lowest values in June
142 (0.001 µg L⁻¹ at DIG_Ssw). In contrast, inland stations (Figure 2a) showed delayed CHL
143 and phaeopigment peaks in June, followed by declines by October, indicating enhanced
144 degradation of pigments in the weeks following the event.

145 Suspended and dissolved materials also reflected flood-related dynamics. Total
146 Suspended Matter (TSM) increased from May to June at inland stations (maximum of
147 272.0 g m⁻³ at CAN), indicative of sediment input and resuspension. Marine responses
148 were variable, with some stations increasing in May (e.g., RE_sw, DIG_Nsw) and others
149 in June (e.g., DxRE_sw, LAM_Ssw), but most returned to near-initial levels by October.

150 Colored Dissolved Organic Matter (CDOM) increased in May due to terrestrial runoff,
151 remained stable in June, and declined sharply by October, often below detection
152 thresholds, at inland stations.

153 Nutrient concentrations displayed clear flood-driven dynamics. Nitrogen (N) spiked
154 immediately after the event in May with an increasing north-south gradient at inland
155 stations as a result of flood-induced runoff, decreased sharply by June, and partially
156 rebounded by October. Marine nitrogen values followed a similar but opposite (i.e.,
157 decreasing north-south) trend, although at lower concentrations. Phosphorus (P) showed
158 more variable patterns: inland values generally increased in June, while marine
159 concentrations remained low, with slight increases by October.

160 These results confirm immediate and pronounced flood-driven changes in environmental
161 parameters, highlighting spatial variability and different recovery trajectories between
162 inland and marine environments. To quantitatively highlight the magnitude of the
163 environmental alterations observed during the 2023 flood event, we compared our
164 observations with historical baseline data from Arpae (2010–2022). Although limited to
165 three inland monitoring stations (RE, DxRE, and LAM), for which historical numerical
166 datasets are available, this comparison underscores the exceptional nature of the
167 recorded anomalies. Several parameters (T, EC, DO, pH, and nutrients) measured during
168 and after the flood exceeded the historical range documented over the previous decades
169 (Figure 3); particularly divergent were DO, pH, and P.

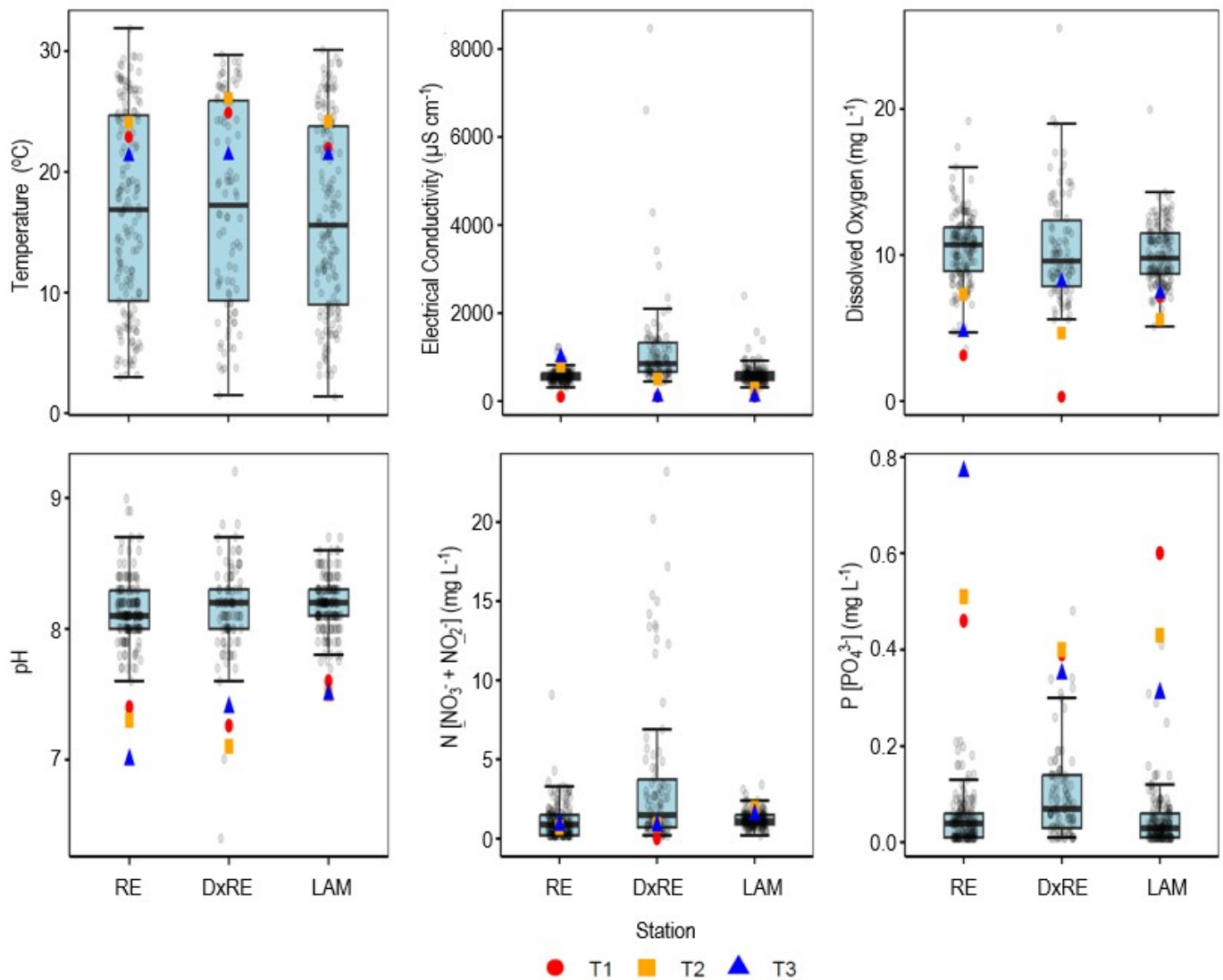
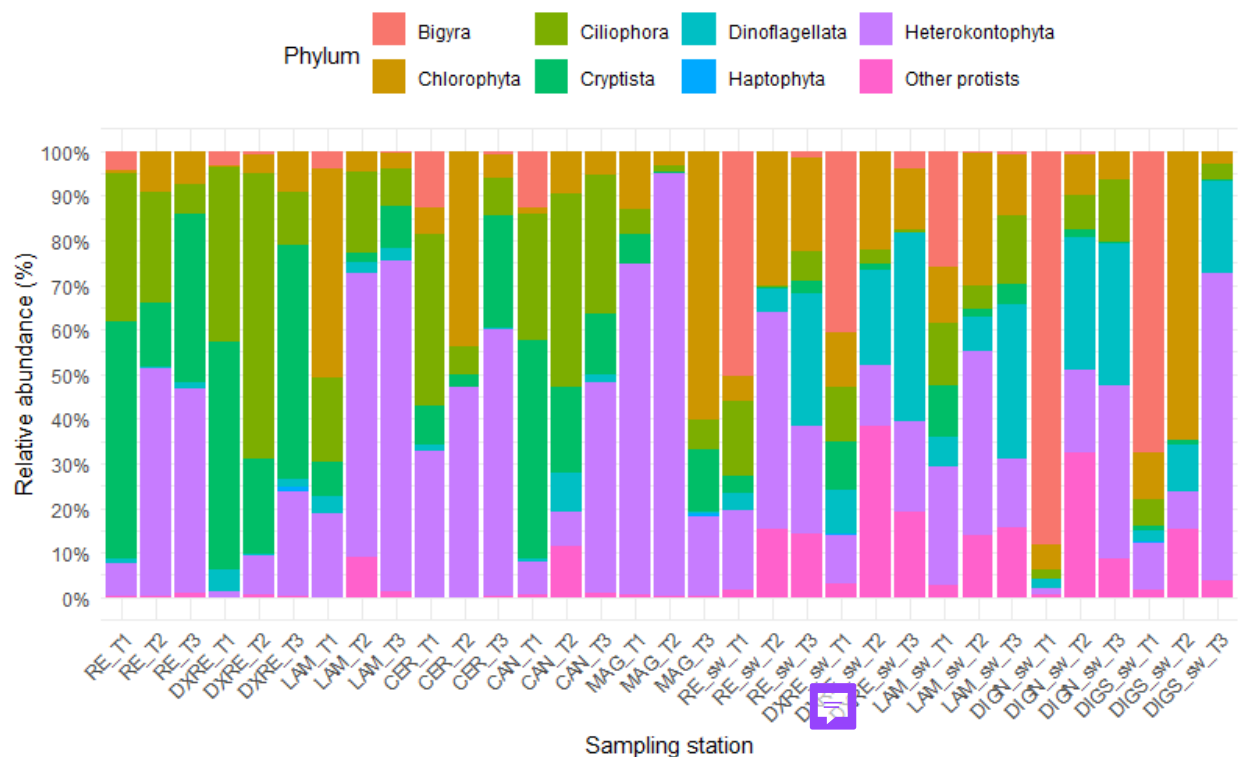


Figure 3 | Comparison of environmental parameters measured during the 2023 flood event with historical baseline data (2010–2022; boxplots) from ARPAE inland monitoring stations RE, DxRE, and LAM. | Panels show:
a | temperature (°C), b | electrical conductivity ($\mu\text{S cm}^{-1}$), (c) dissolved oxygen (mg L^{-1}), (d) pH, (e) dissolved inorganic nitrogen ($\text{NO}_3^- + \text{NO}_2^-$) (mg L^{-1}), and (f) dissolved inorganic phosphorus (PO_4^{3-}) (mg L^{-1}). Historical data distributions are displayed as boxplots, while colored symbols indicate the 2023 post-flood sampling periods. Note the pronounced deviations recorded during the flood event, indicative of substantial environmental alterations.

178 **Protist communities**

179 The eDNA metabarcoding analysis of protist community composition revealed clear
180 differences between freshwater and marine sampling stations. After data filtering, seven
181 main phyla were identified and are shown in Figure 4.



182 **Figure 4 | Relative abundance (%) of protist communities at the phylum level across sampling stations and**
183 **time points, based on eDNA metabarcoding.**

184 Taxa belonging to non-photosynthetic groups were collectively assigned to "Other
185 protists", except for Ciliophora, which were represented separately to highlight their
186 marked post-flood increase in abundance. A total of 74 taxa were detected, distributed
187 across 29 different classes, whose relative abundances are provided in Supplementary
188 Figure S1.

Inland stations were predominantly characterized by high abundances of Heterokontophyta (mainly diatoms), Cryptista, Ciliophora, and Chlorophyta. Conversely, marine stations exhibited higher diversity, dominated mainly by Heterokontophyta and Dinoflagellata. Immediately following the flood (May, T1), marine stations experienced an influx of freshwater-associated taxa, particularly Bigyra, Chlorophyta, and Ciliophora, reflecting freshwater intrusion. This anomaly diminished notably by subsequent sampling periods (June T2 and October T3), as typical marine taxa (Dinoflagellata and Heterokontophyta) progressively increased, signaling ecological recovery to normal conditions. Indeed, these observations align with typical seasonal phytoplankton assemblages reported in the Arpaе annual inland monitoring reports, which serve as a reference for expected marine community conditions during this period. To examine how environmental variables drove the observed community patterns, we performed a redundancy analysis (RDA) using S, T, DO, TSM, and nutrients (N and P) as constraining variables (Figure 5). The first two RDA's axes explained 31.7% of the variance in the community structure, with RDA1 (21.4%) separating freshwater and marine stations based on S, DO, total N and P, and TSM, and RDA2 (10.3%) capturing temporal variation associated primarily with water temperature.

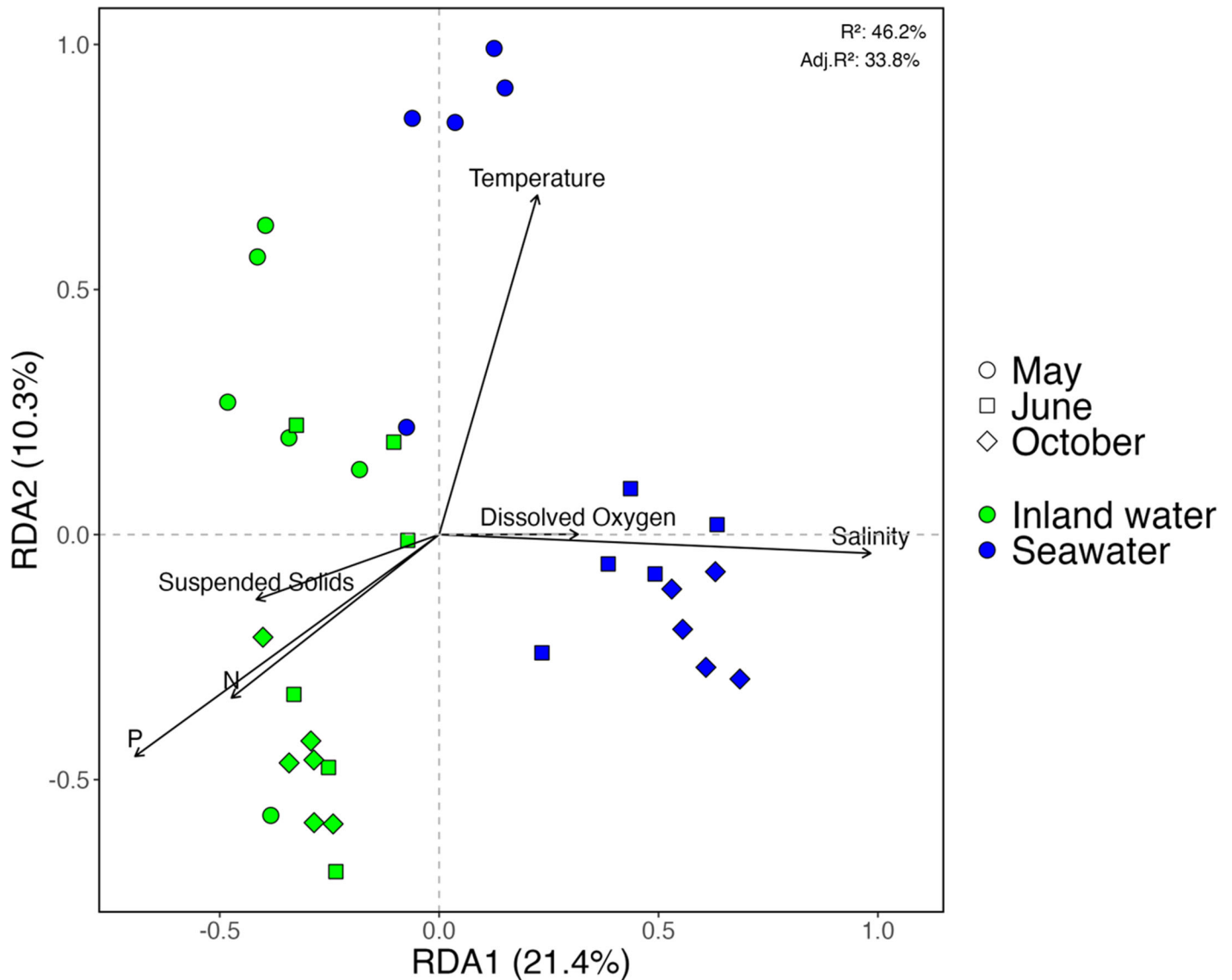


Figure 5 | Redundancy Analysis (RDA) showing the relationship between phytoplankton community structure and environmental variables across sampling stations. Arrows represent the direction and strength of environmental gradients.

ANOVAs confirmed that all environmental predictors significantly influenced the communities composition (S: $p < 0.001$; T: $p < 0.01$; DO: $p < 0.01$; TSM, N, P: all $p < 0.05$; Table 1). Inland samples were more dispersed immediately after post-flood (May–June), becoming clustered by October, reflecting gradual stabilization. These patterns indicate

a strong environmental disturbance driven by the flood event, followed by a clear trend toward recovery and resilience in the subsequent months.

Table 1 | Results of ANOVAs testing the influence of each environmental variable on protist community structure based on redundancy analysis (RDA). | All predictors significantly influenced community structure, with S, T, DO, TSM, total N and P showing varying degrees of explanatory power. Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Terms	Df	Variance	F	Pr(>F)	
S (psu)	1	0.0811	6.3741	0.0001	***
T (°C)	1	0.0352	2.7704	0.004	**
DO (mg L ⁻¹)	1	0.0302	2.3735	0.0097	**
TSM (g m ⁻³)	1	0.0272	2.1362	0.0117	*
N (mg L ⁻¹)	1	0.0261	2.0504	0.0202	*
P (mg L ⁻¹)	1	0.0313	2.4605	0.0032	**
Residual	26	0.3308			

Contaminants of emerging concern (CECs)

Chemical analyses via LC-MS/MS revealed widespread contamination by contaminants of emerging concern (CECs), particularly Bisphenol A (BPA) and pharmaceutical compounds (Figure 6; see Supplementary Tables S1–S2 for the full list). BPA was detected in all samples, ranging from 0.72 to 77.85 ng L⁻¹. The highest BPA concentrations occurred at the inland riverine station RE in October (77.85 ng L⁻¹), while other inland stations (DxRE: 28.15 ng L⁻¹, LAM: 22.25 ng L⁻¹, MAG: 9.4 ng L⁻¹) showed peak values immediately post-flood (T1, May), declining thereafter. On the other hand,

229 marine stations consistently recorded lower BPA levels, with clear decreasing trends
230 post-flood (e.g., RE_sw: 4.25 ng L⁻¹ in May, declining to 1.85 ng L⁻¹ in October).

231 Pharmaceutical contamination, dominated by anti-inflammatory drugs (e.g., Ketoprofen,
232 Diclofenac, Ibuprofen, Naproxen), diuretics, and antipyretics (see the full pharmaceuticals
233 list in Supplementary Table S2), showed notable spatial variability. Inland station MAG
234 displayed extremely high total pharmaceutical concentrations in May (395.98 ng L⁻¹),
235 significantly decreasing in June (42.83 ng L⁻¹), then rebounding by October (395.77 ng L⁻¹
236 ¹). Other inland stations (RE, LAM, DxRE) exhibited similarly elevated contamination in
237 May (RE: 72.24 ng L⁻¹, LAM: 70.62 ng L⁻¹, DxRE: 27.33 ng L⁻¹), decreasing in subsequent
238 months. Marine stations consistently demonstrated lower pharmaceutical concentrations,
239 exhibiting gradual temporal decreases (e.g., RE_sw: 24.95 ng L⁻¹ in May to 10.45 ng L⁻¹
240 in October).

241 Overall, a decreasing trend of contamination from inland towards seawater has been
242 documented in other reports^{27,28}. Data also highlights a contamination decrease from May
243 to October in marine stations. Differently, an increase in BPA concentrations is observed
244 in the Reno river, which was not directly involved in the flooding, possibly due to seasonal
245 fluctuations.

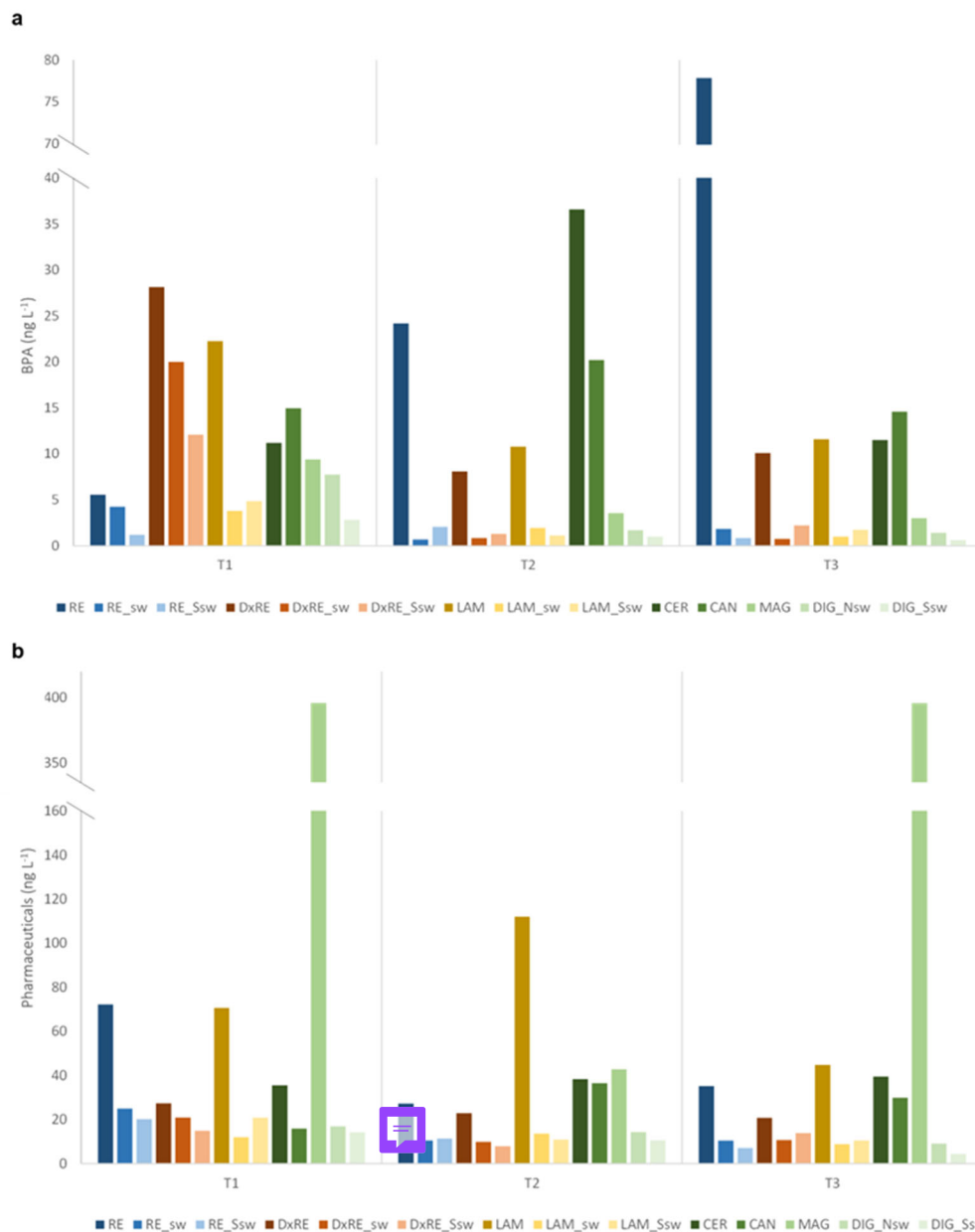


Figure 6 | Emerging contaminants measured in water samples collected during three campaigns in 2023. a | Bisphenol A. b | the sum of the seven pharmaceuticals tested. Limit of quantification (ng L⁻¹) and relative standard deviation (RSD %) (n=3) for each compound analyzed are indicated in Materials and Methods.

Remote Sensing and Image-Based Water Quality

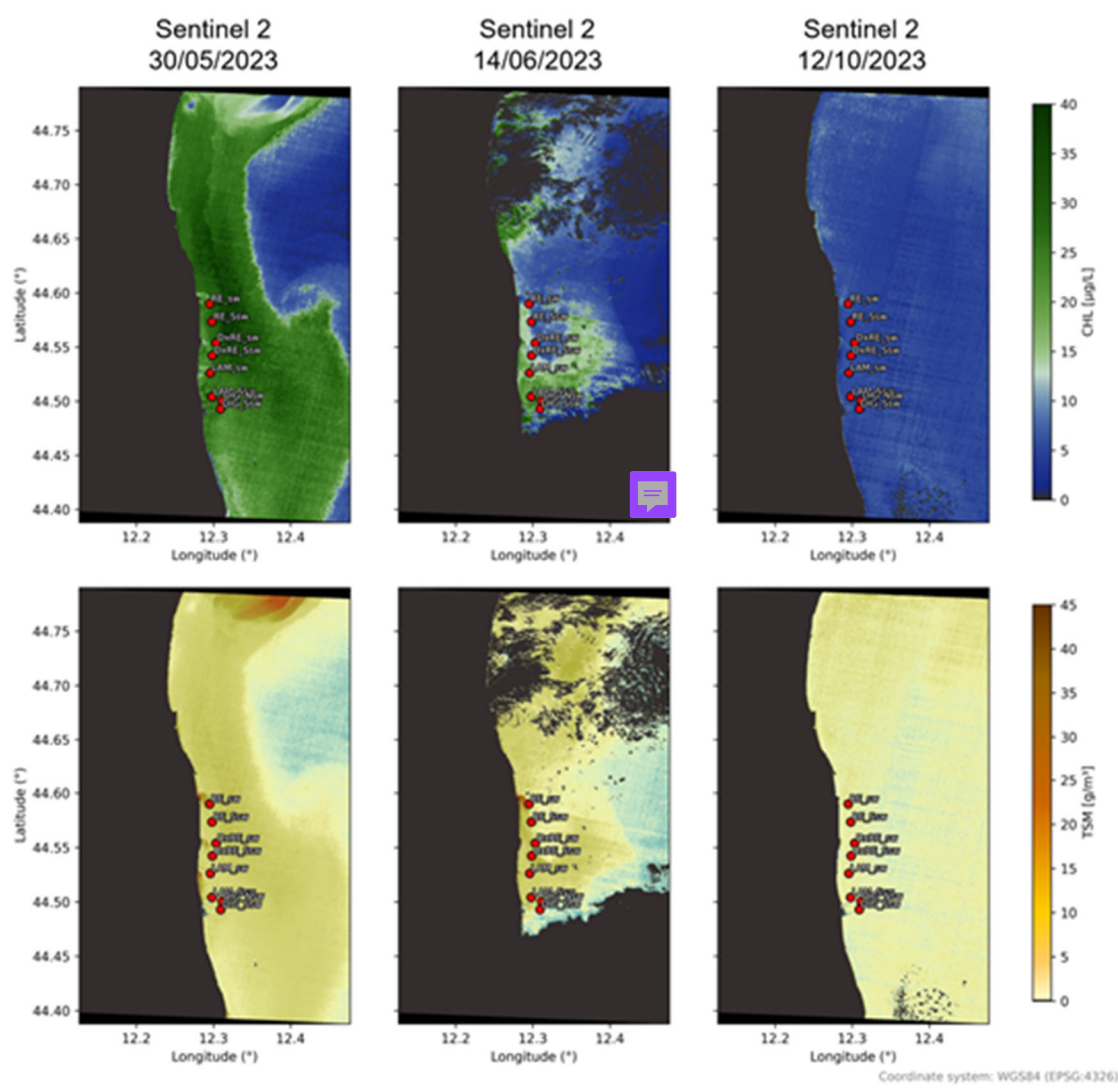
We evaluated the performance of both on-board Sentinel-3 OLCI and semi-operational Sentinel-2 water quality retrievals (via ACOLITE and C2Nets) against in situ measurements of CHL and TSM during the key post-flood periods. Only the best-performing algorithms for each date and sensor are summarized in Table 2, based on MAE% relative to in situ means. Full performance metrics for all tested algorithms are reported in Supplementary Tables S3 (CHL) and S4 (TSM).

Table 2 | Summary of the best-performing algorithms for chlorophyll-a (CHL, in $\mu\text{g L}^{-1}$) and total suspended matter (TSM, in g m^{-3}) retrieval from Sentinel-2 and Sentinel-3 imagery. | MAE% and RMSE% were calculated relative to the average of *in situ* measurements. See Supplementary Tables S3–S4 for a full comparison of all algorithms tested.

Date	Parameter	Sensor	Spatial Resolution (m)	Processor - Product	Algorithm	In-Situ min-max	Estimated min-max	MAE	RMSE	Bias
May 2023	CHL	Sentinel 2	20	C2Nets	C2XCOMPLEX	10.3 - 31.8 $\mu\text{g L}^{-1}$	19.0- 28.5 $\mu\text{g L}^{-1}$	34.3% (6.8 $\mu\text{g L}^{-1}$)	41.3% (9.2 $\mu\text{g L}^{-1}$)	4.9
				ACOLITE	chl_oc3		16.7 -24.8 $\mu\text{g L}^{-1}$	31.8% (6.3 $\mu\text{g L}^{-1}$)	36.3% (7.2 $\mu\text{g L}^{-1}$)	-0.5
	TSM	Sentinel 2	20	C2Nets	C2X	11.0 - 44.0 g m^{-3}	10.7 - 16.9 g m^{-3}	53.6% (13.2 g m^{-3})	73.1% (18.0 g m^{-3})	-11.7
					C2XCOMPLEX		8.8 - 14.8 g m^{-3}	57.7% (14.2 g m^{-3})	78.4% (19.3 g m^{-3})	-13.5
June 2023	CHL	Sentinel 2	20	ACOLITE	chl_oc2	0.8 - 2.1 $\mu\text{g L}^{-1}$	4.2 - 7.9 $\mu\text{g L}^{-1}$	243.6%(3.8 $\mu\text{g L}^{-1}$)	262.8%(4.1 $\mu\text{g L}^{-1}$)	3.8
		Sentinel 3 OLCI	300	SENTINEL 3 WFR	chl_nn		2.8 - 6.1 $\mu\text{g L}^{-1}$	179.5% (2.8 $\mu\text{g L}^{-1}$)	185.9% (2.9 $\mu\text{g L}^{-1}$)	2.8
	TSM	Sentinel 2	20	C2Nets	C2X	9.0 - 14.0 g m^{-3}	7.5 - 15.7 g m^{-3}	18.4% (2.3 g m^{-3})	25.6% (3.2 g m^{-3})	-0.1
					C2XCOMPLEX		5.9 - 12.4 g m^{-3}	21.6% (2.7 g m^{-3})	26.4% (3.3 g m^{-3})	-2.3
October 2023	CHL	Sentinel 2	20	C2Nets	C2XCOMPLEX	6.9 - 13.0 $\mu\text{g L}^{-1}$	5.0 - 11.0 $\mu\text{g L}^{-1}$	19.1% (1.8 $\mu\text{g L}^{-1}$)	26.5% (2.9 $\mu\text{g L}^{-1}$)	-1.6
		Sentinel 2		ACOLITE	chl_re_gons		7.2 - 13.5 $\mu\text{g L}^{-1}$	20.1% (1.9 $\mu\text{g L}^{-1}$)	24.4% (2.3 $\mu\text{g L}^{-1}$)	0.9
	TSM	Sentinel 2	20	C2Nets	C2X	8.0 - 21.0 g m^{-3}	6.6 - 12.9 g m^{-3}	49.1% (8.1 g m^{-3})	55.2% (9.1 g m^{-3})	-8.1
		Sentinel 3 OLCI	300	SENTINEL 3 WFR	tsm_nn		3.0 -12.7 g m^{-3}	56.4% (9.3 g m^{-3})	63.0% (10.4 g m^{-3})	-8.9

263 In May, under highly turbid, flood-affected waters, Sentinel2 algorithms performed best.
264 The ACOLITE *chl_oc3* model delivered the lowest MAE of 31.8 % (RMSE 36.3 %, bias
265 -0.5), closely followed by C2Nets' neural-network variant *C2XCOMPLEX* (MAE 34.3 %,
266 bias +4.9). For TSM, C2X again captured the flood-induced particulate peak, with MAE
267 of 53.6 % and moderate underestimation (bias -11.7), showing robustness in extreme
268 optical conditions. By June, when turbidity began declining, Sentinel3 OLCI *chl_nn*
269 achieved slightly better CHL estimates (MAE 179.5 %) than Sentinel2's *chl_oc2* (MAE
270 243.6 %), yet the coarse 300 m resolution obscured important near-shore heterogeneity.
271 TSM retrieval remained accurate via C2X (MAE 18.4 %, bias -0.1), reflecting improved
272 water clarity but still substantial residual load. By October, both C2Nets' *C2XCOMPLEX*
273 (MAE 19.1 %) and ACOLITE's *chl_re_gons740* (MAE 20.1 %) produced reliable CHL
274 estimates, with low RMSE and near-zero bias, indicating stabilization of water optics. C2X
275 continued to be the preferred model for TSM (MAE 49.1 %, bias -8.1), although accuracy
276 improved in line with environmental recovery. Bias trends further reinforce these findings:
277 ACOLITE's *chl_oc3* consistently underestimated CHL, contrasted with *chl_re_gons740*,
278 which corrected its initial positive bias to become unbiased by October. Meanwhile, C2X
279 and *C2XCOMPLEX* exhibited stable, moderate biases throughout the campaign.
280 Additionally, we compared satellite-derived estimates of CDOM absorption (a_{cdom} at
281 443nm) with laboratory measurements, where available. Since only the C2Nets
282 framework and Sentinel-3 OLCI WFR currently offer CDOM retrievals from satellite
283 imagery, this comparison was limited to a subset of algorithms and dates. The results
284 indicated substantial overestimations and high error levels, suggesting limited reliability

285 over the test period. Given the exploratory nature and limited accuracy of these outputs,
286 CDOM retrieval metrics are presented exclusively in Supplementary Table S5. Spatial
287 distribution maps (Figure 7) show a clear temporal decline in both CHL and TSM
288 concentrations across marine areas, consistent with in-situ observations.



289 **Figure 7 | Maps are generated with the C2X processor (C2RCC plugin, SNAP) from Sentinel-2 imagery. |**
290 **Chlorophyll-a (CHL, µg L⁻¹). b) Total Suspended Solids (TSM, g m⁻³).** Dates of acquisition are shown above each panel.
291 Sampling points are marked in red. The 20 m maps were first masked with the Land/Sea Mask operator, retaining only
292 pixels classified as water in the Sen2Cor Scene Classification Layer, to remove both inland-water and land pixels.

High values in May reflect flood-induced particulate and phytoplankton inputs, followed by progressive decreases in June and stabilization by October. These satellite-derived trends align with field measurements, supporting the potential of remote sensing to complement traditional monitoring in capturing short-term flood impacts and recovery dynamics.

3 Discussion

The May 2023 flood event dramatically altered environmental, biological, and chemical conditions across the study region. A massive freshwater inflow drastically reduced the salinity concentration at marine stations, while simultaneously elevating dissolved oxygen and nutrient levels, and enhancing ediment transport. Although limited pre-event baseline data are available for individual stations, comparisons with the historical regional datasets provide evidence of the unprecedented impacts induced by this extreme event. In addition, clear deviations from historical datasets strongly emphasize the necessity for widespread and continuous environmental monitoring to capture responses to extreme hydrological events.

The impacts observed here are consistent with previous flood events in this region, although in several aspects they have proved even more severe. Notably, the Po River floods of October 2000, described in²⁹, and the May 2014 flood, analyzed in³⁰, both induced major alterations in the marine system, but with distinct quantitative differences. For instance, during the 2000 flood, surface salinity dropped to 6–7 psu, while in 2014 minimum salinity values did not fall below 29 psu. In our case, despite a more restricted

study area, salinity minima extended broadly across all marine stations, reaching 9–10 psu, confirming significant freshwater input.

Similarly, CDOM absorption (a_{443} up to 1.9 m^{-1}) and TSM values (up to 44 mg m^{-3}) exceeded maxima previously recorded for high discharge conditions in the northern Adriatic Sea^{30,31}, suggesting an even greater input of sediments and terrestrial, humic-rich material³². However, concentrations of nutrients such as N and P were lower than those recorded following both the 2000 and 2014 flood events, suggesting potential dilution effects due to the high-water volume or rapid biological uptake.

The exceedance of historical environmental values observed post-event is primarily attributable to the floodwater volumes, which mobilized contaminants from both agricultural and urbanized areas, generating urban runoff and delivering a concentrated pulse of pollutants to the inland system. The failure of the drainage network to manage the unprecedented water load further aggravated environmental pressure.

In line with the documented physico-chemical alterations, our biological observations confirmed that marine protist communities reacted promptly to the environmental stress induced by the flood event. In particular, the sharp decrease in salinity, combined with elevated nutrient concentrations and high TSM levels, favored the intrusion and proliferation of freshwater-associated taxa, mainly Bigyra, Chlorophyta and Cryptista, into marine inland waters. This reflects the strong advection of riverine and canal waters carrying both dissolved and biological material towards the sea. Such patterns are consistent with established evidence showing that pulses of nutrient-rich freshwater, combined with altered light availability and water column mixing, promote the dominance

of opportunistic, fast-growing species^{33–35}. The rapid increase in Cryptista and other nutrient-tolerant groups observed at marine stations is consistent with post-extreme event dynamics described in other estuarine and coastal systems^{36,37}. In parallel, we also recorded a temporary increase in heterotrophic taxa belonging to the phylum Bigyra and Ciliophora, typically associated with high organic matter availability and turbid, mixed inland waters. Their transient dominance likely reflects the immediate post-flood conditions, characterized by abundant particulate and dissolved organic material transported by riverine inputs, which provided favorable conditions for heterotrophic and osmotrophic protists, as previously observed³⁴. As salinity progressively increased and organic matter concentrations declined, Bigyra abundance rapidly decreased, and environmental conditions gradually shifted towards typical seasonal marine patterns. Interestingly, during the first post-flood sampling (T1, May), marine stations as well as satellite images showed unexpectedly high chlorophyll-a concentrations, coupled with low salinity and high turbidity. This suggests that the initial freshwater inflow not only delivered substantial nutrients but also transported phytoplankton biomass from upstream areas, temporarily enhancing photosynthetic biomass in marine waters despite adverse optical conditions. Such short-term biomass peaks associated with flood plumes are reported in other coastal systems following major hydrological events^{30,37}. Another hypothesis could be that phytoplankton increased the light-harvesting pigments content as a response to river-borne organic material, which caused water browning³⁴. By June, in marine stations, salinity had nearly returned to typical values (35 psu), and TSM decreased, indicating a progressive attenuation of the flood's immediate influence.

358 However, measurements and satellite data show that chlorophyll-a concentrations
359 dropped very fast, suggesting that, despite physical recovery, optical conditions likely
360 remain unfavorable for phytoplankton growth due to residual turbidity and high CDOM
361 levels that could reduce light penetration, limiting in-situ primary production in the
362 immediate aftermath of the flood. This mechanism has been previously highlighted in^{29,38}.
363 In contrast, inland freshwater stations showed a further increase in chlorophyll-a
364 concentrations, where a delayed photosynthetic biomass bloom dominated by
365 Ochrophyta, Heterokontophyta, and Cryptista developed, supported by persistently high
366 nutrient concentrations.

367 Despite this biological bloom, environmental trajectories among inland stations remained
368 more heterogeneous compared to the relatively coherent dynamics observed across
369 marine stations. This reflects the distinct hydrological characteristics, and independent
370 watershed influences of each river or canal system, resulting in site-specific trends in
371 parameters such as salinity, TSM, and nutrient concentrations throughout the study
372 period. However, the biological community at inland stations displayed more consistent
373 patterns. eDNA metabarcoding analyses revealed an initial dominance of opportunistic
374 groups, including Ciliophora and Cryptista, during the early post-flood phase (T1, May),
375 favored by nutrient enrichment and altered water column structure. Over time, these taxa
376 declined, while Heterokontophyta progressively increased, eventually becoming the
377 predominant phytoplanktonic component typical of freshwater-influenced transitional
378 environments. This community's change through time appeared broadly consistent

across inland stations, suggesting that ecological succession following extreme events may follow common pathways, even under variable local environmental conditions. By October, marine stations showed clear signs of recovery, with salinity, dissolved oxygen, and TSM stabilizing, and communities returning to seasonal assemblages dominated by Dinoflagellata and Heterokontophyta. Redundancy analysis (RDA) identified salinity, dissolved oxygen, and nutrient loads as the primary drivers shaping protist community structures, consistent with global findings in flood-impacted systems^{35,39}. Additionally, eDNA metabarcoding effectively captured subtle post-flood community shifts, especially among cryptic heterotrophic protists, highlighting its value as a sensitive monitoring approach.

These spatial patterns of ecological disturbance and gradual recovery were mirrored by the clear temporal and spatial gradients of emerging contaminants, including bisphenol A and pharmaceuticals across the study area. Overall, contaminant levels decreased from inland stations towards marine stations, both immediately after the flood and during subsequent months. Such patterns are consistent with previous studies reporting dilution and dispersion processes at the land-sea interface as reported in^{27,28}, although our data highlight the influence of local hydrodynamics and persistent upstream sources.

Drainage channels showed levels of contamination comparable to or even higher than rivers, suggesting the need for monitoring actions to which they are not yet subjected. The highest BPA and pharmaceutical concentrations were recorded at freshwater sites exposed to chronic anthropogenic inputs, particularly MAG and CER, with values progressively decreasing in marine waters downstream of channel mouths, likely due to

dilution, mixing, and degradation processes. We can only speculate that this trend is related to the flooding, because of the lack of previous CECs data for this drainage water. Moreover, a general decline in contaminant concentrations was observed from May to October, especially at marine sites, paralleling the recovery trends recorded for the other physical and chemical parameters, and for the biological communities. While the absence of detailed pre-event baselines limits the considerations, this decline is probably linked to the progressive dissipation of the flood's immediate impact.

Interestingly, divergent trends emerged at certain freshwater stations unaffected by the flood, such as the Reno river, where BPA concentrations increased over time, possibly reflecting seasonal variability or specific local sources independent of the flood dynamics. Environmental and biological changes were also evident in the performance of satellite-based monitoring products, whose accuracy varied across stations and time points, strongly influenced by evolving hydrological conditions. The same optical complexity - due to elevated TSM and CDOM - that affected biological communities and light penetration also posed significant challenges for remote sensing-based monitoring. As reported in⁴⁰, estuaries and coastal zones fall under the so-called Case 2 water⁴¹ where inorganic particulate matter and colored dissolved organic matter play a dominant role in shaping the optical signal, often masking the contribution of chlorophyll-a. In such environments, algorithms exploiting red and near-infrared wavelengths have been proposed to improve chlorophyll-a retrievals⁴²⁻⁴⁵, yet their empirical nature necessitates region-specific tuning to ensure applicability⁴⁶.

Overall, chlorophyll-a retrievals performed best in October (T3), coinciding with the ecological recovery phase, when salinity, CDOM and TSM values approached seasonal baselines and extreme in-situ concentrations of chlorophyll-a were no longer present. This suggests that under stabilized post-flood conditions, the performance of algorithms improves, highlighting their sensitivity to local water quality fluctuations.

Overall, CHL retrieval performance was comparable to, or in some cases better than, values reported for similar coastal systems, such as the northern Adriatic nearshore waters in Veneto region⁴⁷, while other European coastal sites have shown even greater errors⁴⁸.

A similar pattern was found for TSM retrievals. C2Net based products, particularly C2X, exhibited MAE and RMSE comparable to those obtained by Marzano et al. (2020) for the northern Adriatic using C2RCC. However, our results also reveal clear temporal variability in algorithm performance. At T1, during the peak of the flood impact, RMSE reached 19 g m^{-3} , slightly exceeding the values reported in⁴⁷. Conversely, at T2 and T3, RMSE values decreased substantially to 3 g m^{-3} and $8\text{--}9 \text{ g m}^{-3}$, respectively, indicating improved performance and lower retrieval errors compared to previous literature in two out of the three sampling periods. CDOM retrieval performance was limited, with high retrieval errors observed at T1 and T2. Moreover, due to low in-situ CDOM concentrations and unreliable laboratory measurements, no validation was possible for T3. These results reinforce the need for further refinement and local calibration of CDOM products, especially under extreme post-flood conditions where CDOM dynamics play a key ecological role.

These observations highlight that satellite product accuracy is strongly influenced by local hydrological and optical variability, aligning with the dynamic environmental gradients observed in in-situ measurements and biological data throughout the study. Consequently, careful algorithm selection and region-specific calibration remain essential to accurately monitor coastal water quality, particularly under extreme flood conditions that amplify optical complexity. Future efforts should prioritize the development of flexible approaches that integrate evolving biogeochemical, hydrological, and optical characteristics to enhance remote sensing performance in flood-impacted coastal environments.

Overall, our findings provide evidence that, despite the significant disruption caused by the 2023 Emilia-Romagna flood, inland and marine environments demonstrate strong resilience, showing possible signs of recovery within a few months after the event. By October, most physico-chemical variables returned to expected levels, and the community structures were restored, supporting a rapid, intrinsic resilience of the system. Satellite products helped track these trends but still struggled to resolve the extreme spatial and temporal variability characteristic of coastal environments impacted by major flooding.

Results underscore how extreme hydrological events reshape coastal environments through interconnected physical, chemical, and biological alterations, whose impacts propagate from inland waters to the marine domain. These types of extreme events produce cascading effects at multiple temporal and spatial scales, with both immediate and delayed consequences for ecosystems, human health, and economic sectors. However, the limited availability of high-resolution pre-event baselines constrains

comprehensive impact assessments. To enhance predictive capacity and inform management strategies, future efforts should prioritize long-term, integrated monitoring that combines traditional sampling, molecular tools, and adaptive remote-sensing technologies, particularly as climate change is expected to amplify the frequency and intensity of such disturbances in the northern Adriatic.

4 Conclusions

This multidisciplinary study provides a comprehensive snapshot of the short- and medium-term impacts of the May 2023 flood event in Emilia-Romagna, capturing for the first time the environmental, biological, and chemical alterations induced by such an extreme hydrological disturbance in this coastal region. Despite the absence of site-specific pre-event baselines, which represents a critical limitation, this study offers a crucial reference point, a “post-event photograph” against which future monitoring efforts and environmental assessments can be compared. The study demonstrated the importance of applying a sampling design that included rivers and canals, together with coastal marine sites. Thanks to this sampling strategy, it was possible to trace the pathways and characteristic times required for nutrients and pollutants to travel from the plain to the sea. We showed that the flood mobilized contaminants from agricultural and urban areas, delivering a concentrated pulse of pollutants to the coast, further intensified by the failure of the drainage network. In response, marine protist communities showed rapid shifts, with freshwater-associated taxa proliferating due to decreased salinity,

elevated nutrients, and high TSM levels. Right after the flood, both marine stations and satellite data revealed high chlorophyll-a levels, suggesting that nutrient-rich floodwaters and upstream phytoplankton transport temporarily boosted marine biomass despite low salinity and high turbidity.

Despite the severity of the initial impacts, including pronounced shifts in water chemistry, biological communities, and emerging contaminant concentrations, ecosystems demonstrated a notable capacity for resilience and recovery within a few months, particularly evident by October 2023. Although the system demonstrated the capacity for short-term ecological recovery, questions remain regarding its long-term resilience, particularly under scenarios involving increased frequency and intensity of such extreme events driven by climate change. Our findings highlight a critical gap for future research: the urgent need to implement continuous, long-term, multi-parameter monitoring programs that combine conventional assessment protocols, aligned with major legislative frameworks, with innovative analytical approaches, such as high-resolution remote sensing and molecular tools. Such integrated strategies are essential to capture environmental dynamics and assess ecosystem responses under extreme event scenarios, ultimately improving preparedness and management capacity in the face of climate-driven hydrological disturbances.

5 Materials and Methods

5.1 Study Area and Field Measurements

The study focused on the monitoring of rivers and freshwater canals (hereafter indicated as “inland stations”), as well as the Adriatic Sea in front of the Ravenna coast, which were impacted and affected by the May 2023 flood event. Inland sampling stations included the terminal reaches of the Reno, Destra Reno, and Lamone rivers to the north of the city, as well as the Cerba, Canala, and Magni drainage canals, which drain the western part of the city and discharge into the Baiona Canal before reaching the sea (**Error! Reference source not found.**). Reno River and Cerba drainage canal were designed as control points as they remained unaffected by the flood. Although the Reno River catchment experienced elevated water levels during the rainfall period, no flooding was recorded within its watershed. Similarly, the Cerba canal drains a small coastal basin in the north of Ravenna that did not experience inundation. As such, these sites served as reference points for water quality and biological analyses, providing representative conditions for non-impacted areas.

Marine sampling stations were selected about 1 km offshore and located in front of each river mouth and at the midpoints between them. Two additional marine stations were situated 1.5 km offshore, in the south and north of the Ravenna port’s jetties. Due to the presence of the long jetty infrastructure (2.4 km) acting as a physical barrier, the southern station was used as control point because protected from the direct influence of northern

fluvial and canal plumes originating by the flood. It was considered suitable reference points for assessing baseline marine conditions unaffected by the flood-induced inputs.

Three monitoring campaigns were carried out on the 30th of May, 16th June, and 10th October 2023. This timeline enabled a comprehensive evaluation of both the short- and medium- term impacts of the flooding on inland and marine ecosystems of the study area, as well as the processes of environmental recovery. May 30th was selected as the earliest feasible sampling date, coinciding with the lifting of emergency restrictions related to hydrogeological risk. June was chosen to capture early post-event conditions, while October 10th represented a later time point, allowing evaluation of the system's potential recovery and the re-establishment of pre-event conditions.

At each sampling station, physical and chemical parameters such as temperature (T), electrical conductivity (EC), pH, redox potential (Eh), and dissolved oxygen (DO) were measured by a HQ4300 Portable Multi-Meter (HACH®, Loveland, CO, USA), while samplings of surface water were collected to perform chemical and biological community analysis:

- 0.5 liter for eDNA metabarcoding
- 1 liter for pollutant analysis
- 2 liters for biological analyses (chlorophyll-a (CHL), phaeopigments, inorganic nutrients (N and P), Total Suspended Matter (TSM) and Chromophoric Dissolved Organic Matter (CDOM)

547 Samples were stored in pre-washed rigid 1-liter plastic bottles (10% HCl or NaClO).
548 Salinity (S) was measured in the field using a refractometer.

549 5.2 Water Quality Assessment

550 Water samples of inland costal stations (rivers and drainage canals) (**Error! Reference**
551 **source not found.**) were filtered through a 0.45 µm membrane filter, stored in pre-
552 cleaned 100 mL HDPE plastic bottles until further analysis. Samples for cations and trace
553 elements (TEs) determination were acidified with 1% HNO₃. Major anions and alkalinity
554 were analyzed within 24 hours by Ion Chromatography (883 Basic IC plus Metrohm AG,
555 Herisau, Switzerland) and major cations and PTE by Inductively Coupled Plasma–Optical
556 Emission Spectroscopy (Agilent 5800 ICP-OES, USA). The calibration curve was built
557 using certified standards in water. For both cations and anions, the standards set by the
558 Italian National Environmental Agency, APAT-IRSA 2003 were applied. For all the
559 samples, the ionic balance was ±5%. Considering internal and external standards,
560 accuracy and precision were better than 10% for all elements considered. Results of river
561 samples were compared against the long-term monitoring series (2013 to 2023) of Reno,
562 Destra Reno and Lamone rivers downloaded from the Regional Environmental Protection
563 Agency of the Emilia-Romagna Region (Arpae) website ([https://dati.arpa.e.it/dataset/rete-](https://dati.arpa.e.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023)
564 [regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023](https://dati.arpa.e.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023)). For
565 comparison with historical data from Arpae, nitrate (NO₃⁻) concentrations were used,
566 given that nitrite (NO₂⁻) values were consistently missing from the Arpae dataset,

567 suggesting concentrations below detection limits. Our measured values of dissolved
568 nitrogen represent the sum of nitrate and nitrite ($\text{NO}_3^- + \text{NO}_2^-$).

569 Water samples were analyzed for CHL, inorganic nutrients, CDOM (only marine stations),
570 and TSM.

571 CHL samples were kept cool and dark until analysis. Volumes of 200–600 mL were
572 filtered on Whatman GF/F filters (0.7 μm , 47 mm). Pigments were extracted with 90%
573 acetone, and concentrations measured by spectrophotometer (Jasco V-650) at 750 and
574 665 nm following⁴⁹. Phaeopigments were quantified after acidification to a final
575 concentration of 0.66 M HCl.

576 Nitrate as N [$\text{NO}_3^{2-} + \text{NO}_2^-$] and Phosphorous as P [PO_4^{3-}] were analyzed in filtered water
577 samples (GF/F filters), stored in polyethylene bottles pre-washed with 10% HCl.
578 Spectrophotometric analysis was carried out according to⁵⁰. TSM was measured
579 gravimetrically following the method described in⁵¹. Water samples were filtered onto pre-
580 weighed 0.45 μm membrane filters. For marine samples, filters were rinsed with 0.5 M
581 ammonium formate (2× the filtered volume) to remove residual salts. Filters were then
582 oven-dried at 105 °C and reweighed to determine particulate mass. CDOM absorption
583 was measured spectrophotometrically following⁵², based on UV-visible absorbance
584 spectra collected on filtered samples (0.2 μm) across the 250–800 nm range. CDOM
585 absorption coefficients were specifically determined at 443 nm.

586 CDOM absorption at 443 nm was measured during all three field campaigns. However,
587 at T3 (October), most laboratory-derived values were negative or close to zero, consistent
588 with CDOM concentrations near or below the detection limit and increased instrumental

uncertainty. These values were excluded from the comparative analysis to ensure reliable performance assessment

5.3 Protist communities' assessment

In order to analyze the protist communities, eDNA analysis was performed on all inland and marine water samples. They were pre-filtered on 3 µm nitrocellulose filters and re-filtered on a 0.22 µm nitrocellulose filter. After filtration, filters were stored at -20°C. Total DNA from the filters was extracted using the BioFast Soil Genomic DNA Extraction Kit (BioFlux, Hangzhou, Zhejiang, China), following the manufacturer's instructions, with two negative controls included per extraction batch to check for contaminations. PCR reactions for the V4–V5 region of the 18S rRNA were carried out in a total volume of 20 µL and included 17 µL of AmpliTaq Gold™ 360 Master Mix (Applied Biosystems), 0.5 µL of each primer (F-566, R-1200; 10 µM)⁵³ that already included 12-bp tags for multiplexing, and 2 µL of DNA template, with the following thermal profile: 95°C for 15 min, followed by 35 cycles of 95 °C (45s), 60 °C (45s), 72 °C (1min), and a final extension at 72 °C for 10min. PCR products were evaluated by agarose gel electrophoresis (1.5% gel, 0.5X TBE). For the 18S library, PCR products were pooled and purified with the Macherey-Nagel™ NucleoSpin Gel and PCR Clean-up Kit to remove DNA fragments <70 bp. DNA concentration was measured with a Qubit fluorometer (Broad Range kit, Invitrogen). The libraries were sequenced in-house with a MinION Mk-1C (Oxford Nanopore Technologies). The 18S library was prepared with the SQK-LSK110 kit and sequenced on a FLO-MIN111 flow cell with a 22-hour run. Basecalling was conducted using Guppy

(ONT) with a quality threshold of 8. Demultiplexing and length filtering were performed with OBITOOLS⁵⁴. The taxonomic assignment was conducted using the RDP classifier with the SILVA 138 reference database at genus level^{55,56}. Data were cleaned keeping only protist taxa that had a total read count of at least 10 and a similarity threshold of 97%. Since some samples did not amplify and to ensure consistency, only samples present in both biological and environmental datasets were considered for the Redundancy Analysis (RDA). Environmental parameters considered for the RDA were N, P, TSM, DO, temperature and salinity. Protist abundance data were square-root transformed, and environmental variables were standardized with *decostand()* to allow comparison among different scales. RDA analysis allows the samples and environmental factors to be represented on the same two-dimensional ordination plot to visualize their relationships. RDA was performed with *rda()* using scaling 2, to highlight the effects of explanatory variables (environmental parameters). The significance of each environmental variable in explaining community structure was assessed with *anova.cca()*. All analyses were performed in R version 4.4.1 (R Core Team, 2024), using the vegan package⁵⁷ and ggplot2⁵⁸ for data visualization.

5.4 Contaminants of emerging concern (CECs) analyses

To analyze CECs, water samples were spiked with a mixture of labeled internal standards (BPA-d6 and Ibuprofen-d3) at a concentration of 30 ng L⁻¹. Samples were filtered using glass microfiber filters (1.60 µm), then with cellulose acetate filters (0.45 µm), and extracted using Solid Phase Extraction (SPE) Oasis HLB cartridges as reported in⁵⁹. Cartridges were eluted with 6 mL of methanol, evaporated under a nitrogen gentle stream

up to a volume of 250 μL , and split into two vials of 125 μL each. The first set of vials was added with 125 μL of water (50:50 water/methanol) for chemical analysis of Bisphenol A (BPA); the remaining vials were further evaporated to 25 μL and reconstituted in 250 μL of a mixture of water/methanol (90:10) for LC-MS-MS analysis of pharmaceuticals. Samples were transferred into 2 mL vials, after filtration (0.22 μm CA membrane filters) for analysis. Chemical analysis of BPA in water samples was performed by ultra-high-performance liquid chromatography (ACQUITY UPLC® H-Class) equipped with a triple quadrupole mass spectrometer (Xevo® TQ-S Micro) using a negative electrospray ionization source in multiple-reaction monitoring (MRM) mode. Separation of compounds was achieved through an ACQUITY UPLC® BEH C₁₈ column (100 $\times$ 2.1 mm, 1.7 μm particle size, 130 Å pore size) equipped with a pre-column (BEH C₁₈ VanGuard™ pre-column, 5 $\times$ 2.1 mm i.d., 1.7 μm particle size). The volume injection was 10 μL . Sample extracts concentrated 2000 times were measured along with calibration standards, which corresponded to a range of 1–300 $\mu\text{g L}^{-1}$. Chemical analysis of pharmaceuticals was performed by the IRCCS (Istituto di Ricerche Farmacologiche “Mario Negri”, Department of Environmental Health Sciences), as described in⁶⁰.

5.5 Remote Sensing and Image Processing

The aim of the remote sensing use in this study was to evaluate whether ready-to-use (e.g., Sentinel-3 OLCI) and semi-operational products (based on Sentinel-2 data processing) could reliably estimate water quality parameters, especially under extreme hydrological conditions, such as those that followed the May 2023 flood.

653 We applied and compared multiple algorithms across satellite products to identify those
654 most accurate and operationally useful for post-flood environmental monitoring. Each
655 satellite of the Sentinel-2 constellation is equipped with the Multispectral Instrument (MSI),
656 which captures data across 13 spectral bands, ranging from visible (VIS) and near-
657 infrared (VNIR) to the shortwave infrared (SWIR) spectrum. The MSI provides spatial
658 resolutions of 10 m (VIS and VNIR), 20 m (red-edge and vegetation-related bands), and
659 60 m (bands for atmospheric correction). For this study, Sentinel-2 Level-1C products
660 were downloaded from the Copernicus Browser, accessible at:
661 <https://browser.dataspace.copernicus.eu>.
662 The images selected correspond to dates closest to in-situ sampling. In cases where
663 satellite overpass or high cloud cover prevented acquisition on the exact sampling date,
664 the nearest available image was used (see Supplementary Table S6 for the date list).
665 Images were pre-processed using ESA's SNAP software (v.11.0.0) (software available
666 at: <https://step.esa.int/main/toolboxes/snap>), including subsetting to the area of interest
667 and resampling to a spatial resolution of 20 m. This processing step follows previous
668 findings showing that 20 m resolution provides more stable and accurate water quality
669 estimates from Sentinel-2 images⁶¹. The actual processing of the images included the
670 atmospheric correction followed by the retrieval of two water constituents, CHL and TSM,
671 as well as CDOM absorption at 443 nm. These parameters were retrieved using two
672 distinct methods, each based on different algorithms and coefficients (see Supplementary
673 Table S7):

- 674 ▪ The Case 2 Regional Coast Colour processor (C2RCC), developed by⁶² and
675 integrated within SNAP, applies a two-step neural network inversion approach.
676 First, atmospheric correction is performed by estimating top-of-atmosphere (TOA)
677 radiance contributions (e.g. water vapor, aerosols), followed by the inversion of
678 surface reflectance to derive inherent optical properties (IOPs) of the water column.
679 Neural networks are trained using an extensive dataset (million of simulations)
680 based on radiative transfer model that covers a wide range of IOPs^{62,63}, including
681 pigment absorption (a_{pig}), detrital absorption (a_{det}), CDOM absorption
682 (a_{gelb}), and also scattering by both sediment (b_{part}) and calcareous particles
683 (b_{wit}). Three variants of the model were applied, allowing the processor to adapt
684 to a broad variety of water conditions. Specifically, the suite of C2RCC neural
685 networks (collectively referred to here as "C2Nets") includes: i) C2RCC, optimized
686 for mesotrophic and moderately turbid coastal waters; ii) C2X, designed for highly
687 turbid or extreme optical conditions; and iii) C2XCOMPLEX, targeting optically
688 complex waters with intermediate turbidity levels. All three variants were tested to
689 evaluate their performance under the extreme conditions caused by the flood event.
690
691 ▪ ACOLITE (software available at: <https://github.com/acolite/acolite>, version
692 20231023.0) was also employed for atmospheric correction, applying the Dark
693 Spectrum Fitting (DSF) algorithm, which estimates aerosol optical thickness and
694 path reflectance through dynamic dark pixel selection⁶⁴. ACOLITE is particularly
695 suited for turbid and optically complex waters, providing robust correction under

highly dynamic aquatic conditions. In addition to atmospheric correction, ACOLITE offers a suite of empirical and semi-analytical algorithms (see the full list in Supplementary Table S7) to estimate chlorophyll-a (CHL), turbidity (expressed in Formazin Nephelometric Units, FNU), and total suspended matter (TSM, in g/m^3) from remote sensing reflectance (R_{rs}). While turbidity is an optical parameter related to water clarity, TSM represents the actual concentration of suspended particulate matter. In this study, TSM algorithms were prioritized to ensure direct comparability with in situ TSM gravimetric measurements.

To further assess the potential of ready-to-use satellite products, we also employed data from Sentinel-3, which carries the Ocean and Land Colour Instrument (OLCI), specifically designed for marine and inland water monitoring, among other applications. OLCI is equipped with 21 spectral bands spanning the visible to near-infrared (VIS–NIR) regions, enabling the detection of key water quality parameters at large spatial scales. The OLCI Water Full Resolution (WFR) products are Level-2 outputs providing remote sensing reflectance (R_{rs}) and derived biogeophysical parameters such as CHL and TSM and they are available at: <https://browser.dataspace.copernicus.eu>. These products are generated through ESA's operational processing chains using standard algorithms (see Supplementary Table S7 for a full list of algorithms). OLCI WFR products offer a native spatial resolution of 300 meters, which, while coarser than Sentinel-2, provides the advantage of high temporal coverage and consistent processing standards, making them valuable for large-scale or regional monitoring. Once the Level-2 products were obtained, a match-up analysis was performed between satellite-derived estimates from each

algorithm and the corresponding in-situ measurements. This was conducted separately for the products derived from Sentinel2 (C2Nets-derived and ACOLITE-derived products) and Sentinel-3 OLCI. For each product and acquisition date, a 3x3 pixel window centered on the GPS coordinates of each sampling station was extracted. Within each window, quality flags were analyzed to exclude unreliable pixels, thereby ensuring data quality. Subsequently, the remaining pixel values were averaged to derive a representative satellite-based estimate for comparison with laboratory measurements. To quantitatively evaluate the satellite-derived estimates against in-situ reference measurements, three statistical metrics commonly used for the validation of remote sensing products were employed: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Bias.

6 Data availability (mandatory)

The data that support the findings of this study are available from the corresponding authors upon reasonable request. The datasets will be made publicly available via Zenodo upon request by the journal reviewers or upon acceptance for publication.

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Author contributions

F.C., E.F., B.M.S.G., N.G., L.P., S.S. and P.V. contributed to the conceptualization, methodology, and project administration of the study.

Formal analysis was carried out by B.M.S.G., N.G., L.P., P.V., R.B., A.P., M.L.T., and C.L.

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R.B. and C.C. prepared the original draft. All authors contributed to the review and editing of the manuscript and approved the final version.

These authors jointly supervised this work: F.C., E.F., B.M.S.G., N.G., L.P., S.S. and P.V.

Competing interests

The authors declare no competing interests.

How resilient are inland and marine environments to extreme events? 2023 Emilia-Romagna flood insights

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Abstract

This study uses an integrated and multidisciplinary approach to assess the short- and medium-term effects of 2023 Emilia-Romagna (Italy) flood on inland and marine environments and their recovery capability. To capture the evolution of post-flood conditions, three monitoring campaigns were conducted: (i) immediately after the flood (late May), (ii) approximately after one month (mid-June), and (iii) after five months (early October). During each campaign, we characterized rivers and coastal marine waters by combining in-situ measurements of abiotic and biotic parameters with eDNA-based community assessment, emerging contaminant analyses, and satellite-derived data. Despite the large spatial extent and intensity of the disturbance affecting the entire river-to-coast continuum, most parameters showed partial to near-complete recovery within five months, evidencing strong system resilience. The lack of pre-event baselines constrains precise impact assessment, underscoring the need for long-term, standardized monitoring frameworks that integrate innovative tools to capture environmental consequences of extreme events and evaluate coastal vulnerability.

1 Introduction

Extreme weather events are becoming increasingly frequent and severe, driven by the accelerating effects of climate change. Among these events, flooding is one of the most devastating¹. Floods, categorized into riverine, coastal, urban, and flash types, are caused by prolonged rainfall, rapid storm surges, or the overflow of rivers and streams beyond their banks^{2,3}. Urbanization and land-use changes in inland areas significantly contribute to coastal vulnerability by increasing sediment transport, altering water quality, and disrupting hydrological cycles⁴. These events not only impact terrestrial and aquatic environments but also mobilize pollutants toward downstream areas, altering biogeochemical dynamics and amplifying stress on coastal ecosystems^{5,6}. Excessive nutrient concentrations and terrestrial organic matter from river inputs often lead to harmful algal blooms⁷, hypoxia, and eutrophication, particularly in semi-enclosed seas^{8,9}. These nutrients enhance primary production in surface waters, increasing the deposition of organic matter to sediments, where its decomposition further depletes oxygen levels^{10,11}. Floodwaters also act as vectors for anthropogenic contaminants, including pesticides, heavy metals, and contaminants of emerging concern (CECs) which include perfluorinated compounds, plasticizers, additives (e.g., bisphenol A) and pharmaceuticals. The altered redox conditions during flood-induced deoxygenation events can increase the mobility and toxicity of these pollutants, with profound implications for aquatic ecosystems, water quality, and human health^{12–14}. Among CECs, pharmaceuticals are of increasing relevance, particularly considering their potential mobilization during extreme hydrological events. Recent studies suggest that

intense rainfall and associated sewer overflows may exacerbate pharmaceutical inputs into sensitive coastal environments, raising concern for the health of aquatic ecosystems under climate change scenarios¹⁵. The monitoring after extreme events generally involves the assessment of the immediate and direct impacts on urban infrastructures, ecosystems, and human health. However, understanding the complex interplay between extreme flood events and their visible and unseen cascading effects on coastal and marine ecosystems is crucial but understudied. The short- and long- term monitoring of unseen impacts such as shifts in biological communities, the spread of contaminants (such as CECs), or delayed biological responses often go undetected by routine monitoring but it can be significant for predicting ecosystem resilience, informing coastal management strategies, protecting biodiversity, preventing ecological degradation, economic losses (e.g., fisheries, tourism), and health risks related to water quality.

Between early May (1st – 4th) and mid-May (16th – 17th) 2023, the Emilia-Romagna region in northern Italy, experienced two extreme meteorological events that led to catastrophic flooding, landslides, and widespread destruction^{16–18}. The May 2023 events, described as "unprecedented" in the region's hydrological history, resulted from the convergence of extreme meteorological and hydrological conditions¹⁹. Rainfall return' periods exceeded 100 years in many areas, reaching over 500 years in the most affected zones. The first event was caused by a polar low-pressure system that stalled over central Italy, resulting from the convergence of moist air masses from the Adriatic Sea and cold bora winds from the north. This interaction, intensified by orographic effects from the Apennine Mountains, led to over 200 mm of rainfall in 48 hours in some areas. Two weeks later, a second low-

pressure system exacerbated the crisis, producing even more intense rainfall, up to 240 mm in localized areas, exceeding historical records. Together, these events brought an estimated $350 \times 10^6 \text{ m}^3$ of water, equivalent to six months of average rainfall within a remarkably short period²⁰. Rivers across Emilia-Romagna experienced record-breaking floods that breached embankments at 23 locations and flooded over 540 km² of lowlands. Among the most impacted areas were the city of Ravenna and its surrounding, the catchments of the Lamone, Montone, Ronco, Savio rivers, and the tributaries of the Destra Reno canal (**Error! Reference source not found.**). Along the Adriatic coastal areas, storm surges worsen the flooding by slowing the drainage of floodwaters. The drainage infrastructure, with its narrow embankments not designed to handle this excess water, failed to discharge water to the sea efficiently and, in some cases, water stagnated on crops and cities for several days after the event. In the Apennine region, prolonged saturation triggered nearly 66,000 landslides, disrupting critical infrastructure and isolating several communities. The impacts of this extreme event are well documented. Entire communities were forced to evacuate with 17 deaths and 36,600 evacuees; farmlands were flooded, leading to the destruction and contamination of crops²¹ and death of livestock, while urban areas suffered significant structural damage²². The floods also caused significant environmental impacts²³. Floodwater transported large quantities of sediments, organic matter, and pollutants into the surface water bodies (rivers and drainage networks), eventually reaching the Adriatic Sea. This led to algal blooms, the death of aquatic organisms²⁴, and severe impacts on the local economy.

103 Beyond these impacts, the study aims to assess additional direct and indirect effects on
104 inland and marine waters that were not captured by standard routine monitoring
105 conducted according to major legislative protocols following the May 2023 flood event.
106 Here, a multidisciplinary and integrated protocol is applied to analyze geochemical,
107 environmental, and biological factors, providing a comprehensive understanding of the
108 flood short- and medium- term impacts, and assessing the intrinsic recovery capacity of
109 the system. The approach includes analyses to assess abiotic and biotic parameters,
110 analyzing also protist communities using environmental DNA (eDNA) metabarcoding, and
111 estimating emerging contaminants, along with evaluating remote sensing capacity to
112 assess the marine water quality. The study offers a holistic understanding of complex
113 environmental phenomena and bridges a significant knowledge gap by providing new
114 insights into the interconnected impacts of human-driven disasters on the environment.
115 Our findings show how key physical, chemical, and biological parameters respond to
116 system perturbation caused by the flood event, and underscore the importance of high-
117 resolution, integrated monitoring across terrestrial and marine environments to effectively
118 assess the dynamics and impacts of extreme hydrological events.

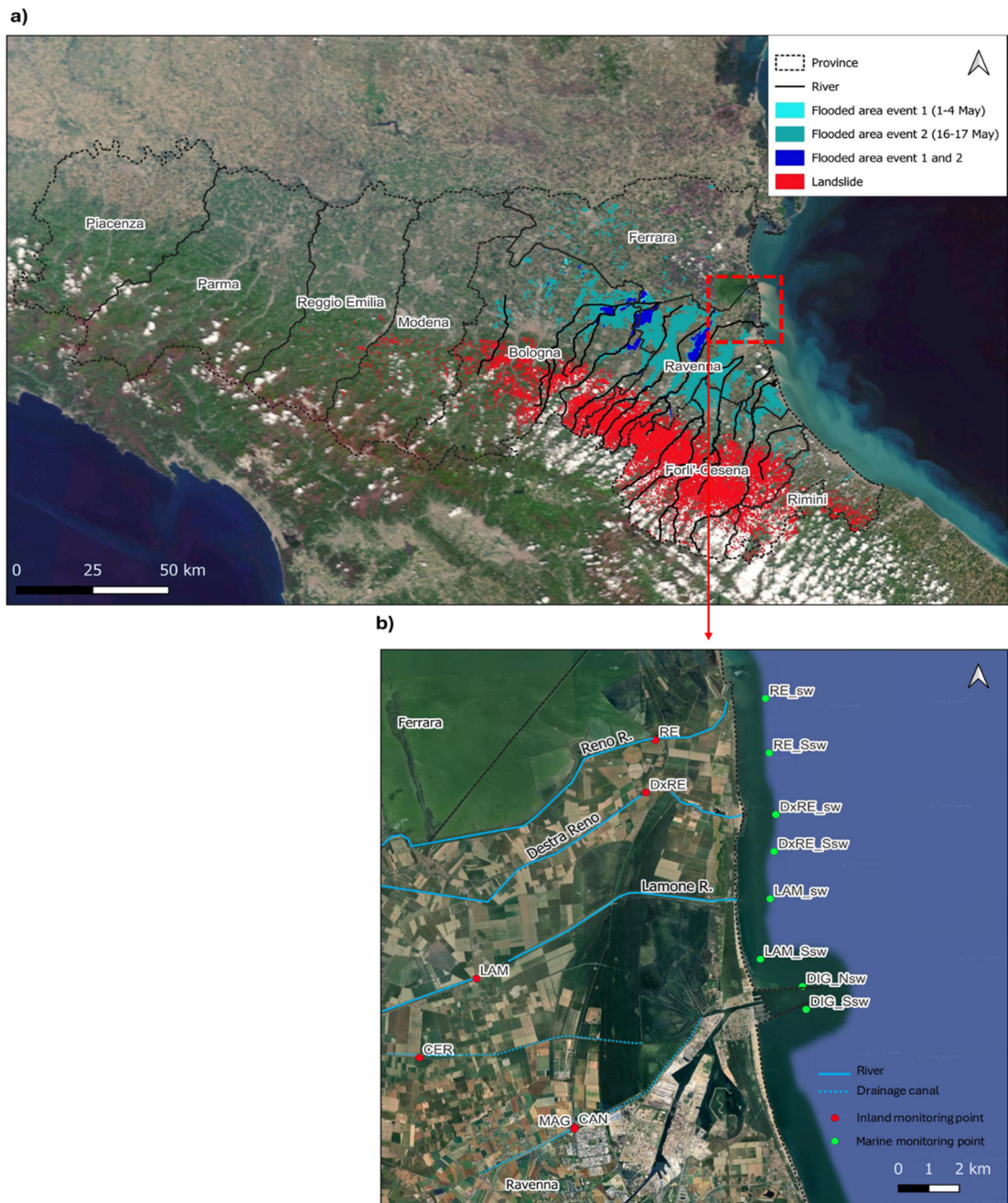


Figure 1 | Areas affected by floods and landslides in May 2023 and location of the study area. a | Rivers (black) and areas of the Emilia Romagna region affected by landslides (red), and floods during the first (light blue), second (green), or both (dark blue) floods. (Data source: Emilia-Romagna data geoportal; base map: European Union, Copernicus Sentinel-2 imagery, date 05/05/2023); **b |** Inland (red) and marine (green) monitoring points selected along the main rivers and drainage channels involved in the flood.

2 Results

Following the flood event in May 2023, significant variations were recorded across all measured environmental parameters (Figure 2).

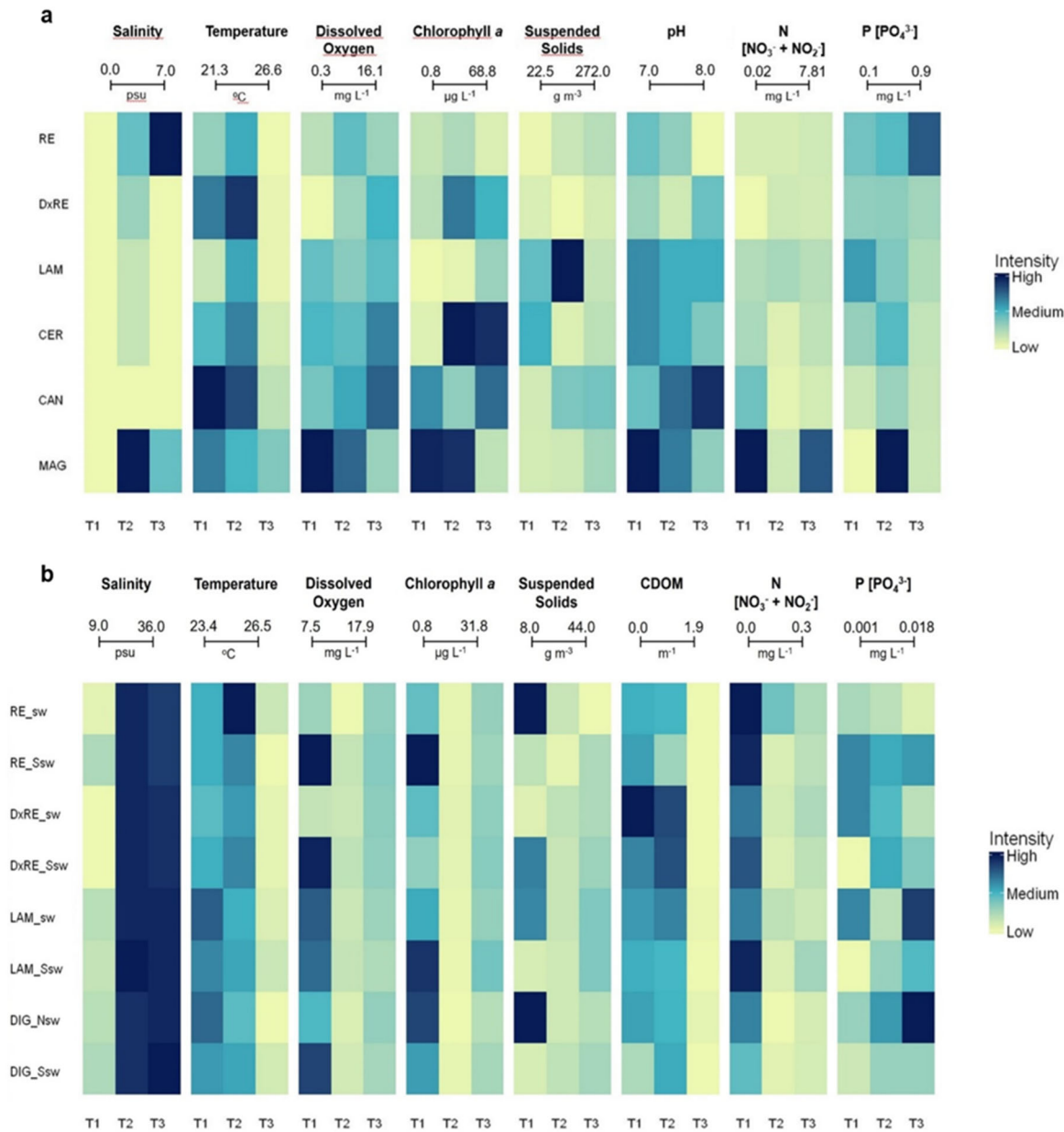


Figure 2 | Heatmap of environmental parameters of inland and marine monitoring points. a | River and canal sampling stations; b | marine sampling stations. Data were normalized per parameter to allow for consistent comparison.

129 Water temperature (T) followed a typical seasonal trend, with maximum value in summer
130 (26.6 °C in June) and minimum with the start of the fall season (21.3 °C in October). Sea
131 salinity (S) dropped markedly due to the freshwater influx from the flood, with a minimum
132 of 9.0 psu at RE_sw and DxRE_sw in May. By October, salinity had returned to typical
133 marine values (~35 psu; Figure 2b). Dissolved oxygen (DO) showed anoxic conditions
134 following the flood (May) in DxRE and reached post-flood minima in June, both at inland
135 (0.3 mg L⁻¹ at DxRE) and marine station (5 mg L⁻¹ RE_sw), reflecting elevated biological
136 oxygen demand.

137 Microalgal pigment concentrations revealed distinct spatial dynamics. Marine stations
138 showed an immediate post-flood chlorophyll-a (CHL) peak in May (up to 31.8 µg L⁻¹ at
139 RE_Ssw), followed by a sharp decline in June and partial recovery by October. This
140 recovery aligns with historical monthly and annual averages observed during Arpae inland
141 monitoring data^{25,26}. Phaeopigments mirrored this trend, with the lowest values in June
142 (0.001 µg L⁻¹ at DIG_Ssw). In contrast, inland stations (Figure 2a) showed delayed CHL
143 and phaeopigment peaks in June, followed by declines by October, indicating enhanced
144 degradation of pigments in the weeks following the event.

145 Suspended and dissolved materials also reflected flood-related dynamics. Total
146 Suspended Matter (TSM) increased from May to June at inland stations (maximum of
147 272.0 g m⁻³ at CAN), indicative of sediment input and resuspension. Marine responses
148 were variable, with some stations increasing in May (e.g., RE_sw, DIG_Nsw) and others
149 in June (e.g., DxRE_sw, LAM_Ssw), but most returned to near-initial levels by October.

150 Colored Dissolved Organic Matter (CDOM) increased in May due to terrestrial runoff,
151 remained stable in June, and declined sharply by October, often below detection
152 thresholds, at inland stations.

153 Nutrient concentrations displayed clear flood-driven dynamics. Nitrogen (N) spiked
154 immediately after the event in May with an increasing north-south gradient at inland
155 stations as a result of flood-induced runoff, decreased sharply by June, and partially
156 rebounded by October. Marine nitrogen values followed a similar but opposite (i.e.,
157 decreasing north-south) trend, although at lower concentrations. Phosphorus (P) showed
158 more variable patterns: inland values generally increased in June, while marine
159 concentrations remained low, with slight increases by October.

160 These results confirm immediate and pronounced flood-driven changes in environmental
161 parameters, highlighting spatial variability and different recovery trajectories between
162 inland and marine environments. To quantitatively highlight the magnitude of the
163 environmental alterations observed during the 2023 flood event, we compared our
164 observations with historical baseline data from Arpae (2010–2022). Although limited to
165 three inland monitoring stations (RE, DxRE, and LAM), for which historical numerical
166 datasets are available, this comparison underscores the exceptional nature of the
167 recorded anomalies. Several parameters (T, EC, DO, pH, and nutrients) measured during
168 and after the flood exceeded the historical range documented over the previous decades
169 (Figure 3); particularly divergent were DO, pH, and P.

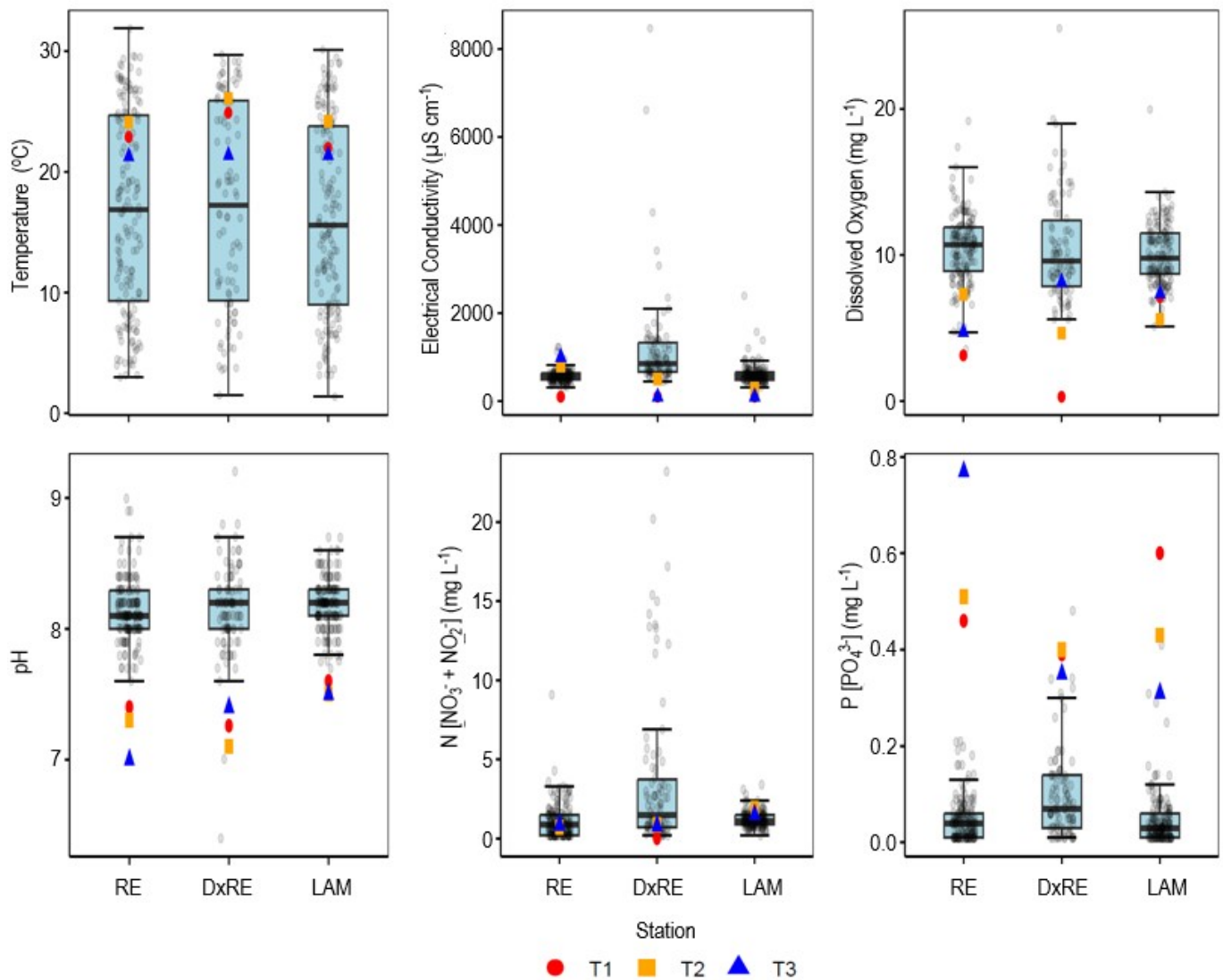
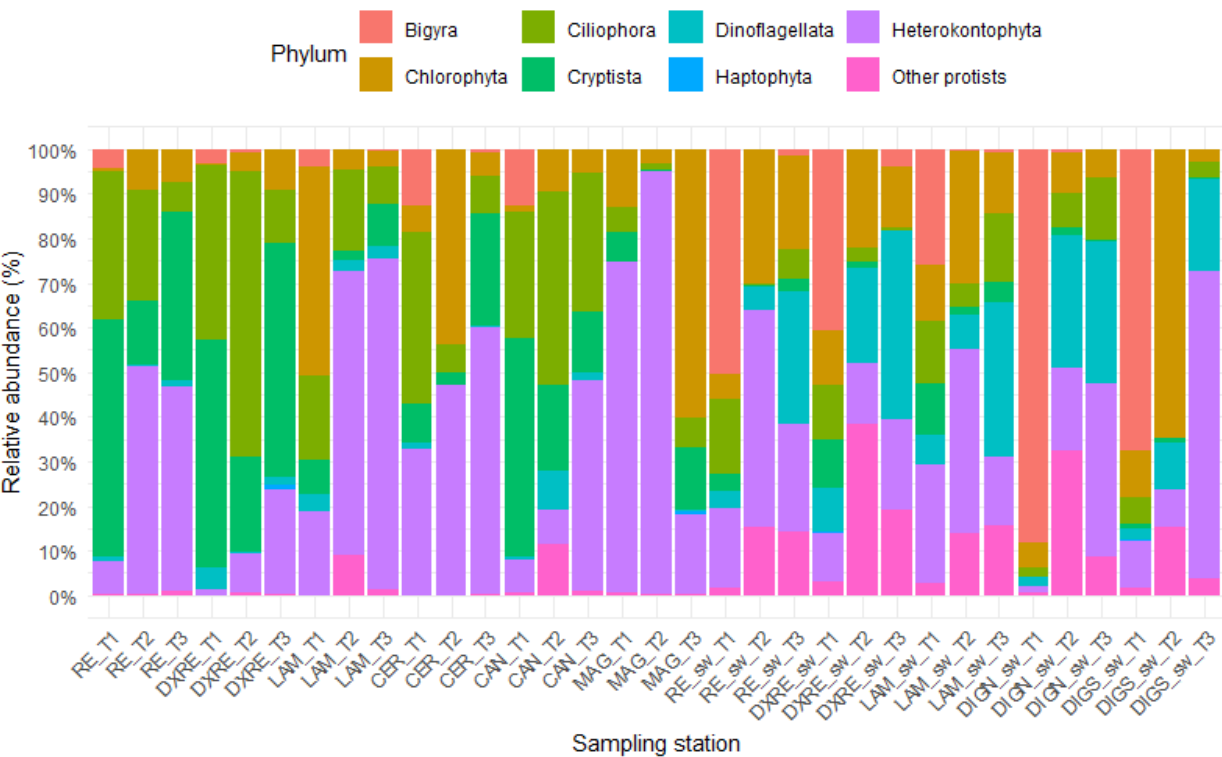


Figure 3 | Comparison of environmental parameters measured during the 2023 flood event with historical baseline data (2010–2022; boxplots) from ARPAE inland monitoring stations RE, DxRE, and LAM. | Panels show:
a | temperature ($^{\circ}\text{C}$), b | electrical conductivity ($\mu\text{S cm}^{-1}$), (c) dissolved oxygen (mg L^{-1}), (d) pH, (e) dissolved inorganic nitrogen ($\text{NO}_3^- + \text{NO}_2^-$) (mg L^{-1}), and (f) dissolved inorganic phosphorus (PO_4^{3-}) (mg L^{-1}). Historical data distributions are displayed as boxplots, while colored symbols indicate the 2023 post-flood sampling periods. Note the pronounced deviations recorded during the flood event, indicative of substantial environmental alterations.

178 **Protist communities**

179 The eDNA metabarcoding analysis of protist community composition revealed clear
180 differences between freshwater and marine sampling stations. After data filtering, seven
181 main phyla were identified and are shown in Figure 4.



182 **Figure 4 | Relative abundance (%) of protist communities at the phylum level across sampling stations and**
183 **time points, based on eDNA metabarcoding.**

184 Taxa belonging to non-photosynthetic groups were collectively assigned to "Other
185 protists", except for Ciliophora, which were represented separately to highlight their
186 marked post-flood increase in abundance. A total of 74 taxa were detected, distributed
187 across 29 different classes, whose relative abundances are provided in Supplementary
188 Figure S1.

Inland stations were predominantly characterized by high abundances of Heterokontophyta (mainly diatoms), Cryptista, Ciliophora, and Chlorophyta. Conversely, marine stations exhibited higher diversity, dominated mainly by Heterokontophyta and Dinoflagellata. Immediately following the flood (May, T1), marine stations experienced an influx of freshwater-associated taxa, particularly Bigyra, Chlorophyta, and Ciliophora, reflecting freshwater intrusion. This anomaly diminished notably by subsequent sampling periods (June T2 and October T3), as typical marine taxa (Dinoflagellata and Heterokontophyta) progressively increased, signaling ecological recovery to normal conditions. Indeed, these observations align with typical seasonal phytoplankton assemblages reported in the Arpae annual inland monitoring reports, which serve as a reference for expected marine community conditions during this period. To examine how environmental variables drove the observed community patterns, we performed a redundancy analysis (RDA) using S, T, DO, TSM, and nutrients (N and P) as constraining variables (Figure 5). The first two RDA's axes explained 31.7% of the variance in the community structure, with RDA1 (21.4%) separating freshwater and marine stations based on S, DO, total N and P, and TSM, and RDA2 (10.3%) capturing temporal variation associated primarily with water temperature.

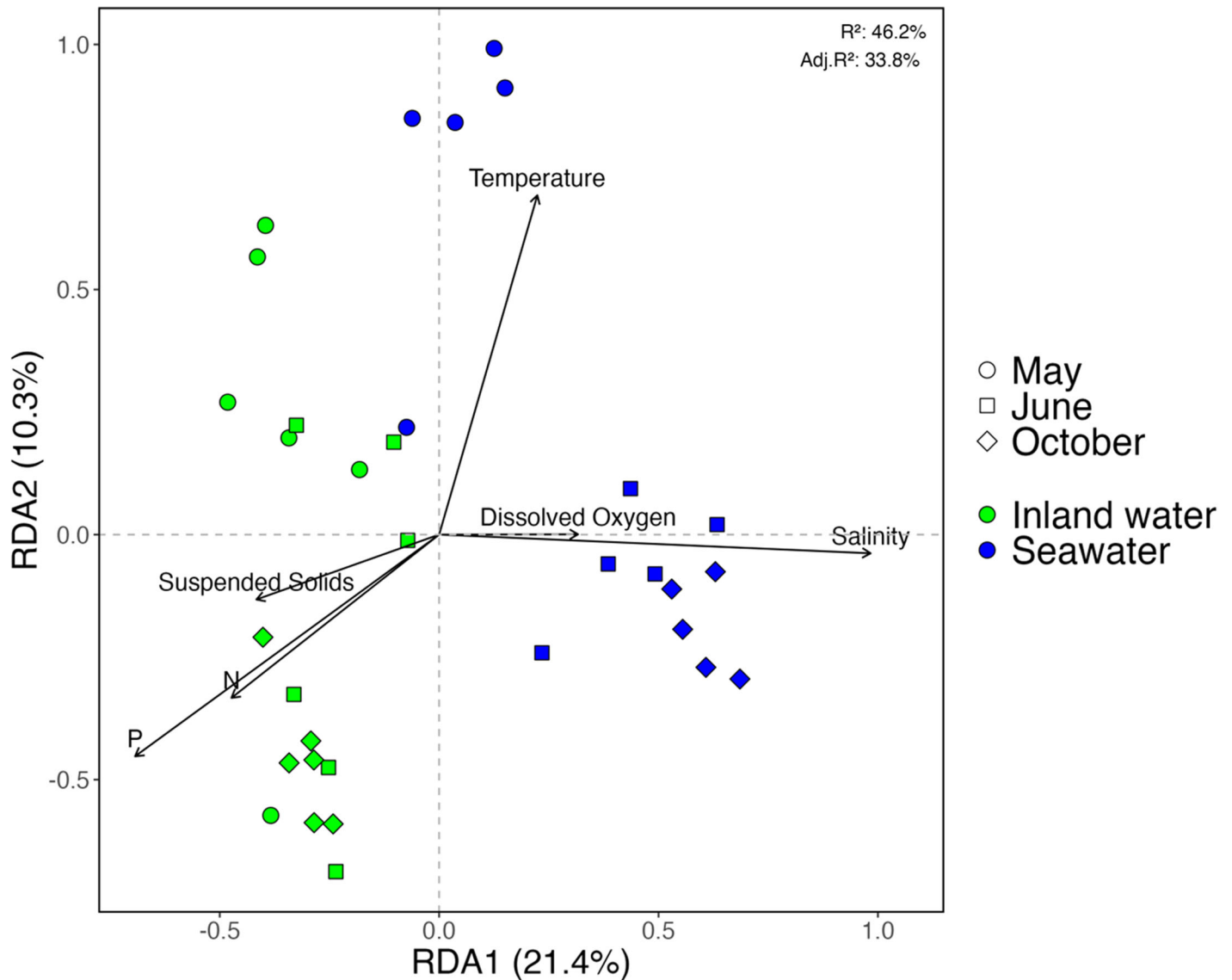


Figure 5 | Redundancy Analysis (RDA) showing the relationship between phytoplankton community structure and environmental variables across sampling stations. Arrows represent the direction and strength of environmental gradients.

ANOVAs confirmed that all environmental predictors significantly influenced the communities composition (S: $p < 0.001$; T: $p < 0.01$; DO: $p < 0.01$; TSM, N, P: all $p < 0.05$; Table 1). Inland samples were more dispersed immediately after post-flood (May–June), becoming clustered by October, reflecting gradual stabilization. These patterns indicate

a strong environmental disturbance driven by the flood event, followed by a clear trend toward recovery and resilience in the subsequent months.

Table 1 | Results of ANOVAs testing the influence of each environmental variable on protist community structure based on redundancy analysis (RDA). | All predictors significantly influenced community structure, with S, T, DO, TSM, total N and P showing varying degrees of explanatory power. Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Terms	Df	Variance	F	Pr(>F)	
S (psu)	1	0.0811	6.3741	0.0001	***
T (°C)	1	0.0352	2.7704	0.004	**
DO (mg L ⁻¹)	1	0.0302	2.3735	0.0097	**
TSM (g m ⁻³)	1	0.0272	2.1362	0.0117	*
N (mg L ⁻¹)	1	0.0261	2.0504	0.0202	*
P (mg L ⁻¹)	1	0.0313	2.4605	0.0032	**
Residual	26	0.3308			

Contaminants of emerging concern (CECs)

Chemical analyses via LC-MS/MS revealed widespread contamination by contaminants of emerging concern (CECs), particularly Bisphenol A (BPA) and pharmaceutical compounds (Figure 6; see Supplementary Tables S1–S2 for the full list). BPA was detected in all samples, ranging from 0.72 to 77.85 ng L⁻¹. The highest BPA concentrations occurred at the inland riverine station RE in October (77.85 ng L⁻¹), while other inland stations (DxRE: 28.15 ng L⁻¹, LAM: 22.25 ng L⁻¹, MAG: 9.4 ng L⁻¹) showed peak values immediately post-flood (T1, May), declining thereafter. On the other hand,

229 marine stations consistently recorded lower BPA levels, with clear decreasing trends
230 post-flood (e.g., RE_sw: 4.25 ng L⁻¹ in May, declining to 1.85 ng L⁻¹ in October).

231 Pharmaceutical contamination, dominated by anti-inflammatory drugs (e.g., Ketoprofen,
232 Diclofenac, Ibuprofen, Naproxen), diuretics, and antipyretics (see the full pharmaceuticals
233 list in Supplementary Table S2), showed notable spatial variability. Inland station MAG
234 displayed extremely high total pharmaceutical concentrations in May (395.98 ng L⁻¹),
235 significantly decreasing in June (42.83 ng L⁻¹), then rebounding by October (395.77 ng L⁻¹
236 ¹). Other inland stations (RE, LAM, DxRE) exhibited similarly elevated contamination in
237 May (RE: 72.24 ng L⁻¹, LAM: 70.62 ng L⁻¹, DxRE: 27.33 ng L⁻¹), decreasing in subsequent
238 months. Marine stations consistently demonstrated lower pharmaceutical concentrations,
239 exhibiting gradual temporal decreases (e.g., RE_sw: 24.95 ng L⁻¹ in May to 10.45 ng L⁻¹
240 in October).

241 Overall, a decreasing trend of contamination from inland towards seawater has been
242 documented in other reports^{27,28}. Data also highlights a contamination decrease from May
243 to October in marine stations. Differently, an increase in BPA concentrations is observed
244 in the Reno river, which was not directly involved in the flooding, possibly due to seasonal
245 fluctuations.

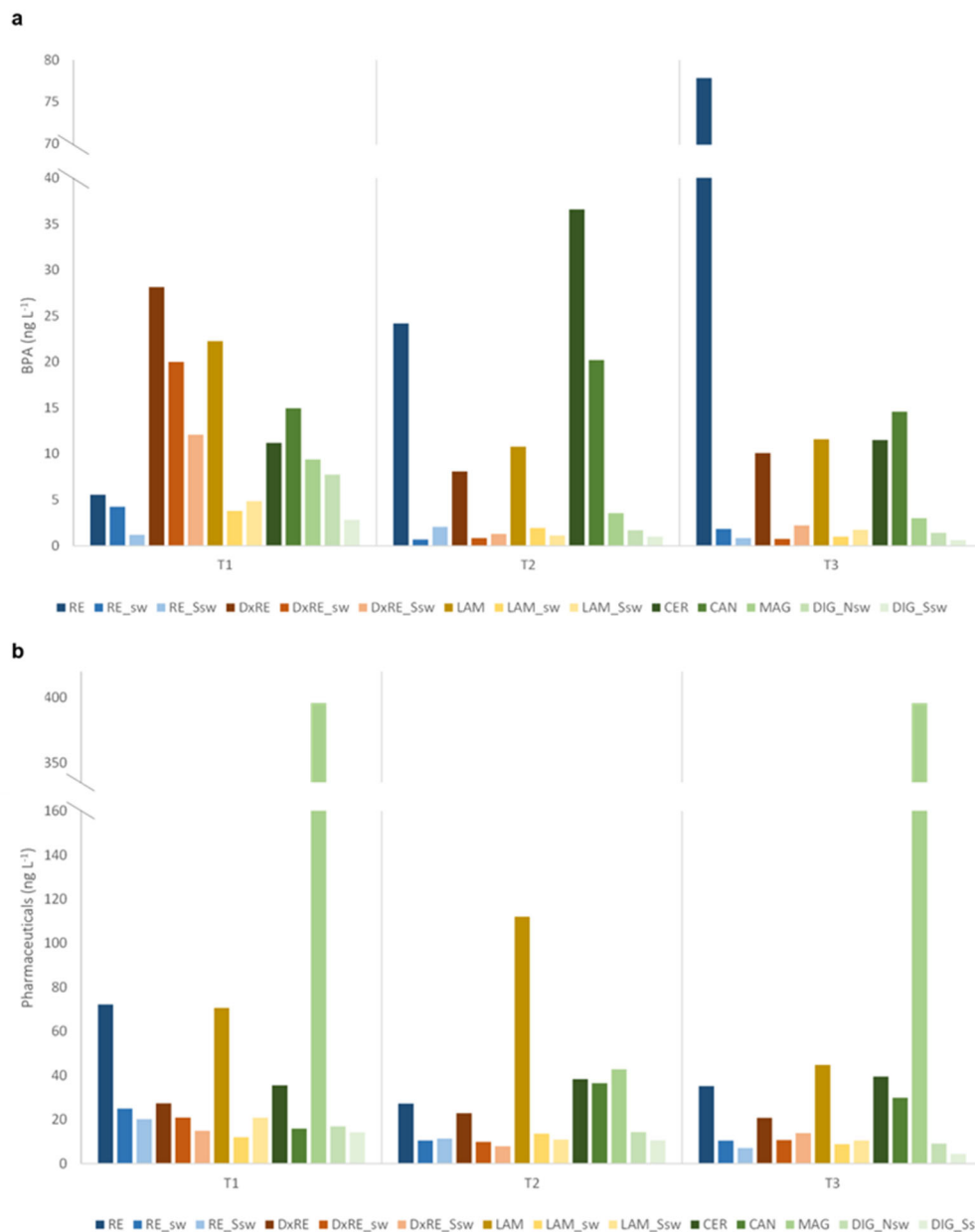


Figure 6 | Emerging contaminants measured in water samples collected during three campaigns in 2023. a | Bisphenol A. b | the sum of the seven pharmaceuticals tested. Limit of quantification (ng L⁻¹) and relative standard deviation (RSD %) (n=3) for each compound analyzed are indicated in Materials and Methods.

Remote Sensing and Image-Based Water Quality

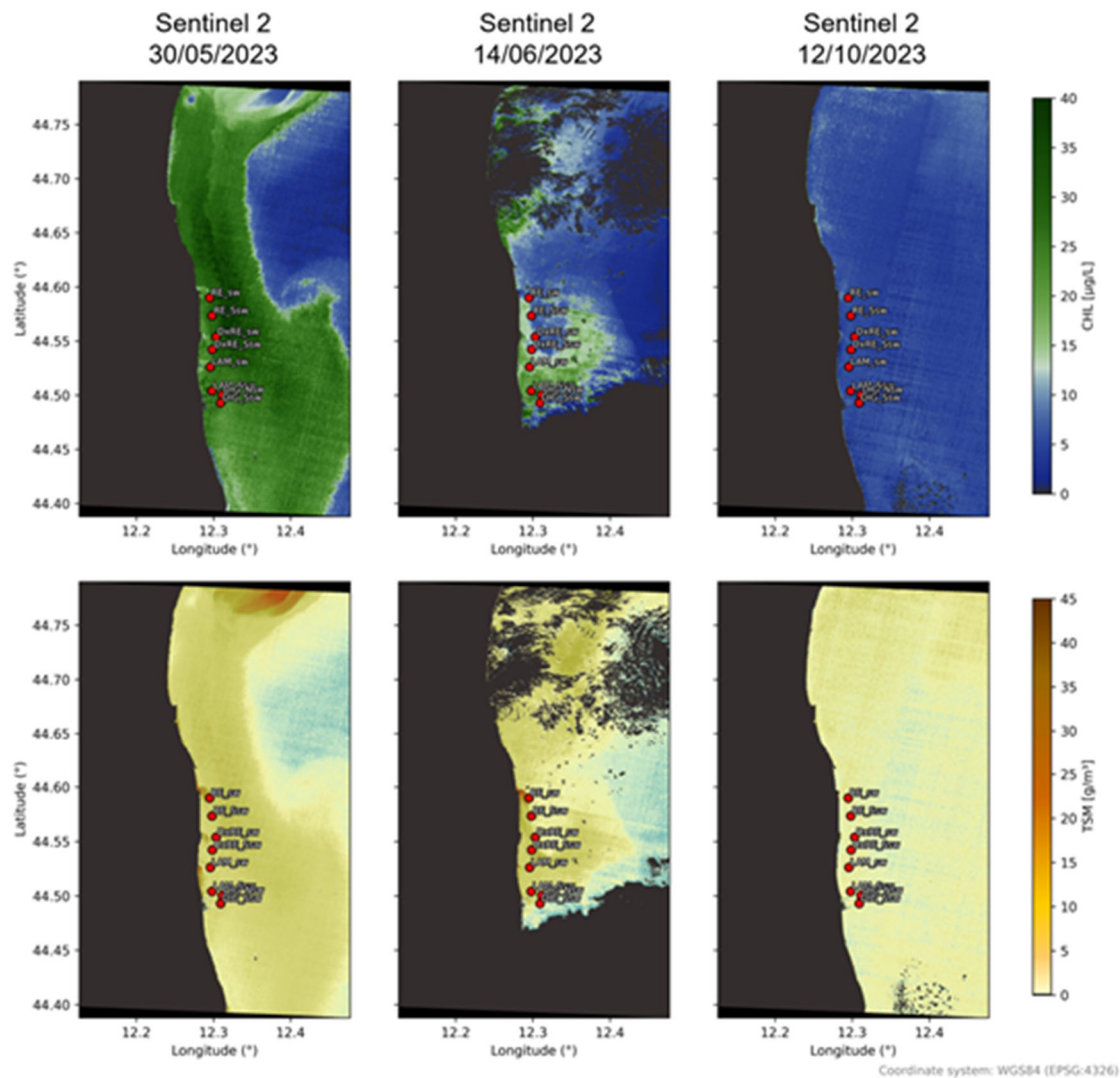
We evaluated the performance of both on-board Sentinel-3 OLCI and semi-operational Sentinel-2 water quality retrievals (via ACOLITE and C2Nets) against in situ measurements of CHL and TSM during the key post-flood periods. Only the best-performing algorithms for each date and sensor are summarized in Table 2, based on MAE% relative to in situ means. Full performance metrics for all tested algorithms are reported in Supplementary Tables S3 (CHL) and S4 (TSM).

Table 2 | Summary of the best-performing algorithms for chlorophyll-a (CHL, in $\mu\text{g L}^{-1}$) and total suspended matter (TSM, in g m^{-3}) retrieval from Sentinel-2 and Sentinel-3 imagery. | MAE% and RMSE% were calculated relative to the average of *in situ* measurements. See Supplementary Tables S3–S4 for a full comparison of all algorithms tested.

Date	Parameter	Sensor	Spatial Resolution (m)	Processor - Product	Algorithm	In-Situ min-max	Estimated min-max	MAE	RMSE	Bias
May 2023	CHL	Sentinel 2	20	C2Nets	C2XCOMPLEX	10.3 - 31.8 $\mu\text{g L}^{-1}$	19.0- 28.5 $\mu\text{g L}^{-1}$	34.3% (6.8 $\mu\text{g L}^{-1}$)	41.3% (9.2 $\mu\text{g L}^{-1}$)	4.9
				ACOLITE	chl_oc3		16.7 -24.8 $\mu\text{g L}^{-1}$	31.8% (6.3 $\mu\text{g L}^{-1}$)	36.3% (7.2 $\mu\text{g L}^{-1}$)	-0.5
	TSM	Sentinel 2	20	C2Nets	C2X	11.0 - 44.0 g m^{-3}	10.7 - 16.9 g m^{-3}	53.6% (13.2 g m^{-3})	73.1% (18.0 g m^{-3})	-11.7
					C2XCOMPLEX		8.8 - 14.8 g m^{-3}	57.7% (14.2 g m^{-3})	78.4% (19.3 g m^{-3})	-13.5
June 2023	CHL	Sentinel 2	20	ACOLITE	chl_oc2	0.8 - 2.1 $\mu\text{g L}^{-1}$	4.2 - 7.9 $\mu\text{g L}^{-1}$	243.6%(3.8 $\mu\text{g L}^{-1}$)	262.8%(4.1 $\mu\text{g L}^{-1}$)	3.8
		Sentinel 3 OLCI	300	SENTINEL 3 WFR	chl_nn		2.8 - 6.1 $\mu\text{g L}^{-1}$	179.5% (2.8 $\mu\text{g L}^{-1}$)	185.9% (2.9 $\mu\text{g L}^{-1}$)	2.8
	TSM	Sentinel 2	20	C2Nets	C2X	9.0 - 14.0 g m^{-3}	7.5 - 15.7 g m^{-3}	18.4% (2.3 g m^{-3})	25.6% (3.2 g m^{-3})	-0.1
					C2XCOMPLEX		5.9 - 12.4 g m^{-3}	21.6% (2.7 g m^{-3})	26.4% (3.3 g m^{-3})	-2.3
October 2023	CHL	Sentinel 2	20	C2Nets	C2XCOMPLEX	6.9 - 13.0 $\mu\text{g L}^{-1}$	5.0 - 11.0 $\mu\text{g L}^{-1}$	19.1% (1.8 $\mu\text{g L}^{-1}$)	26.5% (2.9 $\mu\text{g L}^{-1}$)	-1.6
		Sentinel 2		ACOLITE	chl_re_gons		7.2 - 13.5 $\mu\text{g L}^{-1}$	20.1% (1.9 $\mu\text{g L}^{-1}$)	24.4% (2.3 $\mu\text{g L}^{-1}$)	0.9
	TSM	Sentinel 2	20	C2Nets	C2X	8.0 - 21.0 g m^{-3}	6.6 - 12.9 g m^{-3}	49.1% (8.1 g m^{-3})	55.2% (9.1 g m^{-3})	-8.1
		Sentinel 3 OLCI	300	SENTINEL 3 WFR	tsm_nn		3.0 -12.7 g m^{-3}	56.4% (9.3 g m^{-3})	63.0% (10.4 g m^{-3})	-8.9

263 In May, under highly turbid, flood-affected waters, Sentinel2 algorithms performed best.
264 The ACOLITE *chl_oc3* model delivered the lowest MAE of 31.8 % (RMSE 36.3 %, bias
265 -0.5), closely followed by C2Nets' neural-network variant *C2XCOMPLEX* (MAE 34.3 %,
266 bias +4.9). For TSM, C2X again captured the flood-induced particulate peak, with MAE
267 of 53.6 % and moderate underestimation (bias -11.7), showing robustness in extreme
268 optical conditions. By June, when turbidity began declining, Sentinel3 OLCI *chl_nn*
269 achieved slightly better CHL estimates (MAE 179.5 %) than Sentinel2's *chl_oc2* (MAE
270 243.6 %), yet the coarse 300 m resolution obscured important near-shore heterogeneity.
271 TSM retrieval remained accurate via C2X (MAE 18.4 %, bias -0.1), reflecting improved
272 water clarity but still substantial residual load. By October, both C2Nets' *C2XCOMPLEX*
273 (MAE 19.1 %) and ACOLITE's *chl_re_gons740* (MAE 20.1 %) produced reliable CHL
274 estimates, with low RMSE and near-zero bias, indicating stabilization of water optics. C2X
275 continued to be the preferred model for TSM (MAE 49.1 %, bias -8.1), although accuracy
276 improved in line with environmental recovery. Bias trends further reinforce these findings:
277 ACOLITE's *chl_oc3* consistently underestimated CHL, contrasted with *chl_re_gons740*,
278 which corrected its initial positive bias to become unbiased by October. Meanwhile, C2X
279 and *C2XCOMPLEX* exhibited stable, moderate biases throughout the campaign.
280 Additionally, we compared satellite-derived estimates of CDOM absorption (a_{cdom} at
281 443nm) with laboratory measurements, where available. Since only the C2Nets
282 framework and Sentinel-3 OLCI WFR currently offer CDOM retrievals from satellite
283 imagery, this comparison was limited to a subset of algorithms and dates. The results
284 indicated substantial overestimations and high error levels, suggesting limited reliability

285 over the test period. Given the exploratory nature and limited accuracy of these outputs,
286 CDOM retrieval metrics are presented exclusively in Supplementary Table S5. Spatial
287 distribution maps (Figure 7) show a clear temporal decline in both CHL and TSM
288 concentrations across marine areas, consistent with in-situ observations.



289 **Figure 7 | Maps are generated with the C2X processor (C2RCC plugin, SNAP) from Sentinel-2 imagery. |**
290 **Chlorophyll-a (CHL, $\mu\text{g L}^{-1}$). b) Total Suspended Solids (TSM, g m^{-3}). Dates of acquisition are shown above each panel.**
291 **Sampling points are marked in red. The 20 m maps were first masked with the Land/Sea Mask operator, retaining only**
292 **pixels classified as water in the Sen2Cor Scene Classification Layer, to remove both inland-water and land pixels.**

High values in May reflect flood-induced particulate and phytoplankton inputs, followed by progressive decreases in June and stabilization by October. These satellite-derived trends align with field measurements, supporting the potential of remote sensing to complement traditional monitoring in capturing short-term flood impacts and recovery dynamics.

3 Discussion

The May 2023 flood event dramatically altered environmental, biological, and chemical conditions across the study region. A massive freshwater inflow drastically reduced the salinity concentration at marine stations, while simultaneously elevating dissolved oxygen and nutrient levels, and enhancing sediment transport. Although limited pre-event baseline data are available for individual stations, comparisons with the historical regional datasets provide evidence of the unprecedented impacts induced by this extreme event. In addition, clear deviations from historical datasets strongly emphasize the necessity for widespread and continuous environmental monitoring to capture responses to extreme hydrological events.

The impacts observed here are consistent with previous flood events in this region, although in several aspects they have proved even more severe. Notably, the Po River floods of October 2000, described in²⁹, and the May 2014 flood, analyzed in³⁰, both induced major alterations in the marine system, but with distinct quantitative differences. For instance, during the 2000 flood, surface salinity dropped to 6–7 psu, while in 2014 minimum salinity values did not fall below 29 psu. In our case, despite a more restricted

study area, salinity minima extended broadly across all marine stations, reaching 9–10 psu, confirming significant freshwater input.

Similarly, CDOM absorption (a_{443} up to 1.9 m^{-1}) and TSM values (up to 44 mg m^{-3}) exceeded maxima previously recorded for high discharge conditions in the northern Adriatic Sea^{30,31}, suggesting an even greater input of sediments and terrestrial, humic-rich material³². However, concentrations of nutrients such as N and P were lower than those recorded following both the 2000 and 2014 flood events, suggesting potential dilution effects due to the high-water volume or rapid biological uptake.

The exceedance of historical environmental values observed post-event is primarily attributable to the floodwater volumes, which mobilized contaminants from both agricultural and urbanized areas, generating urban runoff and delivering a concentrated pulse of pollutants to the inland system. The failure of the drainage network to manage the unprecedented water load further aggravated environmental pressure.

In line with the documented physico-chemical alterations, our biological observations confirmed that marine protist communities reacted promptly to the environmental stress induced by the flood event. In particular, the sharp decrease in salinity, combined with elevated nutrient concentrations and high TSM levels, favored the intrusion and proliferation of freshwater-associated taxa, mainly Bigyra, Chlorophyta and Cryptista, into marine inland waters. This reflects the strong advection of riverine and canal waters carrying both dissolved and biological material towards the sea. Such patterns are consistent with established evidence showing that pulses of nutrient-rich freshwater, combined with altered light availability and water column mixing, promote the dominance

of opportunistic, fast-growing species^{33–35}. The rapid increase in Cryptista and other nutrient-tolerant groups observed at marine stations is consistent with post-extreme event dynamics described in other estuarine and coastal systems^{36,37}. In parallel, we also recorded a temporary increase in heterotrophic taxa belonging to the phylum Bigyra and Ciliophora, typically associated with high organic matter availability and turbid, mixed inland waters. Their transient dominance likely reflects the immediate post-flood conditions, characterized by abundant particulate and dissolved organic material transported by riverine inputs, which provided favorable conditions for heterotrophic and osmotrophic protists, as previously observed³⁴. As salinity progressively increased and organic matter concentrations declined, Bigyra abundance rapidly decreased, and environmental conditions gradually shifted towards typical seasonal marine patterns. Interestingly, during the first post-flood sampling (T1, May), marine stations as well as satellite images showed unexpectedly high chlorophyll-a concentrations, coupled with low salinity and high turbidity. This suggests that the initial freshwater inflow not only delivered substantial nutrients but also transported phytoplankton biomass from upstream areas, temporarily enhancing photosynthetic biomass in marine waters despite adverse optical conditions. Such short-term biomass peaks associated with flood plumes are reported in other coastal systems following major hydrological events^{30,37}. Another hypothesis could be that phytoplankton increased the light-harvesting pigments content as a response to river-borne organic material, which caused water browning³⁴. By June, in marine stations, salinity had nearly returned to typical values (35 psu), and TSM decreased, indicating a progressive attenuation of the flood's immediate influence.

358 However, measurements and satellite data show that chlorophyll-a concentrations
359 dropped very fast, suggesting that, despite physical recovery, optical conditions likely
360 remain unfavorable for phytoplankton growth due to residual turbidity and high CDOM
361 levels that could reduce light penetration, limiting in-situ primary production in the
362 immediate aftermath of the flood. This mechanism has been previously highlighted in^{29,38}.
363 In contrast, inland freshwater stations showed a further increase in chlorophyll-a
364 concentrations, where a delayed photosynthetic biomass bloom dominated by
365 Ochrophyta, Heterokontophyta, and Cryptista developed, supported by persistently high
366 nutrient concentrations.

367 Despite this biological bloom, environmental trajectories among inland stations remained
368 more heterogeneous compared to the relatively coherent dynamics observed across
369 marine stations. This reflects the distinct hydrological characteristics, and independent
370 watershed influences of each river or canal system, resulting in site-specific trends in
371 parameters such as salinity, TSM, and nutrient concentrations throughout the study
372 period. However, the biological community at inland stations displayed more consistent
373 patterns. eDNA metabarcoding analyses revealed an initial dominance of opportunistic
374 groups, including Ciliophora and Cryptista, during the early post-flood phase (T1, May),
375 favored by nutrient enrichment and altered water column structure. Over time, these taxa
376 declined, while Heterokontophyta progressively increased, eventually becoming the
377 predominant phytoplanktonic component typical of freshwater-influenced transitional
378 environments. This community's change through time appeared broadly consistent

across inland stations, suggesting that ecological succession following extreme events may follow common pathways, even under variable local environmental conditions. By October, marine stations showed clear signs of recovery, with salinity, dissolved oxygen, and TSM stabilizing, and communities returning to seasonal assemblages dominated by Dinoflagellata and Heterokontophyta. Redundancy analysis (RDA) identified salinity, dissolved oxygen, and nutrient loads as the primary drivers shaping protist community structures, consistent with global findings in flood-impacted systems^{35,39}. Additionally, eDNA metabarcoding effectively captured subtle post-flood community shifts, especially among cryptic heterotrophic protists, highlighting its value as a sensitive monitoring approach.

These spatial patterns of ecological disturbance and gradual recovery were mirrored by the clear temporal and spatial gradients of emerging contaminants, including bisphenol A and pharmaceuticals across the study area. Overall, contaminant levels decreased from inland stations towards marine stations, both immediately after the flood and during subsequent months. Such patterns are consistent with previous studies reporting dilution and dispersion processes at the land-sea interface as reported in^{27,28}, although our data highlight the influence of local hydrodynamics and persistent upstream sources.

Drainage channels showed levels of contamination comparable to or even higher than rivers, suggesting the need for monitoring actions to which they are not yet subjected. The highest BPA and pharmaceutical concentrations were recorded at freshwater sites exposed to chronic anthropogenic inputs, particularly MAG and CER, with values progressively decreasing in marine waters downstream of channel mouths, likely due to

dilution, mixing, and degradation processes. We can only speculate that this trend is related to the flooding, because of the lack of previous CECs data for this drainage water. Moreover, a general decline in contaminant concentrations was observed from May to October, especially at marine sites, paralleling the recovery trends recorded for the other physical and chemical parameters, and for the biological communities. While the absence of detailed pre-event baselines limits the considerations, this decline is probably linked to the progressive dissipation of the flood's immediate impact.

Interestingly, divergent trends emerged at certain freshwater stations unaffected by the flood, such as the Reno river, where BPA concentrations increased over time, possibly reflecting seasonal variability or specific local sources independent of the flood dynamics. Environmental and biological changes were also evident in the performance of satellite-based monitoring products, whose accuracy varied across stations and time points, strongly influenced by evolving hydrological conditions. The same optical complexity - due to elevated TSM and CDOM - that affected biological communities and light penetration also posed significant challenges for remote sensing-based monitoring. As reported in⁴⁰, estuaries and coastal zones fall under the so-called Case 2 water⁴¹ where inorganic particulate matter and colored dissolved organic matter play a dominant role in shaping the optical signal, often masking the contribution of chlorophyll-a. In such environments, algorithms exploiting red and near-infrared wavelengths have been proposed to improve chlorophyll-a retrievals⁴²⁻⁴⁵, yet their empirical nature necessitates region-specific tuning to ensure applicability⁴⁶.

Overall, chlorophyll-a retrievals performed best in October (T3), coinciding with the ecological recovery phase, when salinity, CDOM and TSM values approached seasonal baselines and extreme in-situ concentrations of chlorophyll-a were no longer present. This suggests that under stabilized post-flood conditions, the performance of algorithms improves, highlighting their sensitivity to local water quality fluctuations.

Overall, CHL retrieval performance was comparable to, or in some cases better than, values reported for similar coastal systems, such as the northern Adriatic nearshore waters in Veneto region⁴⁷, while other European coastal sites have shown even greater errors⁴⁸.

A similar pattern was found for TSM retrievals. C2Net based products, particularly C2X, exhibited MAE and RMSE comparable to those obtained by Marzano et al. (2020) for the northern Adriatic using C2RCC. However, our results also reveal clear temporal variability in algorithm performance. At T1, during the peak of the flood impact, RMSE reached 19 g m^{-3} , slightly exceeding the values reported in⁴⁷. Conversely, at T2 and T3, RMSE values decreased substantially to 3 g m^{-3} and $8\text{--}9 \text{ g m}^{-3}$, respectively, indicating improved performance and lower retrieval errors compared to previous literature in two out of the three sampling periods. CDOM retrieval performance was limited, with high retrieval errors observed at T1 and T2. Moreover, due to low in-situ CDOM concentrations and unreliable laboratory measurements, no validation was possible for T3. These results reinforce the need for further refinement and local calibration of CDOM products, especially under extreme post-flood conditions where CDOM dynamics play a key ecological role.

These observations highlight that satellite product accuracy is strongly influenced by local hydrological and optical variability, aligning with the dynamic environmental gradients observed in in-situ measurements and biological data throughout the study. Consequently, careful algorithm selection and region-specific calibration remain essential to accurately monitor coastal water quality, particularly under extreme flood conditions that amplify optical complexity. Future efforts should prioritize the development of flexible approaches that integrate evolving biogeochemical, hydrological, and optical characteristics to enhance remote sensing performance in flood-impacted coastal environments.

Overall, our findings provide evidence that, despite the significant disruption caused by the 2023 Emilia-Romagna flood, inland and marine environments demonstrate strong resilience, showing possible signs of recovery within a few months after the event. By October, most physico-chemical variables returned to expected levels, and the community structures were restored, supporting a rapid, intrinsic resilience of the system. Satellite products helped track these trends but still struggled to resolve the extreme spatial and temporal variability characteristic of coastal environments impacted by major flooding.

Results underscore how extreme hydrological events reshape coastal environments through interconnected physical, chemical, and biological alterations, whose impacts propagate from inland waters to the marine domain. These types of extreme events produce cascading effects at multiple temporal and spatial scales, with both immediate and delayed consequences for ecosystems, human health, and economic sectors. However, the limited availability of high-resolution pre-event baselines constrains

comprehensive impact assessments. To enhance predictive capacity and inform management strategies, future efforts should prioritize long-term, integrated monitoring that combines traditional sampling, molecular tools, and adaptive remote-sensing technologies, particularly as climate change is expected to amplify the frequency and intensity of such disturbances in the northern Adriatic.

4 Conclusions

This multidisciplinary study provides a comprehensive snapshot of the short- and medium-term impacts of the May 2023 flood event in Emilia-Romagna, capturing for the first time the environmental, biological, and chemical alterations induced by such an extreme hydrological disturbance in this coastal region. Despite the absence of site-specific pre-event baselines, which represents a critical limitation, this study offers a crucial reference point, a “post-event photograph” against which future monitoring efforts and environmental assessments can be compared. The study demonstrated the importance of applying a sampling design that included rivers and canals, together with coastal marine sites. Thanks to this sampling strategy, it was possible to trace the pathways and characteristic times required for nutrients and pollutants to travel from the plain to the sea. We showed that the flood mobilized contaminants from agricultural and urban areas, delivering a concentrated pulse of pollutants to the coast, further intensified by the failure of the drainage network. In response, marine protist communities showed rapid shifts, with freshwater-associated taxa proliferating due to decreased salinity,

elevated nutrients, and high TSM levels. Right after the flood, both marine stations and satellite data revealed high chlorophyll-a levels, suggesting that nutrient-rich floodwaters and upstream phytoplankton transport temporarily boosted marine biomass despite low salinity and high turbidity.

Despite the severity of the initial impacts, including pronounced shifts in water chemistry, biological communities, and emerging contaminant concentrations, ecosystems demonstrated a notable capacity for resilience and recovery within a few months, particularly evident by October 2023. Although the system demonstrated the capacity for short-term ecological recovery, questions remain regarding its long-term resilience, particularly under scenarios involving increased frequency and intensity of such extreme events driven by climate change. Our findings highlight a critical gap for future research: the urgent need to implement continuous, long-term, multi-parameter monitoring programs that combine conventional assessment protocols, aligned with major legislative frameworks, with innovative analytical approaches, such as high-resolution remote sensing and molecular tools. Such integrated strategies are essential to capture environmental dynamics and assess ecosystem responses under extreme event scenarios, ultimately improving preparedness and management capacity in the face of climate-driven hydrological disturbances.

5 Materials and Methods

5.1 Study Area and Field Measurements

The study focused on the monitoring of rivers and freshwater canals (hereafter indicated as “inland stations”), as well as the Adriatic Sea in front of the Ravenna coast, which were impacted and affected by the May 2023 flood event. Inland sampling stations included the terminal reaches of the Reno, Destra Reno, and Lamone rivers to the north of the city, as well as the Cerba, Canala, and Magni drainage canals, which drain the western part of the city and discharge into the Baiona Canal before reaching the sea (**Error! Reference source not found.**). Reno River and Cerba drainage canal were designed as control points as they remained unaffected by the flood. Although the Reno River catchment experienced elevated water levels during the rainfall period, no flooding was recorded within its watershed. Similarly, the Cerba canal drains a small coastal basin in the north of Ravenna that did not experience inundation. As such, these sites served as reference points for water quality and biological analyses, providing representative conditions for non-impacted areas.

Marine sampling stations were selected about 1 km offshore and located in front of each river mouth and at the midpoints between them. Two additional marine stations were situated 1.5 km offshore, in the south and north of the Ravenna port’s jetties. Due to the presence of the long jetty infrastructure (2.4 km) acting as a physical barrier, the southern station was used as control point because protected from the direct influence of northern

fluvial and canal plumes originating by the flood. It was considered suitable reference points for assessing baseline marine conditions unaffected by the flood-induced inputs.

Three monitoring campaigns were carried out on the 30th of May, 16th June, and 10th October 2023. This timeline enabled a comprehensive evaluation of both the short- and medium- term impacts of the flooding on inland and marine ecosystems of the study area, as well as the processes of environmental recovery. May 30th was selected as the earliest feasible sampling date, coinciding with the lifting of emergency restrictions related to hydrogeological risk. June was chosen to capture early post-event conditions, while October 10th represented a later time point, allowing evaluation of the system's potential recovery and the re-establishment of pre-event conditions.

At each sampling station, physical and chemical parameters such as temperature (T), electrical conductivity (EC), pH, redox potential (Eh), and dissolved oxygen (DO) were measured by a HQ4300 Portable Multi-Meter (HACH®, Loveland, CO, USA), while samplings of surface water were collected to perform chemical and biological community analysis:

- 0.5 liter for eDNA metabarcoding
- 1 liter for pollutant analysis
- 2 liters for biological analyses (chlorophyll-a (CHL), phaeopigments, inorganic nutrients (N and P), Total Suspended Matter (TSM) and Chromophoric Dissolved Organic Matter (CDOM)

547 Samples were stored in pre-washed rigid 1-liter plastic bottles (10% HCl or NaClO).
548 Salinity (S) was measured in the field using a refractometer.

549 5.2 Water Quality Assessment

550 Water samples of inland costal stations (rivers and drainage canals) (**Error! Reference**
551 **source not found.**) were filtered through a 0.45 µm membrane filter, stored in pre-
552 cleaned 100 mL HDPE plastic bottles until further analysis. Samples for cations and trace
553 elements (TEs) determination were acidified with 1% HNO₃. Major anions and alkalinity
554 were analyzed within 24 hours by Ion Chromatography (883 Basic IC plus Metrohm AG,
555 Herisau, Switzerland) and major cations and PTE by Inductively Coupled Plasma–Optical
556 Emission Spectroscopy (Agilent 5800 ICP-OES, USA). The calibration curve was built
557 using certified standards in water. For both cations and anions, the standards set by the
558 Italian National Environmental Agency, APAT-IRSA 2003 were applied. For all the
559 samples, the ionic balance was ±5%. Considering internal and external standards,
560 accuracy and precision were better than 10% for all elements considered. Results of river
561 samples were compared against the long-term monitoring series (2013 to 2023) of Reno,
562 Destra Reno and Lamone rivers downloaded from the Regional Environmental Protection
563 Agency of the Emilia-Romagna Region (Arpae) website ([https://dati.arpae.it/dataset/rete-](https://dati.arpae.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023)
564 [regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023](https://dati.arpae.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023)). For
565 comparison with historical data from Arpae, nitrate (NO₃⁻) concentrations were used,
566 given that nitrite (NO₂⁻) values were consistently missing from the Arpae dataset,

567 suggesting concentrations below detection limits. Our measured values of dissolved
568 nitrogen represent the sum of nitrate and nitrite ($\text{NO}_3^- + \text{NO}_2^-$).

569 Water samples were analyzed for CHL, inorganic nutrients, CDOM (only marine stations),
570 and TSM.

571 CHL samples were kept cool and dark until analysis. Volumes of 200–600 mL were
572 filtered on Whatman GF/F filters (0.7 μm , 47 mm). Pigments were extracted with 90%
573 acetone, and concentrations measured by spectrophotometer (Jasco V-650) at 750 and
574 665 nm following⁴⁹. Phaeopigments were quantified after acidification to a final
575 concentration of 0.66 M HCl.

576 Nitrate as N [$\text{NO}_3^{2-} + \text{NO}_2^-$] and Phosphorous as P [PO_4^{3-}] were analyzed in filtered water
577 samples (GF/F filters), stored in polyethylene bottles pre-washed with 10% HCl.
578 Spectrophotometric analysis was carried out according to⁵⁰. TSM was measured
579 gravimetrically following the method described in⁵¹. Water samples were filtered onto pre-
580 weighed 0.45 μm membrane filters. For marine samples, filters were rinsed with 0.5 M
581 ammonium formate (2× the filtered volume) to remove residual salts. Filters were then
582 oven-dried at 105 °C and reweighed to determine particulate mass. CDOM absorption
583 was measured spectrophotometrically following⁵², based on UV-visible absorbance
584 spectra collected on filtered samples (0.2 μm) across the 250–800 nm range. CDOM
585 absorption coefficients were specifically determined at 443 nm.

586 CDOM absorption at 443 nm was measured during all three field campaigns. However,
587 at T3 (October), most laboratory-derived values were negative or close to zero, consistent
588 with CDOM concentrations near or below the detection limit and increased instrumental

uncertainty. These values were excluded from the comparative analysis to ensure reliable performance assessment

5.3 Protist communities' assessment

In order to analyze the protist communities, eDNA analysis was performed on all inland and marine water samples. They were pre-filtered on 3 µm nitrocellulose filters and re-filtered on a 0.22 µm nitrocellulose filter. After filtration, filters were stored at -20°C. Total DNA from the filters was extracted using the BioFast Soil Genomic DNA Extraction Kit (BioFlux, Hangzhou, Zhejiang, China), following the manufacturer's instructions, with two negative controls included per extraction batch to check for contaminations. PCR reactions for the V4–V5 region of the 18S rRNA were carried out in a total volume of 20 µL and included 17 µL of AmpliTaq Gold™ 360 Master Mix (Applied Biosystems), 0.5 µL of each primer (F-566, R-1200; 10 µM)⁵³ that already included 12-bp tags for multiplexing, and 2 µL of DNA template, with the following thermal profile: 95°C for 15 min, followed by 35 cycles of 95 °C (45s), 60 °C (45s), 72 °C (1min), and a final extension at 72 °C for 10min. PCR products were evaluated by agarose gel electrophoresis (1.5% gel, 0.5X TBE). For the 18S library, PCR products were pooled and purified with the Macherey-Nagel™ NucleoSpin Gel and PCR Clean-up Kit to remove DNA fragments <70 bp. DNA concentration was measured with a Qubit fluorometer (Broad Range kit, Invitrogen). The libraries were sequenced in-house with a MinION Mk-1C (Oxford Nanopore Technologies). The 18S library was prepared with the SQK-LSK110 kit and sequenced on a FLO-MIN111 flow cell with a 22-hour run. Basecalling was conducted using Guppy

(ONT) with a quality threshold of 8. Demultiplexing and length filtering were performed with OBITOOLS⁵⁴. The taxonomic assignment was conducted using the RDP classifier with the SILVA 138 reference database at genus level^{55,56}. Data were cleaned keeping only protist taxa that had a total read count of at least 10 and a similarity threshold of 97%. Since some samples did not amplify and to ensure consistency, only samples present in both biological and environmental datasets were considered for the Redundancy Analysis (RDA). Environmental parameters considered for the RDA were N, P, TSM, DO, temperature and salinity. Protist abundance data were square-root transformed, and environmental variables were standardized with *decostand()* to allow comparison among different scales. RDA analysis allows the samples and environmental factors to be represented on the same two-dimensional ordination plot to visualize their relationships. RDA was performed with *rda()* using scaling 2, to highlight the effects of explanatory variables (environmental parameters). The significance of each environmental variable in explaining community structure was assessed with *anova.cca()*. All analyses were performed in R version 4.4.1 (R Core Team, 2024), using the vegan package⁵⁷ and ggplot2⁵⁸ for data visualization.

5.4 Contaminants of emerging concern (CECs) analyses

To analyze CECs, water samples were spiked with a mixture of labeled internal standards (BPA-d6 and Ibuprofen-d3) at a concentration of 30 ng L⁻¹. Samples were filtered using glass microfiber filters (1.60 µm), then with cellulose acetate filters (0.45 µm), and extracted using Solid Phase Extraction (SPE) Oasis HLB cartridges as reported in⁵⁹. Cartridges were eluted with 6 mL of methanol, evaporated under a nitrogen gentle stream

up to a volume of 250 μL , and split into two vials of 125 μL each. The first set of vials was added with 125 μL of water (50:50 water/methanol) for chemical analysis of Bisphenol A (BPA); the remaining vials were further evaporated to 25 μL and reconstituted in 250 μL of a mixture of water/methanol (90:10) for LC-MS-MS analysis of pharmaceuticals. Samples were transferred into 2 mL vials, after filtration (0.22 μm CA membrane filters) for analysis. Chemical analysis of BPA in water samples was performed by ultra-high-performance liquid chromatography (ACQUITY UPLC® H-Class) equipped with a triple quadrupole mass spectrometer (Xevo® TQ-S Micro) using a negative electrospray ionization source in multiple-reaction monitoring (MRM) mode. Separation of compounds was achieved through an ACQUITY UPLC® BEH C₁₈ column (100 $\times$ 2.1 mm, 1.7 μm particle size, 130 Å pore size) equipped with a pre-column (BEH C₁₈ VanGuard™ pre-column, 5 $\times$ 2.1 mm i.d., 1.7 μm particle size). The volume injection was 10 μL . Sample extracts concentrated 2000 times were measured along with calibration standards, which corresponded to a range of 1–300 $\mu\text{g L}^{-1}$. Chemical analysis of pharmaceuticals was performed by the IRCCS (Istituto di Ricerche Farmacologiche “Mario Negri”, Department of Environmental Health Sciences), as described in⁶⁰.

5.5 Remote Sensing and Image Processing

The aim of the remote sensing use in this study was to evaluate whether ready-to-use (e.g., Sentinel-3 OLCI) and semi-operational products (based on Sentinel-2 data processing) could reliably estimate water quality parameters, especially under extreme hydrological conditions, such as those that followed the May 2023 flood.

653 We applied and compared multiple algorithms across satellite products to identify those
654 most accurate and operationally useful for post-flood environmental monitoring. Each
655 satellite of the Sentinel-2 constellation is equipped with the Multispectral Instrument (MSI),
656 which captures data across 13 spectral bands, ranging from visible (VIS) and near-
657 infrared (VNIR) to the shortwave infrared (SWIR) spectrum. The MSI provides spatial
658 resolutions of 10 m (VIS and VNIR), 20 m (red-edge and vegetation-related bands), and
659 60 m (bands for atmospheric correction). For this study, Sentinel-2 Level-1C products
660 were downloaded from the Copernicus Browser, accessible at:
661 <https://browser.dataspace.copernicus.eu>.
662 The images selected correspond to dates closest to in-situ sampling. In cases where
663 satellite overpass or high cloud cover prevented acquisition on the exact sampling date,
664 the nearest available image was used (see Supplementary Table S6 for the date list).
665 Images were pre-processed using ESA's SNAP software (v.11.0.0) (software available
666 at: <https://step.esa.int/main/toolboxes/snap>), including subsetting to the area of interest
667 and resampling to a spatial resolution of 20 m. This processing step follows previous
668 findings showing that 20 m resolution provides more stable and accurate water quality
669 estimates from Sentinel-2 imagery⁶¹. The actual processing of the images included the
670 atmospheric correction followed by the retrieval of two water constituents, CHL and TSM,
671 as well as CDOM absorption at 443 nm. These parameters were retrieved using two
672 distinct methods, each based on different algorithms and coefficients (see Supplementary
673 Table S7):

- 674 ▪ The Case 2 Regional Coast Colour processor (C2RCC), developed by⁶² and
675 integrated within SNAP, applies a two-step neural network inversion approach.
676 First, atmospheric correction is performed by estimating top-of-atmosphere (TOA)
677 radiance contributions (e.g. water vapor, aerosols), followed by the inversion of
678 surface reflectance to derive inherent optical properties (IOPs) of the water column.
679 Neural networks are trained using an extensive dataset (million of simulations)
680 based on radiative transfer model that covers a wide range of IOPs^{62,63}, including
681 pigment absorption (a_{pig}), detrital absorption (a_{det}), CDOM absorption
682 (a_{gelb}), and also scattering by both sediment (b_{part}) and calcareous particles
683 (b_{wit}). Three variants of the model were applied, allowing the processor to adapt
684 to a broad variety of water conditions. Specifically, the suite of C2RCC neural
685 networks (collectively referred to here as "C2Nets") includes: i) C2RCC, optimized
686 for mesotrophic and moderately turbid coastal waters; ii) C2X, designed for highly
687 turbid or extreme optical conditions; and iii) C2XCOMPLEX, targeting optically
688 complex waters with intermediate turbidity levels. All three variants were tested to
689 evaluate their performance under the extreme conditions caused by the flood event.
690
691 ▪ ACOLITE (software available at: <https://github.com/acolite/acolite>, version
692 20231023.0) was also employed for atmospheric correction, applying the Dark
693 Spectrum Fitting (DSF) algorithm, which estimates aerosol optical thickness and
694 path reflectance through dynamic dark pixel selection⁶⁴. ACOLITE is particularly
695 suited for turbid and optically complex waters, providing robust correction under

highly dynamic aquatic conditions. In addition to atmospheric correction, ACOLITE offers a suite of empirical and semi-analytical algorithms (see the full list in Supplementary Table S7) to estimate chlorophyll-a (CHL), turbidity (expressed in Formazin Nephelometric Units, FNU), and total suspended matter (TSM, in g/m^3) from remote sensing reflectance (R_{rs}). While turbidity is an optical parameter related to water clarity, TSM represents the actual concentration of suspended particulate matter. In this study, TSM algorithms were prioritized to ensure direct comparability with in situ TSM gravimetric measurements.

To further assess the potential of ready-to-use satellite products, we also employed data from Sentinel-3, which carries the Ocean and Land Colour Instrument (OLCI), specifically designed for marine and inland water monitoring, among other applications. OLCI is equipped with 21 spectral bands spanning the visible to near-infrared (VIS–NIR) regions, enabling the detection of key water quality parameters at large spatial scales. The OLCI Water Full Resolution (WFR) products are Level-2 outputs providing remote sensing reflectance (R_{rs}) and derived biogeophysical parameters such as CHL and TSM and they are available at: <https://browser.dataspace.copernicus.eu>. These products are generated through ESA's operational processing chains using standard algorithms (see Supplementary Table S7 for a full list of algorithms). OLCI WFR products offer a native spatial resolution of 300 meters, which, while coarser than Sentinel-2, provides the advantage of high temporal coverage and consistent processing standards, making them valuable for large-scale or regional monitoring. Once the Level-2 products were obtained, a match-up analysis was performed between satellite-derived estimates from each

algorithm and the corresponding in-situ measurements. This was conducted separately for the products derived from Sentinel2 (C2Nets-derived and ACOLITE-derived products) and Sentinel-3 OLCI. For each product and acquisition date, a 3x3 pixel window centered on the GPS coordinates of each sampling station was extracted. Within each window, quality flags were analyzed to exclude unreliable pixels, thereby ensuring data quality. Subsequently, the remaining pixel values were averaged to derive a representative satellite-based estimate for comparison with laboratory measurements. To quantitatively evaluate the satellite-derived estimates against in-situ reference measurements, three statistical metrics commonly used for the validation of remote sensing products were employed: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Bias.

6 Data availability (mandatory)

The data that support the findings of this study are available from the corresponding authors upon reasonable request. The datasets will be made publicly available via Zenodo upon request by the journal reviewers or upon acceptance for publication.

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Author contributions

F.C., E.F., B.M.S.G., N.G., L.P., S.S. and P.V. contributed to the conceptualization, methodology, and project administration of the study.

Formal analysis was carried out by B.M.S.G., N.G., L.P., P.V., R.B., A.P., M.L.T., and C.L.

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F.C., E.F., B.M.S.G., N.G., L.P., S.S., P.V.

R.B. and C.C. prepared the original draft. All authors contributed to the review and editing of the manuscript and approved the final version.

These authors jointly supervised this work: F.C., E.F., B.M.S.G., N.G., L.P., S.S. and P.V.

Competing interests

The authors declare no competing interests.

How resilient are inland and marine environments to extreme events? 2023 Emilia-Romagna flood insights

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Abstract

This study uses an integrated and multidisciplinary approach to assess the short- and medium-term effects of 2023 Emilia-Romagna (Italy) flood on inland and marine environments and their recovery capability. To capture the evolution of post-flood conditions, three monitoring campaigns were conducted: (i) immediately after the flood (late May), (ii) approximately after one month (mid-June), and (iii) after five months (early October). During each campaign, we characterized rivers and coastal marine waters by combining in-situ measurements of abiotic and biotic parameters with eDNA-based community assessment, emerging contaminant analyses, and satellite-derived data. Despite the large spatial extent and intensity of the disturbance affecting the entire river-to-coast continuum, most parameters showed partial to near-complete recovery within five months, evidencing strong system resilience. The lack of pre-event baselines constrains precise impact assessment, underscoring the need for long-term, standardized monitoring frameworks that integrate innovative tools to capture environmental consequences of extreme events and evaluate coastal vulnerability.

Commented [anon1]: You need to caveat this with a statement on longer term change - this shows recovery from the existing state.

1 Introduction

Extreme weather events are becoming increasingly frequent and severe, driven by the accelerating effects of climate change. Among these events, flooding is one of the most devastating¹. Floods, categorized into riverine, coastal, urban, and flash types, are caused by prolonged rainfall, rapid storm surges, or the overflow of rivers and streams beyond their banks^{2,3}. Urbanization and land-use changes in inland areas significantly contribute to coastal vulnerability by increasing sediment transport, altering water quality, and disrupting hydrological cycles⁴. These events not only ~~impact disturb~~ terrestrial and aquatic environments but also mobilize pollutants toward downstream areas, altering biogeochemical dynamics and amplifying stress on coastal ecosystems^{5,6}. Excessive nutrient concentrations and terrestrial organic matter from river inputs often lead to harmful algal blooms⁷, hypoxia, and eutrophication, particularly in semi-enclosed seas^{8,9}. These nutrients enhance primary production in surface waters, increasing the deposition of organic matter to sediments, where its decomposition further depletes oxygen levels^{10,11}. Floodwaters also act as vectors for anthropogenic contaminants, including pesticides, heavy metals, and contaminants of emerging concern (CECs) which include perfluorinated compounds, plasticizers, additives (e.g., bisphenol A) and pharmaceuticals. The altered redox conditions during flood-induced deoxygenation events can increase the mobility and toxicity of these pollutants, with profound implications for aquatic ecosystems, water quality, and human health^{12–14}. Among CECs, pharmaceuticals are of increasing relevance, particularly considering their potential mobilization during extreme hydrological events. Recent studies suggest that

Commented [anon2]: Examples?

59 intense rainfall and associated sewer overflows may exacerbate pharmaceutical inputs
60 into sensitive coastal environments, raising concern for the health of aquatic ecosystems
61 under climate change scenarios¹⁵. The monitoring after extreme events generally
62 involves the assessment of the immediate and direct impacts on urban infrastructures,
63 ecosystems, and human health. However, understanding the complex interplay between
64 extreme flood events and their visible and unseen cascading effects on coastal and
65 marine ecosystems is crucial but understudied. The short- and long- term monitoring of
66 unseen impacts such as shifts in biological communities, the spread of contaminants
67 (such as CECs), or delayed biological responses often go undetected by routine
68 monitoring but it can be significant for predicting ecosystem resilience, informing coastal
69 management strategies, protecting biodiversity, preventing ecological degradation,
70 economic losses (e.g., fisheries, tourism), and health risks related to water quality.

71 Between early May (1st – 4th) and mid-May (16th – 17th) 2023, the Emilia-Romagna region
72 in northern Italy, experienced two extreme meteorological events that led to catastrophic
73 flooding, landslides, and widespread destruction^{16–18}. The May 2023 events, described
74 as "unprecedented" in the region's hydrological history, resulted from the convergence of
75 extreme meteorological and hydrological conditions¹⁹. Rainfall return' periods exceeded
76 100 years in many areas, reaching over 500 years in the most affected zones. The first
77 event was caused by a polar low-pressure system that stalled over central Italy, resulting
78 from the convergence of moist air masses from the Adriatic Sea and cold bora winds from
79 the north. This interaction, intensified by orographic effects from the Apennine Mountains,
80 led to over 200 mm of rainfall in 48 hours in some areas. Two weeks later, a second low-

pressure system exacerbated the crisis, producing even more intense rainfall, up to 240 mm in localized areas, exceeding historical records. Together, these events brought an estimated 350×10^6 m³ of water, equivalent to six months of average rainfall within a remarkably short period²⁰. Rivers across Emilia-Romagna experienced record-breaking floods that breached embankments at 23 locations and flooded over 540 km² of lowlands. Among the most impacted areas were the city of Ravenna and its surrounding, the catchments of the Lamone, Montone, Ronco, Savio rivers, and the tributaries of the Destra Reno canal ([Error! Reference source not found.Figure 4](#)).

Along the Adriatic coastal areas, storm surges ~~further~~ worsen the flooding by slowing the drainage of floodwaters. The drainage infrastructure, with its narrow embankments not designed to handle this excess water, failed to discharge water to the sea efficiently and, in some cases, water stagnated on crops and cities for several days after the event. In the Apennine region, prolonged saturation triggered nearly 66,000 landslides, disrupting critical infrastructure and isolating several communities. The impacts of this extreme event are well documented. Entire communities were forced to evacuate; ~~there were with~~ 17 deaths and 36,600 evacuees; farmlands were flooded, leading to the destruction and contamination of crops²¹ and death of livestock, while urban areas suffered significant structural damage²². The floods also caused significant environmental impacts²³. Floodwater transported large quantities of sediments, organic matter, and pollutants into the surface water bodies (rivers and drainage networks), eventually reaching the Adriatic Sea. This led to algal blooms, the death of aquatic organisms²⁴, and severe impacts on the local economy.

103 Beyond these impacts, the study aims to assess additional direct and indirect effects on
104 inland and marine waters that were not captured by standard routine monitoring
105 conducted according to major legislative protocols following the May 2023 flood event.

Commented [anon3]: What protocols? This is a confusing sentence.

106 Here, a multidisciplinary and integrated protocol is applied to analyze geochemical,
107 environmental, and biological factors, providing a comprehensive understanding of the
108 flood short- and medium- term impacts, and assessing the intrinsic recovery capacity of
109 the system. The approach includes analyses to assess abiotic and biotic parameters,
110 analyzing also protist communities using environmental DNA (eDNA) metabarcoding, and
111 estimating emerging contaminants, along with evaluating remote sensing capacity to
112 assess the marine water quality. The study offers a holistic understanding of complex
113 environmental phenomena and bridges a significant knowledge gap by providing new
114 insights into the interconnected impacts of human-driven disasters on the environment.

Commented [anon4]: Floods have always happened, so need to add more around the impacts of large floods - but more often and greater intensity. Difficult to identify impacts above and beyond what would have been measured so be careful here.

115 Our findings show how key physical, chemical, and biological parameters respond to
116 system perturbation caused by the flood event, and underscore the importance of high-
117 resolution, integrated monitoring across terrestrial and marine environments to effectively
118 assess the dynamics and impacts of extreme hydrological events.

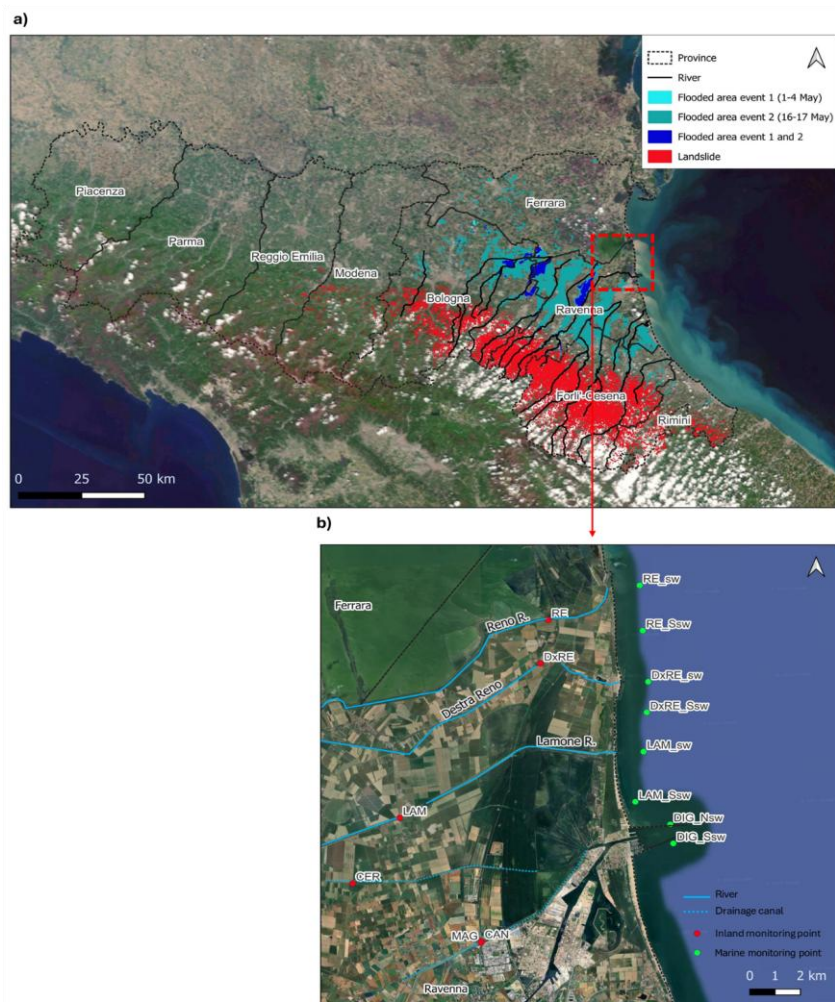
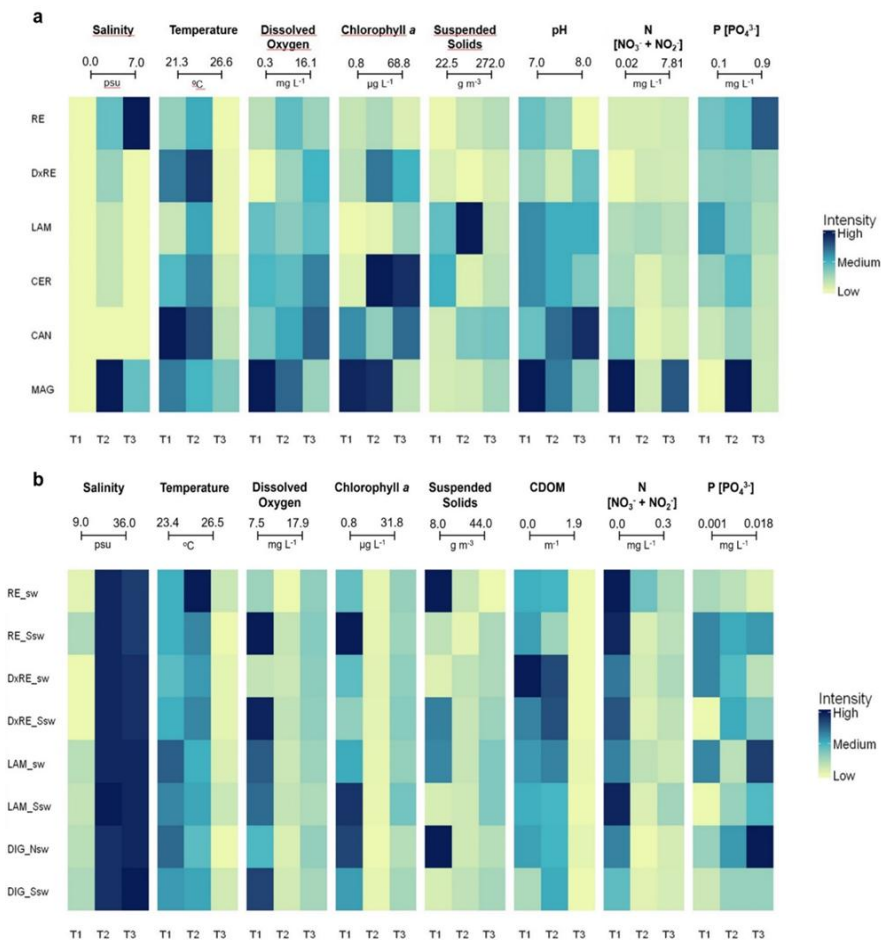


Figure 1 | Areas affected by floods and landslides in May 2023 and location of the study area. a | Rivers (black) and areas of the Emilia Romagna region affected by landslides (red), and floods during the first (light blue), second (green), or both (dark blue) floods. (Data source: Emilia-Romagna data geoportal; base map: European Union, Copernicus Sentinel-2 imagery, date 05/05/2023); **b |** Inland (red) and marine (green) monitoring points selected along the main rivers and drainage channels involved in the flood.

124 2 Results

125 Following the flood event in May 2023, significant variations were recorded across all
126 measured environmental parameters (Figure 2).

Commented [anon5]: Need a better start to your results. More of an explanation of what you collected and where, then go into the statistical data.



127 **Figure 2 | Heatmap of environmental parameters of inland and marine monitoring points. a | River and canal**
128 **sampling stations; b | marine sampling stations. Data were normalized per parameter to allow for consistent comparison.**

129 Water temperature (T) followed a typical seasonal trend, with maximum value in summer
130 (26.6 °C in June) and minimum with the start of the fall season (21.3 °C in October). Sea
131 salinity (S) dropped markedly due to the freshwater influx from the flood, with a minimum
132 of 9.0 psu at RE_sw and DxRE_sw in May. By October, salinity had returned to typical
133 marine values (~35 psu; Figure 2b). Dissolved oxygen (DO) showed anoxic conditions
134 following the flood (May) in DxRE and reached post-flood minima in June, both at inland
135 (0.3 mg L⁻¹ at DxRE) and marine station (5 mg L⁻¹ RE_sw), reflecting elevated biological
136 oxygen demand.

137 Microalgal pigment concentrations revealed distinct spatial dynamics. Marine stations
138 showed an immediate post-flood chlorophyll-a (CHL) peak in May (up to 31.8 µg L⁻¹ at
139 RE_Ssw), followed by a sharp decline in June and partial recovery by October. This
140 recovery aligns with historical monthly and annual averages observed during Arpae inland
141 monitoring data^{25,26}. Phaeopigments mirrored this trend, with the lowest values in June
142 (0.001 µg L⁻¹ at DIG_Ssw). In contrast, inland stations (Figure 2a) showed delayed CHL
143 and phaeopigment peaks in June, followed by declines by October, indicating enhanced
144 degradation of pigments in the weeks following the event.

145 Suspended and dissolved materials also reflected flood-related dynamics. Total
146 Suspended Matter (TSM) increased from May to June at inland stations (maximum of
147 272.0 g m⁻³ at CAN), indicative of sediment input and resuspension. Marine responses
148 were variable, with some stations increasing in May (e.g., RE_sw, DIG_Nsw) and others
149 in June (e.g., DxRE_sw, LAM_Ssw), but most returned to near-initial levels by October.

150 Colored Dissolved Organic Matter (CDOM) increased in May due to terrestrial runoff,
151 remained stable in June, and declined sharply by October, often below detection
152 thresholds, at inland stations.

153 Nutrient concentrations displayed clear flood-driven dynamics. Nitrogen (N) spiked
154 immediately after the event in May with an increasing north-south gradient at inland
155 stations as a result of flood-induced runoff, decreased sharply by June, and partially
156 rebounded by October. Marine nitrogen values followed a similar but opposite (i.e.,
157 decreasing north-south) trend, although at lower concentrations. Phosphorus (P) showed
158 more variable patterns: inland values generally increased in June, while marine
159 concentrations remained low, with slight increases by October.

160 These results confirm immediate and pronounced flood-driven changes in environmental
161 parameters, highlighting spatial variability and different recovery trajectories between
162 inland and marine environments. To quantitatively highlight the magnitude of the
163 environmental alterations observed during the 2023 flood event, we compared our
164 observations with historical baseline data from Arpae (2010–2022). Although limited to
165 three inland monitoring stations (RE, DxRE, and LAM), for which historical numerical
166 datasets are available, this comparison underscores the exceptional nature of the
167 recorded anomalies. Several parameters (T, EC, DO, pH, and nutrients) measured during
168 and after the flood exceeded the historical range documented over the previous decades
169 (Figure 3); particularly divergent were DO, pH, and P.

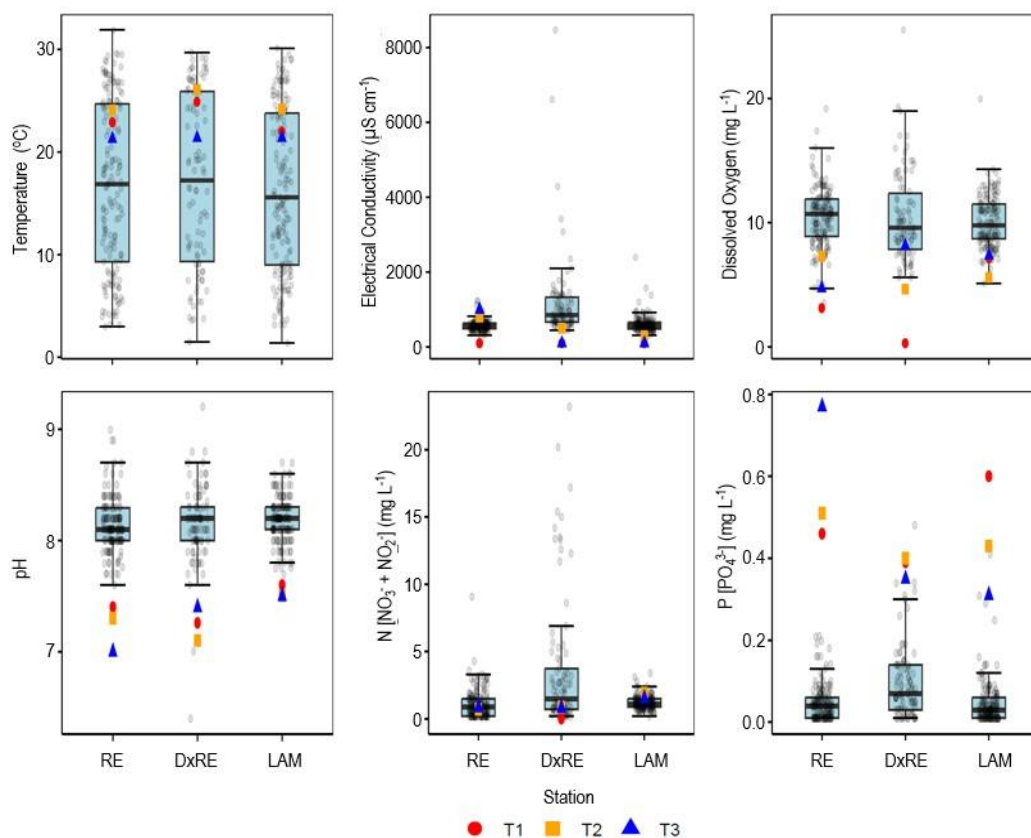
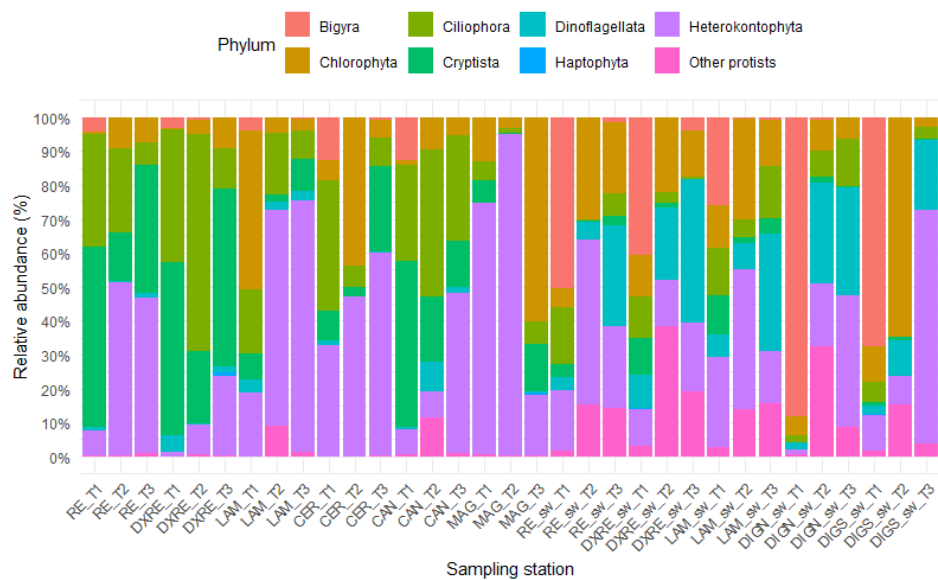


Figure 3 | Comparison of environmental parameters measured during the 2023 flood event with historical baseline data (2010–2022; boxplots) from ARPAE inland monitoring stations RE, DxRE, and LAM. | Panels show:
a | temperature (°C), b | electrical conductivity (µS cm⁻¹), c) dissolved oxygen (mg L⁻¹), d) pH, (e) dissolved inorganic nitrogen (NO₃⁻ + NO₂⁻) (mg L⁻¹), and (f) dissolved inorganic phosphorus (PO₄³⁻) (mg L⁻¹). Historical data distributions are displayed as boxplots, while colored symbols indicate the 2023 post-flood sampling periods. Note the pronounced deviations recorded during the flood event, indicative of substantial environmental alterations.

Commented [anon6]: Are the grey dots what has been measured in the flood event? . Is it only the red or yellow or blue shapes that represent the flood events? Why not have turbidity or some measures of suspended solid as well. I don't think this conveys what it needs too. I suggest comparing mean and SE, or percentiles to show skewed distribution. (NO3 does not look different from long term measurements!)

178 **Protist communities**

179 The eDNA metabarcoding analysis of protist community composition revealed clear
180 differences between freshwater and marine sampling stations. After data filtering, seven
181 main phyla were identified and are shown in Figure 4.



182 **Figure 4 | Relative abundance (%) of protist communities at the phylum level across sampling stations and**
183 **time points, based on eDNA metabarcoding.**

184 Taxa belonging to non-photosynthetic groups were collectively assigned to "Other
185 protists", except for Ciliophora, which were represented separately to highlight their
186 marked post-flood increase in abundance. A total of 74 taxa were detected, distributed
187 across 29 different classes, whose relative abundances are provided in Supplementary
188 Figure S1.

189 Inland stations were predominantly characterized by high abundances of
190 Heterokontophyta (mainly diatoms), Cryptista, Ciliophora, and Chlorophyta. Conversely,
191 marine stations exhibited higher diversity, dominated mainly by Heterokontophyta and
192 Dinoflagellata. Immediately following the flood (May, T1), marine stations experienced an
193 influx of freshwater-associated taxa, particularly Bigyra, Chlorophyta, and Ciliophora,
194 reflecting freshwater intrusion. This anomaly diminished notably by subsequent sampling
195 periods (June T2 and October T3), as typical marine taxa (Dinoflagellata and
196 Heterokontophyta) progressively increased, signaling ecological recovery to normal
197 conditions. Indeed, these observations align with typical seasonal phytoplankton
198 assemblages reported in the Arpae annual inland monitoring reports, which serve as a
199 reference for expected marine community conditions during this period. To examine how
200 environmental variables drove the observed community patterns, we performed a
201 redundancy analysis (RDA) using S, T, DO, TSM, and nutrients (N and P) as constraining
202 variables (Figure 5). The first two RDA's axes explained 31.7% of the variance in the
203 community structure, with RDA1 (21.4%) separating freshwater and marine stations
204 based on S, DO, total N and P, and TSM, and RDA2 (10.3%) capturing temporal variation
205 associated primarily with water temperature.

206

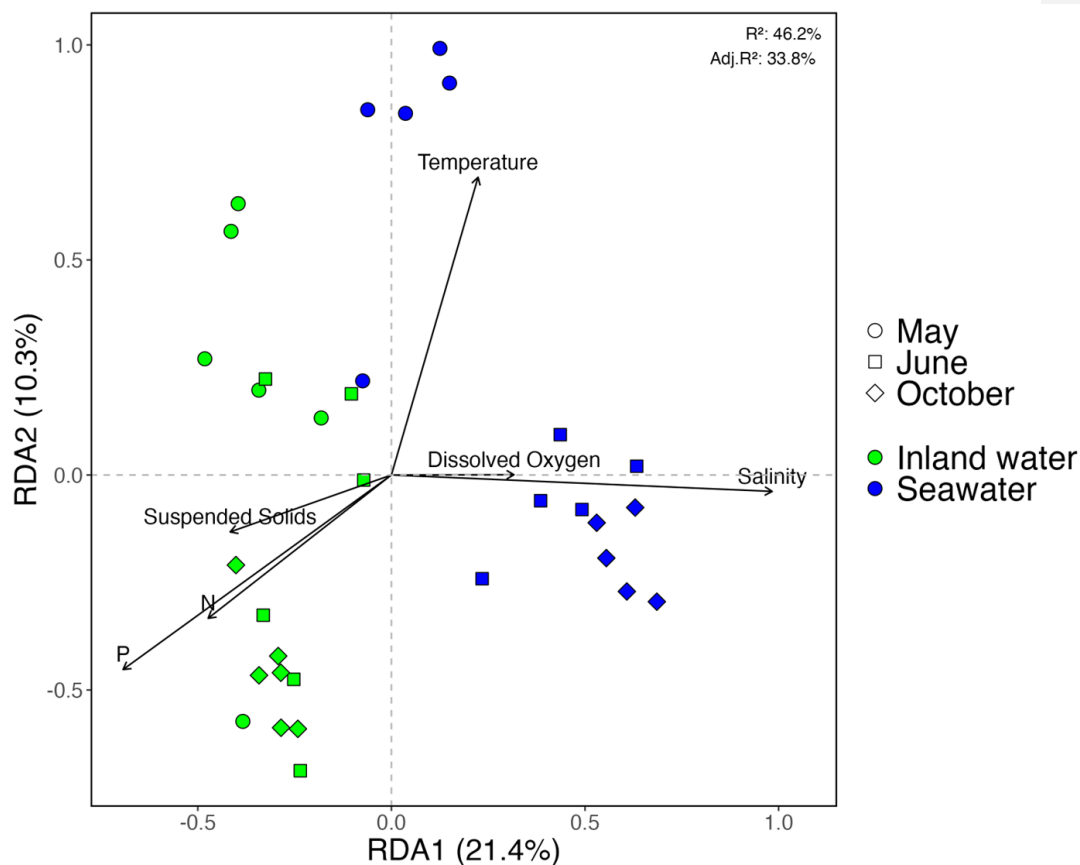


Figure 5 | Redundancy Analysis (RDA) showing the relationship between phytoplankton community structure and environmental variables across sampling stations. Arrows represent the direction and strength of environmental gradients.

Commented [anon7]: You have suspended solid here but do not show it in the water quality data.

ANOVAs confirmed that all environmental predictors significantly influenced the communities composition (S: $p < 0.001$; T: $p < 0.01$; DO: $p < 0.01$; TSM, N, P: all $p < 0.05$; Table 1). Inland samples were more dispersed immediately after post-flood (May–June), becoming clustered by October, reflecting gradual stabilization. These patterns indicate

214 a strong environmental disturbance driven by the flood event, followed by a clear trend
215 toward recovery and resilience in the subsequent months.

216 **Table 1 | Results of ANOVAs testing the influence of each environmental variable on protist community**
217 **structure based on redundancy analysis (RDA).** | All predictors significantly influenced community structure, with S,
218 T, DO, TSM, total N and P showing varying degrees of explanatory power. Significance codes: *** $p < 0.001$; ** $p <$
219 0.01 ; * $p < 0.05$.

Terms	Df	Variance	F	Pr(>F)	
S (psu)	1	0.0811	6.3741	0.0001	***
T (°C)	1	0.0352	2.7704	0.004	**
DO (mg L ⁻¹)	1	0.0302	2.3735	0.0097	**
TSM (g m ⁻³)	1	0.0272	2.1362	0.0117	*
N (mg L ⁻¹)	1	0.0261	2.0504	0.0202	*
P (mg L ⁻¹)	1	0.0313	2.4605	0.0032	**
Residual	26	0.3308			

220
221 **Contaminants of emerging concern (CECs)**
222 Chemical analyses via LC-MS/MS revealed widespread contamination by contaminants
223 of emerging concern (CECs), particularly Bisphenol A (BPA) and pharmaceutical
224 compounds (Figure 6; see Supplementary Tables S1–S2 for the full list). BPA was
225 detected in all samples, ranging from 0.72 to 77.85 ng L⁻¹. The highest BPA
226 concentrations occurred at the inland riverine station RE in October (77.85 ng L⁻¹), while
227 other inland stations (DxRE: 28.15 ng L⁻¹, LAM: 22.25 ng L⁻¹, MAG: 9.4 ng L⁻¹) showed
228 peak values immediately post-flood (T1, May), declining thereafter. On the other hand,

229 marine stations consistently recorded lower BPA levels, with clear decreasing trends
230 post-flood (e.g., RE_sw: 4.25 ng L⁻¹ in May, declining to 1.85 ng L⁻¹ in October).

231 Pharmaceutical contamination, dominated by anti-inflammatory drugs (e.g., Ketoprofen,
232 Diclofenac, Ibuprofen, Naproxen), diuretics, and antipyretics (see the full pharmaceuticals
233 list in Supplementary Table S2), showed notable spatial variability. Inland station MAG
234 displayed extremely high total pharmaceutical concentrations in May (395.98 ng L⁻¹),
235 significantly decreasing in June (42.83 ng L⁻¹), then rebounding by October (395.77 ng L⁻¹).
236 Other inland stations (RE, LAM, DxRE) exhibited similarly elevated contamination in
237 May (RE: 72.24 ng L⁻¹, LAM: 70.62 ng L⁻¹, DxRE: 27.33 ng L⁻¹), decreasing in subsequent
238 months. Marine stations consistently demonstrated lower pharmaceutical concentrations,
239 exhibiting gradual temporal decreases (e.g., RE_sw: 24.95 ng L⁻¹ in May to 10.45 ng L⁻¹
240 in October).

241 Overall, a decreasing trend of contamination from inland towards seawater has been
242 documented in other reports^{27,28}. Data also highlights a contamination decrease from May
243 to October in marine stations. Differently, an increase in BPA concentrations is observed
244 in the Reno river, which was not directly involved in the flooding, possibly due to seasonal
245 fluctuations.

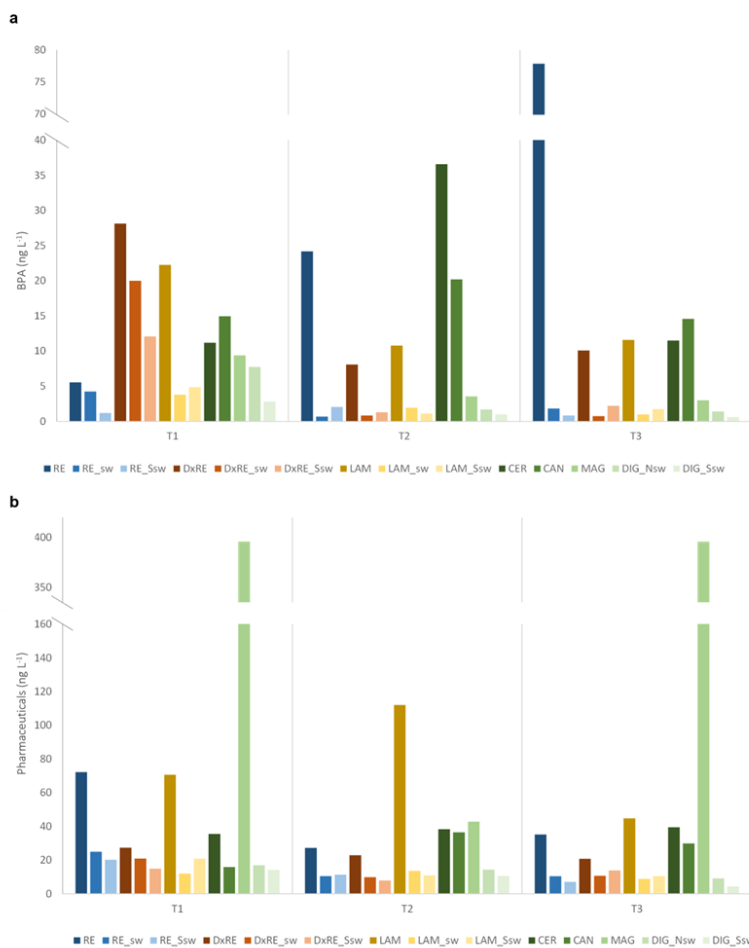


Figure 6 | Emerging contaminants measured in water samples collected during three campaigns in 2023. a | Bisphenol A. b | the sum of the seven pharmaceuticals tested. Limit of quantification (ng L^{-1}) and relative standard deviation (RSD %) ($n=3$) for each compound analyzed are indicated in Materials and Methods.

Commented [anon8]: Very difficult to see, need to have much higher resolution for the paper

252 Remote Sensing and Image-Based Water Quality

253 We evaluated the performance of both on-board Sentinel-3 OLCI and semi-operational
 254 Sentinel-2 water quality retrievals (via ACOLITE and C2Nets) against in situ
 255 measurements of CHL and TSM during the key post-flood periods. Only the best-
 256 performing algorithms for each date and sensor are summarized in Table 2, based on
 257 MAE% relative to in situ means. Full performance metrics for all tested algorithms are
 258 reported in Supplementary Tables S3 (CHL) and S4 (TSM).

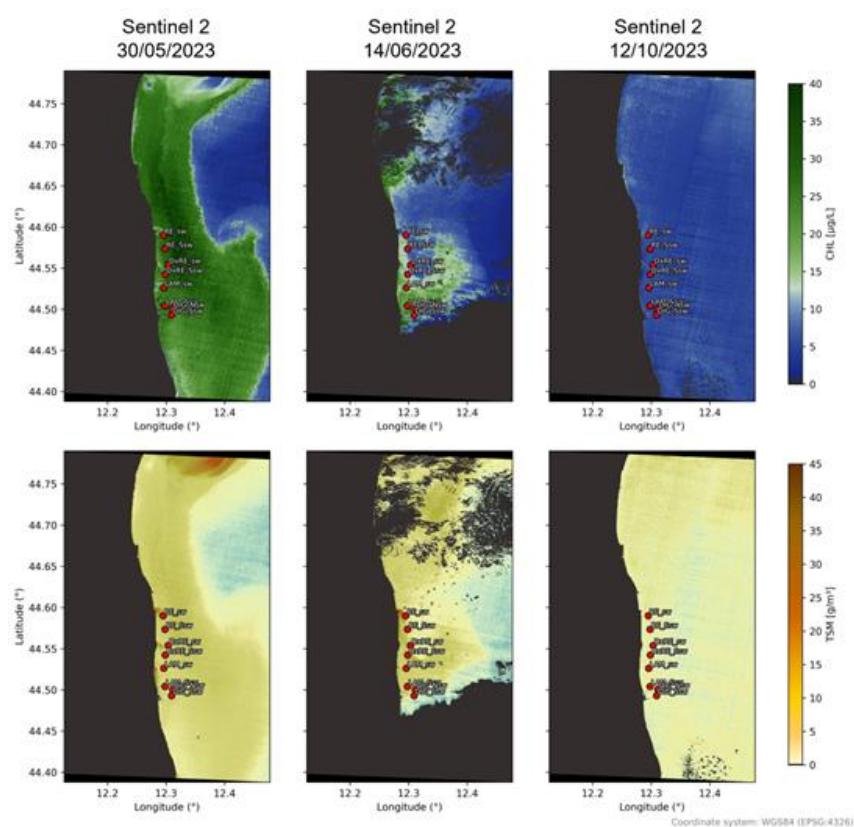
259 **Table 2 | Summary of the best-performing algorithms for chlorophyll-a (CHL, in $\mu\text{g L}^{-1}$) and total suspended**
 260 **matter (TSM, in g m^{-3}) retrieval from Sentinel-2 and Sentinel-3 imagery.** | MAE% and RMSE% were calculated
 261 relative to the average of *in situ* measurements. See Supplementary Tables S3–S4 for a full comparison of all algorithms
 262 tested.

Date	Parameter	Sensor	Spatial Resoluti on (m)	Processor - Product	Algorithm	In-Situ min-max	Estimated min-max	MAE	RMSE	Bias
May 2023	CHL	Sentinel 2	20	C2Nets	C2XCOMPLEX	10.3 - 31.8 $\mu\text{g L}^{-1}$	19.0 - 28.5 $\mu\text{g L}^{-1}$	34.3% (6.8 $\mu\text{g L}^{-1}$)	41.3% (9.2 $\mu\text{g L}^{-1}$)	4.9
				ACOLITE	chl_oc3		16.7 - 24.8 $\mu\text{g L}^{-1}$	31.8% (6.3 $\mu\text{g L}^{-1}$)	36.3% (7.2 $\mu\text{g L}^{-1}$)	-0.5
	TSM	Sentinel 2	20	C2Nets	C2X	11.0 - 44.0 g m^{-3}	10.7 - 16.9 g m^{-3}	53.6% (13.2 g m^{-3})	73.1% (18.0 g m^{-3})	-11.7
					C2XCOMPLEX		8.8 - 14.8 g m^{-3}	57.7% (14.2 g m^{-3})	78.4% (19.3 g m^{-3})	-13.5
June 2023	CHL	Sentinel 2	20	ACOLITE	chl_oc2	0.8 - 2.1 $\mu\text{g L}^{-1}$	4.2 - 7.9 $\mu\text{g L}^{-1}$	243.6%(3.8 $\mu\text{g L}^{-1}$)	262.8%(4.1 $\mu\text{g L}^{-1}$)	3.8
		Sentinel 3 OLCI	300	SENTINEL 3 WFR	chl_nn		2.8 - 6.1 $\mu\text{g L}^{-1}$	179.5% (2.8 $\mu\text{g L}^{-1}$)	185.9% (2.9 $\mu\text{g L}^{-1}$)	2.8
	TSM	Sentinel 2	20	C2Nets	C2X	9.0 - 14.0 g m^{-3}	7.5 - 15.7 g m^{-3}	18.4% (2.3 g m^{-3})	25.6% (3.2 g m^{-3})	-0.1
					C2XCOMPLEX		5.9 - 12.4 g m^{-3}	21.6% (2.7 g m^{-3})	26.4% (3.3 g m^{-3})	-2.3
October 2023	CHL	Sentinel 2	20	C2Nets	C2XCOMPLEX	6.9 - 13.0 $\mu\text{g L}^{-1}$	5.0 - 11.0 $\mu\text{g L}^{-1}$	19.1% (1.8 $\mu\text{g L}^{-1}$)	26.5% (2.9 $\mu\text{g L}^{-1}$)	-1.6
		Sentinel 2		ACOLITE	chl_re_gons		7.2 - 13.5 $\mu\text{g L}^{-1}$	20.1% (1.9 $\mu\text{g L}^{-1}$)	24.4% (2.3 $\mu\text{g L}^{-1}$)	0.9
	TSM	Sentinel 2	20	C2Nets	C2X	8.0 - 21.0 g m^{-3}	6.6 - 12.9 g m^{-3}	49.1% (8.1 g m^{-3})	55.2% (9.1 g m^{-3})	-8.1
		Sentinel 3 OLCI	300	SENTINEL 3 WFR	tsm_nn		3.0 - 12.7 g m^{-3}	56.4% (9.3 g m^{-3})	63.0% (10.4 g m^{-3})	-8.9

Commented [anon9]: Now its TSM, but it was suspended solids in the protist analysis.

263 In May, under highly turbid, flood-affected waters, Sentinel2 algorithms performed best.
264 The ACOLITE *chl_oc3* model delivered the lowest MAE of 31.8 % (RMSE 36.3 %, bias
265 -0.5), closely followed by C2Nets' neural-network variant *C2XCOMPLEX* (MAE 34.3 %,
266 bias +4.9). For TSM, C2X again captured the flood-induced particulate peak, with MAE
267 of 53.6 % and moderate underestimation (bias -11.7), showing robustness in extreme
268 optical conditions. By June, when turbidity began declining, Sentinel3 OLCI *chl_nn*
269 achieved slightly better CHL estimates (MAE 179.5 %) than Sentinel2's *chl_oc2* (MAE
270 243.6 %), yet the coarse 300 m resolution obscured important near-shore heterogeneity.
271 TSM retrieval remained accurate via C2X (MAE 18.4 %, bias -0.1), reflecting improved
272 water clarity but still substantial residual load. By October, both C2Nets' *C2XCOMPLEX*
273 (MAE 19.1 %) and ACOLITE's *chl_re_gons740* (MAE 20.1 %) produced reliable CHL
274 estimates, with low RMSE and near-zero bias, indicating stabilization of water optics. C2X
275 continued to be the preferred model for TSM (MAE 49.1 %, bias -8.1), although accuracy
276 improved in line with environmental recovery. Bias trends further reinforce these findings:
277 ACOLITE's *chl_oc3* consistently underestimated CHL, contrasted with *chl_re_gons740*,
278 which corrected its initial positive bias to become unbiased by October. Meanwhile, C2X
279 and *C2XCOMPLEX* exhibited stable, moderate biases throughout the campaign.
280 Additionally, we compared satellite-derived estimates of CDOM absorption (a_{cdom} at
281 443nm) with laboratory measurements, where available. Since only the C2Nets
282 framework and Sentinel-3 OLCI WFR currently offer CDOM retrievals from satellite
283 imagery, this comparison was limited to a subset of algorithms and dates. The results
284 indicated substantial overestimations and high error levels, suggesting limited reliability

285 over the test period. Given the exploratory nature and limited accuracy of these outputs,
 286 CDOM retrieval metrics are presented exclusively in Supplementary Table S5. Spatial
 287 distribution maps (Figure 7) show a clear temporal decline in both CHL and TSM
 288 concentrations across marine areas, consistent with in-situ observations.



289 **Figure 7 | Maps are generated with the C2X processor (C2RCC plugin, SNAP) from Sentinel-2 imagery. |**
 290 **Chlorophyll-a (CHL, $\mu\text{g L}^{-1}$). b) Total Suspended Solids (TSM, g m^{-3}). Dates of acquisition are shown above each panel.**
 291 **Sampling points are marked in red. The 20 m maps were first masked with the Land/Sea Mask operator, retaining only**
 292 **pixels classified as water in the Sen2Cor Scene Classification Layer, to remove both inland-water and land pixels.**

293 High values in May reflect flood-induced particulate and phytoplankton inputs, followed
294 by progressive decreases in June and stabilization by October. These satellite-derived
295 trends align with field measurements, supporting the potential of remote sensing to
296 complement traditional monitoring in capturing short-term flood impacts and recovery
297 dynamics.

298 3 Discussion

299 The May 2023 flood event dramatically altered environmental, biological, and chemical
300 conditions across the study region. A massive freshwater inflow drastically reduced the
301 salinity concentration at marine stations, while simultaneously elevating dissolved oxygen
302 and nutrient levels, and enhancing sediment transport. Although limited pre-event
303 baseline data are available for individual stations, comparisons with the historical regional
304 datasets provide evidence of the unprecedented impacts induced by this extreme event.
305 In addition, clear deviations from historical datasets strongly emphasize the necessity for
306 widespread and continuous environmental monitoring to capture responses to extreme
307 hydrological events.

308 The impacts observed here are consistent with previous flood events in this region,
309 although in several aspects they have proved even more severe. Notably, the Po River
310 floods of October 2000, described in²⁹, and the May 2014 flood, analyzed in³⁰, both
311 induced major alterations in the marine system, but with distinct quantitative differences.
312 For instance, during the 2000 flood, surface salinity dropped to 6–7 psu, while in 2014
313 minimum salinity values did not fall below 29 psu. In our case, despite a more restricted

Commented [anon10]: You need to have more details about what the RS data actually provided, You could also use RS averages in comparison with the long term averages. You could also use RS to show the changes over time (and demonstrate this with daily averages days to weeks after the event.

Commented [anon11]: How, I don't think this point came out strongly I your results

314 study area, salinity minima extended broadly across all marine stations, reaching 9–10
315 psu, confirming significant freshwater input.

316 Similarly, CDOM absorption (a_{443} up to 1.9 m^{-1}) and TSM values (up to 44 mg m^{-3})
317 exceeded maxima previously recorded for high discharge conditions in the northern
318 Adriatic Sea^{30,31}, suggesting an even greater input of sediments and terrestrial, humic-
319 rich material³². However, concentrations of nutrients such as N and P were lower than
320 those recorded following both the 2000 and 2014 flood events, suggesting potential
321 dilution effects due to the high-water volume or rapid biological uptake.

322 The exceedance of historical environmental values observed post-event is primarily
323 attributable to the floodwater volumes, which mobilized contaminants from both
324 agricultural and urbanized areas, generating urban runoff and delivering a concentrated
325 pulse of pollutants to the inland system. The failure of the drainage network to manage
326 the unprecedented water load further aggravated environmental pressure.

327 In line with the documented physico-chemical alterations, our biological observations
328 confirmed that marine protist communities reacted promptly to the environmental stress
329 induced by the flood event. In particular, the sharp decrease in salinity, combined with
330 elevated nutrient concentrations and high TSM levels, favored the intrusion and
331 proliferation of freshwater-associated taxa, mainly Bigyra, Chlorophyta and Cryptista, into
332 marine inland waters. This reflects the strong advection of riverine and canal waters
333 carrying both dissolved and biological material towards the sea. Such patterns are
334 consistent with established evidence showing that pulses of nutrient-rich freshwater,
335 combined with altered light availability and water column mixing, promote the dominance

Commented [anon12]: But the RS may show late blooms associated with the input of nutrients over the flood period. There needs to be more discussion on this fact

336 of opportunistic, fast-growing species^{33–35}. The rapid increase in Cryptista and other
337 nutrient-tolerant groups observed at marine stations is consistent with post-extreme event
338 dynamics described in other estuarine and coastal systems^{36,37}. In parallel, we also
339 recorded a temporary increase in heterotrophic taxa belonging to the phylum Bigyra and
340 Ciliophora, typically associated with high organic matter availability and turbid, mixed
341 inland waters. Their transient dominance likely reflects the immediate post-flood
342 conditions, characterized by abundant particulate and dissolved organic material
343 transported by riverine inputs, which provided favorable conditions for heterotrophic and
344 osmotrophic protists, as previously observed³⁴. As salinity progressively increased and
345 organic matter concentrations declined, Bigyra abundance rapidly decreased, and
346 environmental conditions gradually shifted towards typical seasonal marine patterns.
347 Interestingly, during the first post-flood sampling (T1, May), marine stations as well as
348 satellite images showed unexpectedly high chlorophyll-a concentrations, coupled with low
349 salinity and high turbidity. This suggests that the initial freshwater inflow not only delivered
350 substantial nutrients but also transported phytoplankton biomass from upstream areas,
351 temporarily enhancing photosynthetic biomass in marine waters despite adverse optical
352 conditions. Such short-term biomass peaks associated with flood plumes are reported in
353 other coastal systems following major hydrological events^{30,37}. Another hypothesis could
354 be that phytoplankton increased the light-harvesting pigments content as a response to
355 river-borne organic material, which caused water browning³⁴.
356 By June, in marine stations, salinity had nearly returned to typical values (35 psu), and
357 TSM decreased, indicating a progressive attenuation of the flood's immediate influence.

358 However, measurements and satellite data show that chlorophyll-a concentrations
359 dropped very fast, suggesting that, despite physical recovery, optical conditions likely
360 remain unfavorable for phytoplankton growth due to residual turbidity and high CDOM
361 levels that could reduce light penetration, limiting in-situ primary production in the
362 immediate aftermath of the flood. This mechanism has been previously highlighted in^{29,38}.
363 In contrast, inland freshwater stations showed a further increase in chlorophyll-a
364 concentrations, where a delayed photosynthetic biomass bloom dominated by
365 Ochrophyta, Heterokontophyta, and Cryptista developed, supported by persistently high
366 nutrient concentrations.

367 Despite this biological bloom, environmental trajectories among inland stations remained
368 more heterogeneous compared to the relatively coherent dynamics observed across
369 marine stations. This reflects the distinct hydrological characteristics, and independent
370 watershed influences of each river or canal system, resulting in site-specific trends in
371 parameters such as salinity, TSM, and nutrient concentrations throughout the study
372 period. However, the biological community at inland stations displayed more consistent
373 patterns. eDNA metabarcoding analyses revealed an initial dominance of opportunistic
374 groups, including Ciliophora and Cryptista, during the early post-flood phase (T1, May),
375 favored by nutrient enrichment and altered water column structure. Over time, these taxa
376 declined, while Heterokontophyta progressively increased, eventually becoming the
377 predominant phytoplanktonic component typical of freshwater-influenced transitional
378 environments. This community's change through time appeared broadly consistent

379 across inland stations, suggesting that ecological succession following extreme events
380 may follow common pathways, even under variable local environmental conditions.

381 By October, marine stations showed clear signs of recovery, with salinity, dissolved
382 oxygen, and TSM stabilizing, and communities returning to seasonal assemblages
383 dominated by Dinoflagellata and Heterokontophyta. Redundancy analysis (RDA)
384 identified salinity, dissolved oxygen, and nutrient loads as the primary drivers shaping
385 protist community structures, consistent with global findings in flood-impacted systems
386 ^{35,39} Additionally, eDNA metabarcoding effectively captured subtle post-flood community
387 shifts, especially among cryptic heterotrophic protists, highlighting its value as a sensitive
388 monitoring approach.

389 These spatial patterns of ecological disturbance and gradual recovery were mirrored by
390 the clear temporal and spatial gradients of emerging contaminants, including bisphenol A
391 and pharmaceuticals across the study area. Overall, contaminant levels decreased from
392 inland stations towards marine stations, both immediately after the flood and during
393 subsequent months. Such patterns are consistent with previous studies reporting dilution
394 and dispersion processes at the land-sea interface as reported in^{27,28}, although our data
395 highlight the influence of local hydrodynamics and persistent upstream sources.

396 Drainage channels showed levels of contamination comparable to or even higher than
397 rivers, suggesting the need for monitoring actions to which they are not yet subjected.

398 The highest BPA and pharmaceutical concentrations were recorded at freshwater sites
399 exposed to chronic anthropogenic inputs, particularly MAG and CER, with values
400 progressively decreasing in marine waters downstream of channel mouths, likely due to

401 dilution, mixing, and degradation processes. We can only speculate that this trend is
402 related to the flooding, because of the lack of previous CECs data for this drainage water.
403 Moreover, a general decline in contaminant concentrations was observed from May to
404 October, especially at marine sites, paralleling the recovery trends recorded for the other
405 physical and chemical parameters, and for the biological communities. While the absence
406 of detailed pre-event baselines limits the considerations, this decline is probably linked to
407 the progressive dissipation of the flood's immediate impact.
408 Interestingly, divergent trends emerged at certain freshwater stations **unaffected by the**
409 **flood, such as the Reno river,** where BPA concentrations increased over time, possibly
410 reflecting seasonal variability or specific local sources independent of the flood dynamics.
411 Environmental and biological changes were also evident in the performance of satellite-
412 based monitoring products, whose accuracy varied across stations and time points,
413 strongly influenced by evolving hydrological conditions. The same optical complexity -
414 due to elevated TSM and CDOM - that affected biological communities and light
415 penetration also posed significant challenges for remote sensing-based monitoring. As
416 reported in⁴⁰, estuaries and coastal zones fall under the so-called Case 2 water⁴¹ where
417 inorganic particulate matter and colored dissolved organic matter play a dominant role in
418 shaping the optical signal, often masking the contribution of chlorophyll-a. In such
419 environments, algorithms exploiting red and near-infrared wavelengths have been
420 proposed to improve chlorophyll-a retrievals⁴²⁻⁴⁵, yet their empirical nature necessitates
421 region-specific tuning to ensure applicability⁴⁶.

Commented [SS13]: chiariamo questo concetto di non influenza della flood prima nell'articolo' scusa, mi deve essere sfuggito, forse cmq è bene mettere in grande evidenza già nell'Intro se ci sono siti affetti e siti non affetti dalla flood

422 Overall, chlorophyll-a retrievals performed best in October (T3), coinciding with the
423 ecological recovery phase, when salinity, CDOM and TSM values approached seasonal
424 baselines and extreme in-situ concentrations of chlorophyll-a were no longer present.
425 This suggests that under stabilized post-flood conditions, the performance of algorithms
426 improves, highlighting their sensitivity to local water quality fluctuations.

427 Overall, CHL retrieval performance was comparable to, or in some cases better than,
428 values reported for similar coastal systems, such as the northern Adriatic nearshore
429 waters in Veneto region⁴⁷, while other European coastal sites have shown even greater
430 errors⁴⁸.

431 A similar pattern was found for TSM retrievals. C2Net based products, particularly C2X,
432 exhibited MAE and RMSE comparable to those obtained by Marzano et al. (2020) for the
433 northern Adriatic using C2RCC. However, our results also reveal clear temporal variability
434 in algorithm performance. At T1, during the peak of the flood impact, RMSE reached
435 19 g m^{-3} , slightly exceeding the values reported in⁴⁷. Conversely, at T2 and T3, RMSE
436 values decreased substantially to 3 g m^{-3} and $8\text{--}9 \text{ g m}^{-3}$, respectively, indicating
437 improved performance and lower retrieval errors compared to previous literature in two
438 out of the three sampling periods. CDOM retrieval performance was limited, with high
439 retrieval errors observed at T1 and T2. Moreover, due to low in-situ CDOM concentrations
440 and unreliable laboratory measurements, no validation was possible for T3. These results
441 reinforce the need for further refinement and local calibration of CDOM products,
442 especially under extreme post-flood conditions where CDOM dynamics play a key
443 ecological role.

Commented [anon14]: There is an abundance of literature of mapping flood plumes with remote sensing. You have not really explained how other aspects of the RS data can help understand the extent and duration of the flood plume - note work in Great Barrier Reef and elsewhere - Petus et al, Devlin et al., Waterhouse et al. - it would have been useful to see these types of flood metrics used alongside the WQ retrievals.

444 These observations highlight that satellite product accuracy is strongly influenced by local
445 hydrological and optical variability, aligning with the dynamic environmental gradients
446 observed in in-situ measurements and biological data throughout the study. Consequently,
447 careful algorithm selection and region-specific calibration remain essential to accurately
448 monitor coastal water quality, particularly under extreme flood conditions that amplify
449 optical complexity. Future efforts should prioritize the development of flexible approaches
450 that integrate evolving biogeochemical, hydrological, and optical characteristics to
451 enhance remote sensing performance in flood-impacted coastal environments.

452 Overall, our findings provide evidence that, despite the significant disruption caused by
453 the 2023 Emilia-Romagna flood, inland and marine environments demonstrate strong
454 resilience, showing possible signs of recovery within a few months after the event. By
455 October, most physico-chemical variables returned to expected levels, and the
456 community structures were restored, supporting a rapid, intrinsic resilience of the system.
457 Satellite products helped track these trends but still struggled to resolve the extreme
458 spatial and temporal variability characteristic of coastal environments impacted by major
459 flooding.

460 Results underscore how extreme hydrological events reshape coastal environments
461 through interconnected physical, chemical, and biological alterations, whose impacts
462 propagate from inland waters to the marine domain. These types of extreme events
463 produce cascading effects at multiple temporal and spatial scales, with both immediate
464 and delayed consequences for ecosystems, human health, and economic sectors.
465 However, the limited availability of high-resolution pre-event baselines constrains

466 comprehensive impact assessments. To enhance predictive capacity and inform
467 management strategies, future efforts should prioritize long-term, integrated monitoring
468 that combines traditional sampling, molecular tools, and adaptive remote-sensing
469 technologies, particularly as climate change is expected to amplify the frequency and
470 intensity of such disturbances in the northern Adriatic.

471

472 4 Conclusions

473 This multidisciplinary study provides a comprehensive snapshot of the short- and
474 medium-term impacts of the May 2023 flood event in Emilia-Romagna, capturing for the
475 first time the environmental, biological, and chemical alterations induced by such an
476 extreme hydrological disturbance in this coastal region. Despite the absence of site-
477 specific pre-event baselines, which represents a critical limitation, this study offers a
478 crucial reference point, a “post-event photograph” against which future monitoring efforts
479 and environmental assessments can be compared. The study demonstrated the
480 importance of applying a sampling design that included rivers and canals, together with
481 coastal marine sites. Thanks to this sampling strategy, it was possible to trace the
482 pathways and characteristic times required for nutrients and pollutants to travel from the
483 plain to the sea. We showed that the flood mobilized contaminants from agricultural and
484 urban areas, delivering a concentrated pulse of pollutants to the coast, further intensified
485 by the failure of the drainage network. In response, marine protist communities showed
486 rapid shifts, with freshwater-associated taxa proliferating due to decreased salinity,

Commented [anon15]: You have not presented flow data. This could be an important part of your understanding - what type of flow event occurred and measure this against long term flow of major river/rivers.
In the absence of flow data - why not use long term rainfall data to set the historical context.

487 elevated nutrients, and high TSM levels. Right after the flood, both marine stations and
488 satellite data revealed high chlorophyll-a levels, suggesting that nutrient-rich floodwaters
489 and upstream phytoplankton transport temporarily boosted marine biomass despite low
490 salinity and high turbidity.

491 Despite the severity of the initial impacts, including pronounced shifts in water chemistry,
492 biological communities, and emerging contaminant concentrations, ecosystems
493 demonstrated a notable capacity for resilience and recovery within a few months,
494 particularly evident by October 2023. Although the system demonstrated the capacity for
495 short-term ecological recovery, questions remain regarding its long-term resilience,
496 particularly under scenarios involving increased frequency and intensity of such extreme
497 events driven by climate change. Our findings highlight a critical gap for future research:
498 the urgent need to implement continuous, long-term, multi-parameter monitoring
499 programs that combine conventional assessment protocols, aligned with major legislative
500 frameworks, with innovative analytical approaches, such as high-resolution remote
501 sensing and molecular tools. Such integrated strategies are essential to capture
502 environmental dynamics and assess ecosystem responses under extreme event
503 scenarios, ultimately improving preparedness and management capacity in the face of
504 climate-driven hydrological disturbances.

505

506

5 Materials and Methods

5.1 Study Area and Field Measurements

The study focused on the monitoring of rivers and freshwater canals (hereafter indicated as “inland stations”), as well as the Adriatic Sea in front of the Ravenna coast, which were impacted and affected by the May 2023 flood event. Inland sampling stations included the terminal reaches of the Reno, Destra Reno, and Lamone rivers to the north of the city, as well as the Cerba, Canala, and Magni drainage canals, which drain the western part of the city and discharge into the Baiona Canal before reaching the sea ([Error! Reference source not found. Figure 4](#)). Reno River and Cerba drainage canal were designed as control points as they remained unaffected by the flood. Although the Reno River catchment experienced elevated water levels during the rainfall period, no flooding was recorded within its watershed. Similarly, the Cerba canal drains a small coastal basin in the north of Ravenna that did not experience inundation. As such, these sites served as reference points for water quality and biological analyses, providing representative conditions for non-impacted areas.

Marine sampling stations were selected about 1 km offshore and located in front of each river mouth and at the midpoints between them. Two additional marine stations were situated 1.5 km offshore, in the south and north of the Ravenna port’s jetties. Due to the presence of the long jetty infrastructure (2.4 km) acting as a physical barrier, the southern station was used as control point because protected from the direct influence of northern

527 fluvial and canal plumes originating by the flood. It was considered suitable reference
528 points for assessing baseline marine conditions unaffected by the flood-induced inputs.
529 Three monitoring campaigns were carried out on the 30th of May, 16th June, and 10th
530 October 2023. This timeline enabled a comprehensive evaluation of both the short- and
531 medium- term impacts of the flooding on inland and marine ecosystems of the study area,
532 as well as the processes of environmental recovery. May 30th was selected as the earliest
533 feasible sampling date, coinciding with the lifting of emergency restrictions related to
534 hydrogeological risk. June was chosen to capture early post-event conditions, while
535 October 10th represented a later time point, allowing evaluation of the system's potential
536 recovery and the re-establishment of pre-event conditions.

537 At each sampling station, physical and chemical parameters such as temperature (T),
538 electrical conductivity (EC), pH, redox potential (Eh), and dissolved oxygen (DO) were
539 measured by a HQ4300 Portable Multi-Meter (HACH®, Loveland, CO, USA), while
540 samplings of surface water were collected to perform chemical and biological community
541 analysis:

- 542 ▪ 0.5 liter for eDNA metabarcoding
- 543 ▪ 1 liter for pollutant analysis
- 544 ▪ 2 liters for biological analyses (chlorophyll-a (CHL), phaeopigments, inorganic
545 nutrients (N and P), Total Suspended Matter (TSM) and Chromophoric Dissolved
546 Organic Matter (CDOM)

547 Samples were stored in pre-washed rigid 1-liter plastic bottles (10% HCl or NaClO).
548 Salinity (S) was measured in the field using a refractometer.

549 5.2 Water Quality Assessment

550 Water samples of inland costal stations (rivers and drainage canals) ([Error! Reference](#)
551 [source not found, Figure 4](#)) were filtered through a 0.45 µm membrane filter, stored in
552 pre-cleaned 100 mL HDPE plastic bottles until further analysis. Samples for cations and
553 trace elements (TEs) determination were acidified with 1% HNO₃. Major anions and
554 alkalinity were analyzed within 24 hours by Ion Chromatography (883 Basic IC plus
555 Metrohm AG, Herisau, Switzerland) and major cations and PTE by Inductively Coupled
556 Plasma–Optical Emission Spectroscopy (Agilent 5800 ICP-OES, USA). The calibration
557 curve was built using certified standards in water. For both cations and anions, the
558 standards set by the Italian National Environmental Agency, APAT-IRSA 2003 were
559 applied. For all the samples, the ionic balance was ±5%. Considering internal and external
560 standards, accuracy and precision were better than 10% for all elements considered.
561 Results of river samples were compared against the long-term monitoring series (2013 to
562 2023) of Reno, Destra Reno and Lamone rivers downloaded from the Regional
563 Environmental Protection Agency of the Emilia-Romagna Region (Arpae) website
564 ([https://dati.arpae.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-](https://dati.arpae.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023)
565 [fluviali-dati-2010-2023](https://dati.arpae.it/dataset/rete-regionale-per-la-qualita-ambientale-acque-superficiali-fluviali-dati-2010-2023)). For comparison with historical data from Arpae, nitrate (NO₃⁻)
566 concentrations were used, given that nitrite (NO₂⁻) values were consistently missing from

the Arpae dataset, suggesting concentrations below detection limits. Our measured values of dissolved nitrogen represent the sum of nitrate and nitrite ($\text{NO}_3^- + \text{NO}_2^-$). Water samples were analyzed for CHL, inorganic nutrients, CDOM (only marine stations), and TSM.

CHL samples were kept cool and dark until analysis. Volumes of 200–600 mL were filtered on Whatman GF/F filters (0.7 μm , 47 mm). Pigments were extracted with 90% acetone, and concentrations measured by spectrophotometer (Jasco V-650) at 750 and 665 nm following⁴⁹. Phaeopigments were quantified after acidification to a final concentration of 0.66 M HCl.

Nitrate as N [$\text{NO}_3^{2-} + \text{NO}_2^-$] and Phosphorous as P [PO_4^{3-}] were analyzed in filtered water samples (GF/F filters), stored in polyethylene bottles pre-washed with 10% HCl. Spectrophotometric analysis was carried out according to⁵⁰. TSM was measured gravimetrically following the method described in⁵¹. Water samples were filtered onto pre-weighed 0.45 μm membrane filters. For marine samples, filters were rinsed with 0.5 M ammonium formate (2× the filtered volume) to remove residual salts. Filters were then oven-dried at 105 °C and reweighed to determine particulate mass. CDOM absorption was measured spectrophotometrically following⁵², based on UV-visible absorbance spectra collected on filtered samples (0.2 μm) across the 250–800 nm range. CDOM absorption coefficients were specifically determined at 443 nm.

CDOM absorption at 443 nm was measured during all three field campaigns. However, at T3 (October), most laboratory-derived values were negative or close to zero, consistent with CDOM concentrations near or below the detection limit and increased instrumental

589 uncertainty. These values were excluded from the comparative analysis to ensure reliable
590 performance assessment

591 5.3 Protist communities' assessment

592 In order to analyze the protist communities, eDNA analysis was performed on all inland
593 and marine water samples. They were pre-filtered on 3 µm nitrocellulose filters and re-
594 filtered on a 0.22 µm nitrocellulose filter. After filtration, filters were stored at -20°C. Total
595 DNA from the filters was extracted using the BioFast Soil Genomic DNA Extraction Kit
596 (BioFlux, Hangzhou, Zhejiang, China), following the manufacturer's instructions, with two
597 negative controls included per extraction batch to check for contaminations. PCR
598 reactions for the V4–V5 region of the 18S rRNA were carried out in a total volume of 20
599 µL and included 17 µL of AmpliTaq Gold™ 360 Master Mix (Applied Biosystems), 0.5 µL
600 of each primer (F-566, R-1200; 10 µM)⁵³ that already included 12-bp tags for multiplexing,
601 and 2 µL of DNA template, with the following thermal profile: 95°C for 15 min, followed by
602 35 cycles of 95 °C (45s), 60 °C (45s), 72 °C (1min), and a final extension at 72 °C for
603 10min. PCR products were evaluated by agarose gel electrophoresis (1.5% gel, 0.5X
604 TBE). For the 18S library, PCR products were pooled and purified with the Macherey-
605 Nagel™ NucleoSpin Gel and PCR Clean-up Kit to remove DNA fragments <70 bp. DNA
606 concentration was measured with a Qubit fluorometer (Broad Range kit, Invitrogen). The
607 libraries were sequenced in-house with a MinION Mk-1C (Oxford Nanopore
608 Technologies). The 18S library was prepared with the SQK-LSK110 kit and sequenced
609 on a FLO-MIN111 flow cell with a 22-hour run. Basecalling was conducted using Guppy

(ONT) with a quality threshold of 8. Demultiplexing and length filtering were performed with OBITOOLS⁵⁴. The taxonomic assignment was conducted using the RDP classifier with the SILVA 138 reference database at genus level^{55,56}. Data were cleaned keeping only protist taxa that had a total read count of at least 10 and a similarity threshold of 97%. Since some samples did not amplify and to ensure consistency, only samples present in both biological and environmental datasets were considered for the Redundancy Analysis (RDA). Environmental parameters considered for the RDA were N, P, TSM, DO, temperature and salinity. Protist abundance data were square-root transformed, and environmental variables were standardized with *decostand()* to allow comparison among different scales. RDA analysis allows the samples and environmental factors to be represented on the same two-dimensional ordination plot to visualize their relationships. RDA was performed with *rda()* using scaling 2, to highlight the effects of explanatory variables (environmental parameters). The significance of each environmental variable in explaining community structure was assessed with *anova.cca()*. All analyses were performed in R version 4.4.1 (R Core Team, 2024), using the vegan package⁵⁷ and ggplot2⁵⁸ for data visualization.

5.4 Contaminants of emerging concern (CECs) analyses

To analyze CECs, water samples were spiked with a mixture of labeled internal standards (BPA-d6 and Ibuprofen-d3) at a concentration of 30 ng L⁻¹. Samples were filtered using glass microfiber filters (1.60 µm), then with cellulose acetate filters (0.45 µm), and extracted using Solid Phase Extraction (SPE) Oasis HLB cartridges as reported in⁵⁹.

631 Cartridges were eluted with 6 mL of methanol, evaporated under a nitrogen gentle stream
632 up to a volume of 250 μL , and split into two vials of 125 μL each. The first set of vials was
633 additioned with 125 μL of water (50:50 water/methanol) for chemical analysis of Bisphenol
634 A (BPA); the remaining vials were further evaporated to 25 μL and reconstituted in 250
635 μL of a mixture of water/methanol (90:10) for LC-MS-MS analysis of pharmaceuticals.
636 Samples were transferred into 2 mL vials, after filtration (0.22 μm CA membrane filters)
637 for analysis. Chemical analysis of BPA in water samples was performed by ultra-high-
638 performance liquid chromatography (ACQUITY UPLC® H-Class) equipped with a triple
639 quadrupole mass spectrometer (Xevo® TQ-S Micro) using a negative electrospray
640 ionization source in multiple-reaction monitoring (MRM) mode. Separation of compounds
641 was achieved through an ACQUITY UPLC® BEH C₁₈ column (100 $\times$ 2.1 mm, 1.7 μm
642 particle size, 130 Å pore size) equipped with a pre-column (BEH C₁₈ VanGuard™ pre-
643 column, 5 $\times$ 2.1 mm i.d., 1.7 μm particle size). The volume injection was 10 μL . Sample
644 extracts concentrated 2000 times were measured along with calibration standards, which
645 corresponded to a range of 1–300 $\mu\text{g L}^{-1}$. Chemical analysis of pharmaceuticals was
646 performed by the IRCCS (Istituto di Ricerche Farmacologiche “Mario Negri”, Department
647 of Environmental Health Sciences), as described in⁶⁰.

648 5.5 Remote Sensing and Image Processing

649 The aim of the remote sensing use in this study was to evaluate whether ready-to-use
650 (e.g., Sentinel-3 OLCI) and semi-operational products (based on Sentinel-2 data
651 processing) could reliably estimate water quality parameters, especially under extreme
652 hydrological conditions, such as those that followed the May 2023 flood.

653 We applied and compared multiple algorithms across satellite products to identify those
654 most accurate and operationally useful for post-flood environmental monitoring. Each
655 satellite of the Sentinel-2 constellation is equipped with the Multispectral Instrument (MSI),
656 which captures data across 13 spectral bands, ranging from visible (VIS) and near-
657 infrared (VNIR) to the shortwave infrared (SWIR) spectrum. The MSI provides spatial
658 resolutions of 10 m (VIS and VNIR), 20 m (red-edge and vegetation-related bands), and
659 60 m (bands for atmospheric correction). For this study, Sentinel-2 Level-1C products
660 were downloaded from the Copernicus Browser, accessible at:
661 <https://browser.dataspace.copernicus.eu>.
662 The images selected correspond to dates closest to in-situ sampling. In cases where
663 satellite overpass or high cloud cover prevented acquisition on the exact sampling date,
664 the nearest available image was used (see Supplementary Table S6 for the date list).
665 Images were pre-processed using ESA's SNAP software (v.11.0.0) (software available
666 at: <https://step.esa.int/main/toolboxes/snap>), including subsetting to the area of interest
667 and resampling to a spatial resolution of 20 m. This processing step follows previous
668 findings showing that 20 m resolution provides more stable and accurate water quality
669 estimates from Sentinel-2 imagery⁶¹. The actual processing of the images included the
670 atmospheric correction followed by the retrieval of two water constituents, CHL and TSM,
671 as well as CDOM absorption at 443 nm. These parameters were retrieved using two
672 distinct methods, each based on different algorithms and coefficients (see Supplementary
673 Table S7):

- The Case 2 Regional Coast Colour processor (C2RCC), developed by⁶² and integrated within SNAP, applies a two-step neural network inversion approach. First, atmospheric correction is performed by estimating top-of-atmosphere (TOA) radiance contributions (e.g. water vapor, aerosols), followed by the inversion of surface reflectance to derive inherent optical properties (IOPs) of the water column. Neural networks are trained using an extensive dataset (million of simulations) based on radiative transfer model that covers a wide range of IOPs^{62,63}, including pigment absorption (a_{pig}), detrital absorption (a_{det}), CDOM absorption (a_{gelb}), and also scattering by both sediment (b_{part}) and calcareous particles (b_{wit}). Three variants of the model were applied, allowing the processor to adapt to a broad variety of water conditions. Specifically, the suite of C2RCC neural networks (collectively referred to here as "C2Nets") includes: i) C2RCC, optimized for mesotrophic and moderately turbid coastal waters; ii) C2X, designed for highly turbid or extreme optical conditions; and iii) C2XCOMPLEX, targeting optically complex waters with intermediate turbidity levels. All three variants were tested to evaluate their performance under the extreme conditions caused by the flood event.
- ACOLITE (software available at: <https://github.com/acolite/acolite>, version 20231023.0) was also employed for atmospheric correction, applying the Dark Spectrum Fitting (DSF) algorithm, which estimates aerosol optical thickness and path reflectance through dynamic dark pixel selection⁶⁴. ACOLITE is particularly suited for turbid and optically complex waters, providing robust correction under

highly dynamic aquatic conditions. In addition to atmospheric correction, ACOLITE offers a suite of empirical and semi-analytical algorithms (see the full list in Supplementary Table S7) to estimate chlorophyll-a (CHL), turbidity (expressed in Formazin Nephelometric Units, FNU), and total suspended matter (TSM, in g/m³) from remote sensing reflectance (Rrs). While turbidity is an optical parameter related to water clarity, TSM represents the actual concentration of suspended particulate matter. In this study, TSM algorithms were prioritized to ensure direct comparability with in situ TSM gravimetric measurements.

To further assess the potential of ready-to-use satellite products, we also employed data from Sentinel-3, which carries the Ocean and Land Colour Instrument (OLCI), specifically designed for marine and inland water monitoring, among other applications. OLCI is equipped with 21 spectral bands spanning the visible to near-infrared (VIS–NIR) regions, enabling the detection of key water quality parameters at large spatial scales. The OLCI Water Full Resolution (WFR) products are Level-2 outputs providing remote sensing reflectance (Rrs) and derived biogeophysical parameters such as CHL and TSM and they are available at: <https://browser.dataspace.copernicus.eu>. These products are generated through ESA's operational processing chains using standard algorithms (see Supplementary Table S7 for a full list of algorithms). OLCI WFR products offer a native spatial resolution of 300 meters, which, while coarser than Sentinel-2, provides the advantage of high temporal coverage and consistent processing standards, making them valuable for large-scale or regional monitoring. Once the Level-2 products were obtained, a match-up analysis was performed between satellite-derived estimates from each

718 algorithm and the corresponding in-situ measurements. This was conducted separately
719 for the products derived from Sentinel2 (C2Nets-derived and ACOLITE-derived products)
720 and Sentinel-3 OLCI. For each product and acquisition date, a 3x3 pixel window centered
721 on the GPS coordinates of each sampling station was extracted. Within each window,
722 quality flags were analyzed to exclude unreliable pixels, thereby ensuring data quality.
723 Subsequently, the remaining pixel values were averaged to derive a representative
724 satellite-based estimate for comparison with laboratory measurements. To quantitatively
725 evaluate the satellite-derived estimates against in-situ reference measurements, three
726 statistical metrics commonly used for the validation of remote sensing products were
727 employed: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Bias.

728 6 Data availability (mandatory)

729 The data that support the findings of this study are available from the corresponding
730 authors upon reasonable request. The datasets will be made publicly available via
731 Zenodo upon request by the journal reviewers or upon acceptance for publication.

732 7 References

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900

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Author contributions

F.C., E.F., B.M.S.G., N.G., L.P., S.S. and P.V. contributed to the conceptualization, methodology, and project administration of the study.

Formal analysis was carried out by B.M.S.G., N.G., L.P., P.V., R.B., A.P., M.L.T., and C.L.

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R.B. and C.C. prepared the original draft. All authors contributed to the review and editing of the manuscript and approved the final version.

These authors jointly supervised this work: F.C., E.F., B.M.S.G., N.G., L.P., S.S. and P.V.

Competing interests

The authors declare no competing interests.