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Brief communication: On the environmental impacts of the 2023 floods in Emilia-Romagna (Italy)

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Abstract. The impacts of floods on environmental assets are often not assessed. In this communication, we reflect on this issue by analysing the reported environmental consequences of the 2023 Emilia-Romagna floods. The information on the environmental impacts is constructed by collecting data from reports, press releases, and interviews in the aftermath of the events. The most frequently reported damage involves water resources and water-related ecosystems, with cultural and supporting ecosystem services particularly affected. Indirect effects in time and space, intrinsic recovery capacity, cascade impacts on socio-economic systems, and the lack of established monitoring activities appear to be the most challenging aspects for future research.

1 Introduction

Floods are among the most damaging natural hazards (Munich Re, 2023). Direct economic damages such as those to homeowners or companies are well known since affected citizens ask insurance companies or public authorities for compensation. On the other hand, damage to public properties, such as natural areas, fades to the background because they receive less attention than other losses in the media and in the political agenda. Moreover, for a long time, the belief that, being a natural phenomenon, flooding has limited effect on natural ecosystems has probably prevented a deep investigation on its potential impacts on the environment. However, we are no longer in the time when flooding brings relevant benefits to human activities (e.g. Nile River floods for agriculture in ancient Egypt). At present, natural areas have been shrunken by human development and urbanization and are reduced to spots of territory (in some cases even protected by law to avoid their disappearance) immersed in anthropized areas (Ren et al., 2023). Human activities have reduced floodplains worldwide (Rajib et al., 2023), also reducing the recurrence of flood events and altering riparian ecosystems (Walker et al., 2022). Moreover, when a flood occurs, many sources of pollution might be affected by flood waters and undesired substances can be transported to many different environmental matrices, phenomena referred to as "Natech events" (Suarez-Paba et al., 2019).

Flooding can have a significant impact on the biodiversity of natural ecosystems and the degree of impact depends on species and environmental and flood characteristics (e.g. scour of riverbed sediment) (Zhang et al., 2021; Francoeur and Biggs, 2006). Flooding also influences the abundance of riverine species, their migration patterns, and the ingress of non-native species (Sueyoshi et al., 2023; Thomaz, 2022).

Although ecologists have been studying specific problems related to the influence of flooding on specific habitats or species, systematic mapping of environmental areas or habitats potentially exposed to flooding is often not included in flood risk management plans (e.g. maps and risk management plans required by the EU Flood Directive). This could also be attributed to the fact that several characteristics of environmental damage are still not clear or are difficult to qualitatively and quantitatively estimate. Perhaps, aspects deserving more attention include, first, the identification of the types of natural environments that can be threatened or damaged by floods and, second, the quantification of the potential degree of damage, its nature (indirect, direct, intangi-

ble, monetizable), and its persistence in time with respect to the natural resilience of ecosystems. Finally, it is also worth mentioning that the potential for cascade effects to human health and economy is still mostly unrevealed.

This brief communication aims at bringing up the subject of flood impacts on the environment by highlighting the impacts reported after the 2023 floods in Emilia-Romagna on natural environment and resources. Specifically, the objective is to reflect on the lack of methodological background and shared methods for the territorial analysis of flood-induced environmental impacts by identifying (1) available data and their representativeness, (2) the most significant environmental consequences and affected ecosystems, and (3) the physical mechanisms behind such consequences. A greater consciousness on the relevance of these topics is essential to foster additional investigation and greater attention by our community.

2 Case study and method

2.1 The 2023 floods in Emilia-Romagna (Italy)

In May 2023, the Emilia-Romagna (ER) region (northern Italy), one of the most economically developed areas in the country, experienced severe and spatially extended flooding. This was the consequence of particular hydrological and weather conditions reached after two major intense rainfall events that hit the same area: a first event on 1–4 May and a second one on 16–18 May. The second event, in particular, was due to a vast area of low atmospheric pressure affecting the entire central Mediterranean basin that channelled moisture-laden air masses from North African coasts toward the Italian peninsula. The cyclone circulation moved the air masses towards central Italy, where the combination with cold air coming from the north and the hills of the Apennines caused the persistence of heavy rainfall over eastern ER and Marche regions. Several gauging stations on hill basins recorded rainfall of more than 200 mm in 48 h (the highest value ever recorded in some cases since their installation), with an overall estimation of roughly 350×10^6 m^3 of water (equivalent to that on average expected over a 6-month period in the same region) falling in 36 h (Barnes et al., 2023).

The impact of such events was devastating, also because they hit basins and rivers already affected by intense rainfall and floods (i.e. levee overtopping and failures) occurring after the 1–4 May event: 23 rivers overflowed, affecting 100 municipalities, and more than 400 landslides severely damaged infrastructure (e.g. road, railways, electrical networks), also limiting rescue activities. In total, the events caused more than 36 000 people to be displaced and 15 deaths (Agenzia per la sicurezza territoriale e la protezione civile, 2023).

The area affected is one of Italy's most important economic regions, relevant for agriculture and industrial activities, as well as being a tourist attraction. Thus, a first rough estimate pointed out damages of EUR 8.8 billion, a value that probably depicts a fraction of the real economic impact.

In fact, the region is also characterized by relevant and important natural resources (e.g. the UNESCO biosphere reserve of the Po River delta) that were affected by the flooding too. However, impacts (economic and otherwise) on them are hardly estimated and not considered in the current economic damage estimates.

2.2 Data collection and analysis

Differently than other type of damage (e.g. private houses, economic activities), environmental impacts of the events were not systematically recorded by the authorities. In the aftermath of the Emilia-Romagna floods, from June to September 2023, a web-based search of the string "Romagna flood environmental damage" ("*alluvione Romagna danni ambientali*" in Italian) was carried out and has been repeated over time to look for newspaper articles, press releases, interviews, and videos. Whenever possible the areas where environmental damage was reported have been georeferenced. Flooded areas have been retrieved from the Copernicus Rapid Mapping service and other tools available to local authorities (e.g. ESA mapping services). All the observed impacts have been listed, described, and then grouped according to the physical cause of the damage and the driving flood mechanism responsible for the damage. The type of environmental assets uncovered and the main ecosystem services affected have been reconstructed based on the search of environmentally protected areas listed in national and regional geographic databases.

3 Results and discussion

3.1 Observed environmental impacts

Figure 1 shows the map of inundated areas (blue shades), protected areas (dashed green line) and the reported impacts containing enough information for their georeferencing. Protected areas include Natura 2000 areas, wetlands, and national and regional parks. According to the collected data, 12 different types of environmental impacts have been observed, which are summarized in Table 1. The most frequent impact observed is the bathing ban issued by the Regional Environmental Protection Agency (ARPAE, 2023) for 11 beaches due to levels of faecal microorganisms above bathing water quality limits (light blue symbol in Fig. 1). In fact, the flood events affected wastewater treatment plants (WWTPs) and sewerage systems with a consequent release of untreated wastewater in rivers.

The second most frequent environmental impact reported is the interruption of nesting by species such as seagulls, terns, avocets, flamingos, and black-winged stilts (magenta symbol in Fig. 1) (M. Costa, 2023). This impact occurred

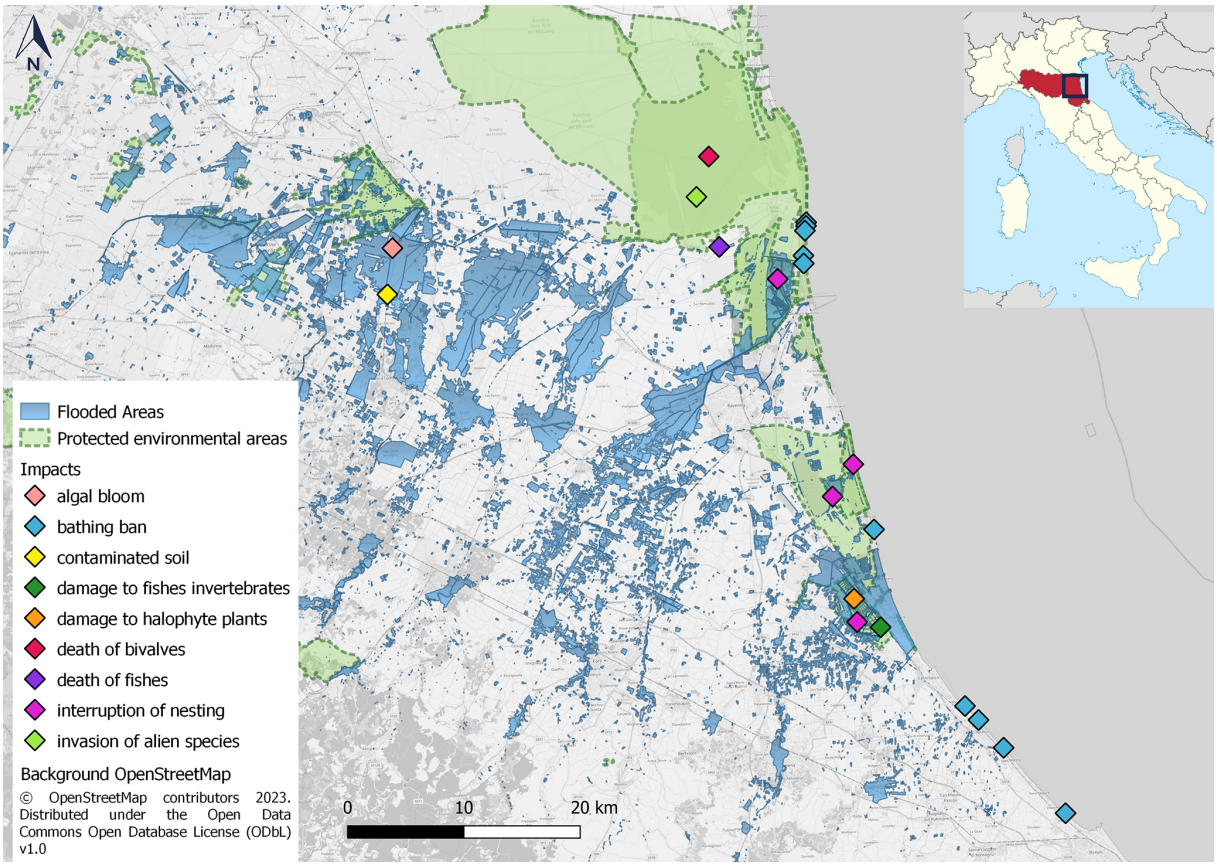

Figure 1. Setting of the study area (top right), map of inundation, protected areas, and observed environmental impacts.

in coastal wetlands and river mouths that were flooded, particularly in three areas listed according to Ramsar convention, i.e. the salt pan of Cervia (national natural reserve), Ortazzo e Ortazzino, and Pialassa della Baiona (the latter both Natura 2000 areas, in the regional park of the Po River delta).

Other reported impacts were algal blooms and death of fishes in rivers (some of them without precise geographic position) that were reported as consequences of high concentration of nutrients and anoxia in freshwaters due to WWTPs and sewerage inefficiencies and wash-off from agricultural surfaces (ARPAE, 2023). Reports of damage to plants (halophyte) and fauna (e.g. bivalves, micro invertebrates) were also described for several species typical of hypersaline ecosystems, altered by freshwater ingress (M. Costa, 2023; Bovenzi, 2023). Also, the sudden invasion of alien species (*Callinectes sapidus*) in these environments has been attributed to a change in salinity (T. Costa, 2023).

Finally, one reported case of contaminated soil affected the area of the municipality of Conselice, where floodwaters stagnated for about 2 weeks and residents were evacuated for sanitary reasons. Other impacts mentioned involved riparian habitats of flooded rivers due to the erosion of banks and vegetation removal (Agenzia per la sicurezza territoriale e la protezione civile, 2023).

As summarized in Table 1 (last column) three main flood-related processes are here recognized as responsible for damage to environmental assets, namely (i) contamination and transport of pollutants, (ii) submersion, and (iii) erosion.

To better understand environmental impacts of flooding, other recent events have been explored to allow for a data comparison. From a national perspective, the September 2022 flood in the Marche region was analysed; however, due to the period of occurrence (end of the bathing season) no assessment of the presence of coliform bacteria in bathing waters was available. Moreover, no significant environmentally protected areas were flooded except for the Parco Nazionale dello Zolfo di Marche e Romagna (Sulfur National Park). Here, some riverine ecosystems were affected due to bank erosion and consequent human restoration but no official data from news or public authorities were available.

At the European level, flooding in July 2021 raised media attention of chemical pollution due to flooding (Völker et al., 2023) and of an acute and unusual release of organic pollutants due to river sediment remobilization (Weber et al., 2023; Schwanen et al., 2023), which ultimately might affect human health. Besides these works on European flooding in

Table 1. Summary of impacts and their proposed classification. The asterisk (*) identifies additional impacts without associated geographic information (not reported in Fig. 1).

Observed impact	Description	Cause	Classification of flood processes generating environmental impacts
Bathing ban	*Escherichia coli* in seawater above safety limits for bathing water quality	Persistent flooding, sewerage, and WWTP failure	Contamination and transport of pollutants
Soil contamination	Deposition/stagnation of sediments and wastes in flooded area		
Algal bloom	Change of colour of surface river water (red or dark)	High nutrient concentrations and consequent anoxia	
Death of fishes	Fishes found dead in channels and rivers		
Water contamination*	Presence of hydrocarbons and other pollutants (e.g. fertilizers) in surface waters and flood waters	Release of fuel tanks and wash-off from agricultural surfaces	
Interruption of nesting	Nests of several bird species submerged or swept away during reproductive season	Submerged nesting area	Floodwater submersion
Damage to bivalves	Bivalves found dead in coastal lagoons where shellfish farming is carried out	Hypersaline ecosystem alteration	
Damage to fishes and invertebrates	Death of species and alteration of reproductive season		
Damage to halophyte plants	Plants and flora withering due to freshwater submersion		
Invasion of alien species	Ingress of alien species (*Callinectes sapidus*) and increased competition with native species due to changes in coastal lagoon salinity		
Damage to riverbanks habitats*	Destruction of animal shelters and interruption of nesting in riverbanks	Bank erosion/ levee failure	Erosion
Damage to riparian vegetation*	Interruption of nesting		

2021, most attention was focused on direct losses (e.g. to infrastructure) (Jonkman et al., 2023).

3.2 Space dimension of impacts

From a spatial point of view, the map of Fig. 1 clearly shows how reported environmental impacts of the flood occurred downstream of the most inundated areas, i.e. river mouths, coasts, and coastal wetlands. The identification and characterization of these impacts is however rather accidental and cannot be seen as the outcome of an established monitoring activity of environmental damage due to floods. These major events occurred right before the start of the bathing season that, according to law, entails an increase in the frequency of coliform monitoring activities performed by public authorities. Such circumstances enabled spotting the impact even in areas not directly affected by inundation. On the other hand, the attention given to bathing areas might have led to an underestimation of water quality impacts along upstream rivers stretches, where monitoring was not performed, despite being the origin of the pollution. Some exceptions apart, as in the cases where the environmental agency was called in an emergency due to the sudden reported red colour of river waters, impacts on natural rivers were not considered and thus monitored. Similarly, spring is the reproductive season of many bird species, which brought the attention to the impacts of the events on coastal ecosystems of ecological value (Fig. 1, green shaded areas). These two aspects have contributed to moving the focus of attention on the reported impacts towards the coast.

3.3 Time dimension of impacts

From a temporal perspective it is possible to recognize both a direct time-dependent exposure, e.g. nesting activity occurring in a specific season, and an indirect flood damage that occurs and persists after the events.

In fact, the bathing bans disappeared with different velocities according to location, and after about 30–45 d from the flooding all bathing waters were reported safe. About the interruption of nesting, experts reported that a second nesting attempt in 2023 was improbable for most of the bird species, due to the late occurrence of flooding with respect to reproductive time. No information was available in relation to the persistence of polluted soils and freshwaters anoxic conditions or to the recovery of flora and fauna in wetlands and riparian habitats. The dynamic behaviour of environmental matrices and their intrinsic resilience demonstrates that the time for quantifying the impacts can be different for each ecosystem. Proposing resilience-based metrics could be appropriate, but only after a deeper understanding of the behaviours of different ecosystem compartments that are still poorly known.

3.4 Impact metrics

According to the collected information, the most-affected environmental assets have been the water resources and water ecosystems, i.e. freshwater, transitional and marine waters, and terrestrial ecosystems, including Natura 2000 areas of biodiversity conservation and Ramsar wetlands. It should also be noted that these areas were also not reported as flooded, i.e. exposed, as permanent waterbodies are automatically excluded by flood maps during satellite image processing.

In terms of losses to ecosystem services the most-affected categories have been recreational functions (cultural values), in the case of the prolonged bathing ban, and biodiversity functions (supporting value) when animal and plant species have been affected. Valuing flood losses in terms of a reduction in provided ecosystem services could set the base for a quantitative damage metric for environmental assets. Moreover, although river water quality was not systematically monitored, we can also imagine losses to regulating and provisioning services since the importance of ecological status of waterbodies in providing such ecosystem services has been demonstrated (Grizzetti et al., 2019).

The consequence of damaged environmental assets extends to economic activities, such as tourism and food production (e.g. aquaculture); thus although the mentioned losses are mostly intangible, some cascading aspects could be monetizable. Repercussions of environmental damage to human health are still unrevealed, although the increase in diseases, such as hepatitis or gastrointestinal disorders due to ingestion of contaminated water, could be potentially monitored.

Most of the observed damage and the natural recovery capacity of environmental systems are, however, difficult to quantify with present technical and scientific knowledge. Moreover, the heterogeneity of damage sources and potential consequences, and their spatial and temporal dimensions, make very difficult to select one or a few impact metrics fitting this diversity.

4 Conclusions

In this brief communication the ex post analysis of the 2023 Emilia-Romagna floods highlighted the occurrence of different types of environmental impacts, especially on waterbodies (rivers, bathing seawaters, and coastal wetlands in particular) and water and terrestrial ecosystems, with supporting and cultural ecosystems services affected by the events. The three main flood processes identified as responsible for damage to environmental assets are (i) contamination and transport of pollutants, (ii) submersion, and (iii) erosion.

However, flood damage to environmental assets is often overlooked. This happens since damage to ecosystems is hardly monetizable and quantifiable and because of the lack of established monitoring activities devoted to their assessment. Moreover, most natural ecosystems have an inner capability to self-recover after a shock, without human intervention (i.e. costs), unless tipping points are overcome. Environmental impacts show different time and space patterns, also due to seasonal drivers. However, such dynamics remain largely unknown due to the paucity of information (even in scientific literature) and absence of specific monitoring protocols. Little scientific attention so far and the lack of policy prescription at EU level make the understanding of environmental consequences of floods a neglected objective.

From the analysis of these events and other recent events, some general reflections arise with regards to our consciousness of the environmental impacts of floods and of their extent and current practices for their monitoring. With respect to other types of impacts, e.g. structural losses, flood damage to the environment requires a more holistic and multidisciplinary understanding able to embrace the underlying ecological system dependencies among temporal and spatial phenomena. From a temporal perspective, environmental losses can occur immediately through direct contact with water, e.g. submersion of nests, but there might be prolonged indirect repercussions, e.g. on later population dynamics. In this sense, the resilience of each environmental matrix (e.g. soil, water) or even each living species (e.g. plants, birds) has its own dynamics and natural recovery ability, which requires specific expertise. From a spatial point of view, environmental flood impacts might also extend beyond the directly inundated area, e.g. coliform bacteria in bathing waters downstream of flooded areas, thus revealing their intrinsic direct and indirect nature. The flood impacts on several ecosystems services also suggest cascading consequences on health and

socio-economic activities, such as water abstraction, aquaculture, and tourism, which again remain largely unclear and difficult to quantify.

Further research should focus on better understanding of the environmental areas that can suffer from floods and their specific vulnerabilities. Moreover, future research should move towards the conceptualization of potential direct, indirect, and cascading impacts of flooding on the environment to support their inclusion in flood risk mapping and management processes.

Data availability. The data set is available from Arrighi and Domeneghetti (2024) (https://doi.org/10.17632/yzddsc67gy.1).

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