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Causes and Impacts of Flood Events in Emilia-Romagna (Italy) in May 2023

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Abstract: On 1–3 May 2023, severe hydro-meteorological events occurred in the Italian Emilia-Romagna region. Such events caused extensive flooding, landslides, isolation of many areas, evacuation of many families, and severe damage to infrastructure, agriculture, buildings, and essential services. Several municipalities were affected, thousands of civilians had to be evacuated, and losses of life occurred. The consequences beyond the recorded immediate impacts on infrastructure and life were impressive, and extended to the regional economy, specifically in the Fruit Valley, where, in addition to immediate yield losses, long-term damage to orchard production is expected due to persistent flooding. The civil and cultural building heritage has also been heavily affected, both in the countryside and in inhabited centers. Some of the damage, direct and indirect, caused by flooding on buildings will also see an evolution in the medium- to long-term that needs to be addressed. This paper analyzes the manifold aspects of such an atmospheric phenomenon and its impacts to understand the potential increasing occurrence of similar events in the climate change context.

Keywords: flood events; meteorological events; environmental impacts

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1. Introduction

Frequency and impacts of extreme events have been growing, and floodings now pose potential threats in many world areas.

On 1–3 May 2023, the Italian Emilia-Romagna region was severely affected by exceptionally intense and prolonged rains, mostly critical in the Forlì-Cesena, Ravenna, Bologna, Modena, and Reggio Emilia territories. On 16–17 May 2023, a further intense meteorological event occurred in the same territories, extending also to neighbors Rimini and Pesaro-Urbino. Such unexpected weather events gave rise to many floods and landslides, causing isolations, evacuation of people, and considerable damage to infrastructures, farms, public and private buildings, thus leading to requests for important rescue and protection actions.

The local return period to the accumulated rainfalls recorded at the ground according to WMO standards was more than 500 years, especially in the basins of Senio, Lamone, and Montone, making it difficult to estimate the actual probability of occurrence of such two subsequent extreme events.

The total flooded area, mostly occurring in the flat plane sites [1,2], was approximately 58 km^2, with an average 11 cm standing water and some notable cases exceeding 68 cm height as, for example, near the Ronco and Savio rivers.

Contrary to the consolidated literature about the hilly and Emilia portions of the regional territory [3–8], the evolution of the afflicted area is not fully referenced. The land-

scape's relatively recent physiography results from repeated variations of the equilibrium relationships between sea level, solid inputs from watercourses, extent of subsidence, and, not least, on human activities. Traces of both natural and man-made evolution are in fact clear, especially in the last century.

Local morphological structure is mostly shaped by paleo-rifts, differently aged flood cones, dune belts testifying the rapid eastward propagation of the coastline, and several depressed areas located at the site of marsh or lagoon basins. The flooding-affected closed or semi-closed depressions are characterized by a low-energy hydrodynamic environment and, therefore, waterproof by fine sediments, silt-clays, and peats, impeding the discharge of water to the sea.

The rivers in the area, although having a torrential hydraulic character, are characterized by low outflow rates and poor transport capacity. During overflows or floods, the abrupt decrease in hydrodynamics and the consequent standing sediment in the beds causes the water to rise above the surrounding plain.

During the advancing phases of the plain, accelerations in the compaction of sediments have not been sufficiently compensated for by the solid river input, forming large swampy areas, denoted valleys. Today almost completely reclaimed, the outcropping soils present marked clayey-peaty characteristics with high compressibility often associated with difficult vertical drainage [5].

Generally, the most recent physiographic–environmental evolution has been characterized by natural and induced subsidence phenomena, the latter linked to human actions. The effects, due to the size and weight of large artifacts such as building agglomerations, lead to embankments, extending their size to the overall hydrogeological conditions of the entire land.

Water extraction from shallow- or medium-depth aquifers to an extent exceeding the possibilities of spontaneous recharging, methaniferous extraction from quaternary deposits, water draining for industrial and agricultural utilizations, and draining of the abandoned wetlands significantly lowered the ground level over the last half-century, both in relation to the mechanical compaction of sediments, and the oxidation of their peat component.

In the context of such recent and delicate morphological evolution, the necessity for increased resilience is starkly evident in an environment currently dominated by extreme climatic conditions.

This current study aims to identify physical causes of the unusual flood event, identify major impacts, and outline some mitigation measures to enhance adaptive capacity while preserving the landscape and social and economic functions.

2. Analysis of the Events

2.1. Pedo-Morphological Analysis at the Site

The Emilia-Romagna region covers approximately 22,452 km^2, including a 5635 km^2 mountain area, 6084 km^2 hilly area, and a 10,733 km^2 plain area (Po Valley). The geomorphology is diverse, featuring the Apennines mountains in the south and southwest while the large plane occupies most of the northern and northeastern sectors. Apennine peak altitude reaches 2165 m above sea level (Monte Cimone).

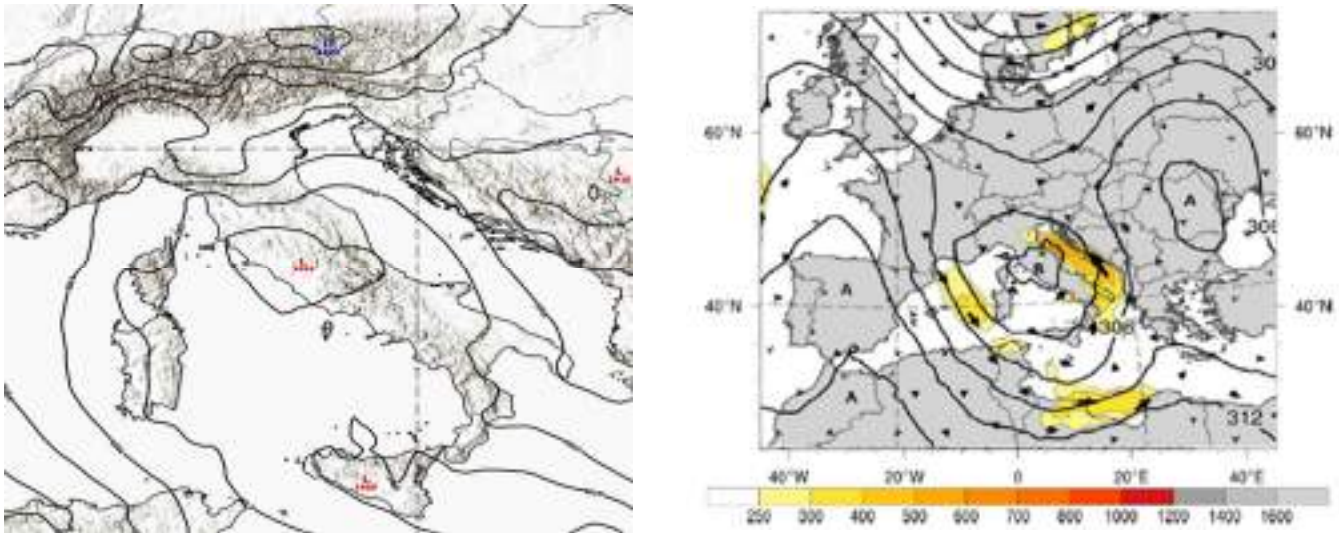
The Ligurian Domain is the upper structural unit, and it is extensively present in the Apennines. This formation, dating back to Upper Jurassic age through to the lower Eocene, consists of tectonic melanges and olistostromes with a high clay content that expands in the presence of water. These formations are overlaid by a thick series of calcareous or arenaceous turbidites, which make them susceptible to erosion and landslides. Furthermore, sandstones of the Middle Eocene Epi-ligure Sequence are resistant to degradation processes, except for clay breccias and olistostromes, which have similar lithological characteristics to the Ligurian units. In the Romagna area, turbidite sequences are widely visible [1]. The plain area is a subsiding geosyncline filled by alluvial materials covering the marine clays of the coastal environment. The most recent filling was produced by the depositional activity of the Po River-Delta system with axial feeding towards the east, and by the Apennine river

systems with transversal feeding from the south. These Pleistocene–Holocene sediments have remarkably complex depositional and geometric characteristics that correlate with the deposits of river's erosion; currently, terraced river deposits' formation is linked to the continuous variation of river levels [9].

2.2. Synoptic and Mesoscale Analysis of the Event 1–3 May 2023

The first extreme rainfall event occurred between 1–3 May 2023, when a low atmospheric pressure close to the ground on the Iberian Peninsula, in its evolution eastwards, entered into a phase with cold air coming from the north, leading to the formation of a great cyclonic circulation over the central Mediterranean. Simultaneously, a sub-tropical anticyclone in eastern Europe slowed the evolution of the cyclonic circulation, blocking the baric minimum in central Italy on 2nd May. A frontal system persisted for many hours over Emilia-Romagna, due to the continuous feed of hot and humid air masses from the southeast which converged with colder flows from the northeast. The occluded branch's interaction with these weather systems contributes to the prolonged and intense precipitation event [10].

Figure 1 shows the baric analysis at 12 UTC on 2 May 2023 at the surface (Figure 1a) and at 700 hPa (Figure 1b). At 12 UTC on 2 May 2023, the low pressure close to central Italy was characterized by a high baric gradient over the northeastern Italian regions due to the increase of the pressure in the Alpine arc due to the accumulation of colder and denser air coming from central Europe. The depression over central Italy attracted a mass of warm air extremely rich in water vapor from the southeast represented by high values of Integrated Vapor Transport (IVT, Figure 1b), which was channeled along the Adriatic.



(**a**) (**b**)

Figure 1. (**a**) Surface pressure fields at 12 UTC on 2 May 2023. Source: IFS-ECMWF [11]. (**b**) Geopotential heigh at 700 hPa at 12 UTC on 2 May 2023. Source: GFS model (https://www.wetterzentrale.de/en/topkarten.php?model=gfs, accessed on 14 September 2024).

IVT is an integrated measurement of the flow of water vapor along the atmospheric column, which combines wind speed and water vapor concentration. It is calculated using wind speed and relative humidity data along different levels of the troposphere according to this relationship:

$$IVT = \sqrt{\left(\int_0^{p_s} qudp\right)^2 + \left(\int_0^{p_s} qvdp\right)^2} \quad (1)$$

where q is the mixing ratio (g/kg), u and v are the horizontal components of wind speed in m/s, p is the atmospheric pressure in hPa, and ps is the surface pressure in hPa.

The air mass with high IVT values (>400 kg/m·s) entered in the Po Valley from the east, then converged with the colder air flow from the northeast. The resulting flow impacted the Apennines, and the orographic barrier increased the upwind precipitations due to forced vertical motions.

The cyclonic vortex remained stationary throughout 2 May 2023. It slowly moved east in the early hours on 3 May 2023, and this led to moderate rainfall persisting for many hours in the central-eastern sector of Emilia-Romagna. The event lasted for around 36 h, resulting in extreme precipitation accumulation in some river basins. The precipitation was mainly stratiform with low to moderate average hourly intensities (2–5 mm/h), occasionally interrupted by short storm showers with a maximum rain rate of 15–20 mm/h, mainly in the hill areas.

Figure 2 illustrates the anomaly of precipitable water in mm between 12:00 and 18:00 UTC on 2 May 2023 over Italy. It shows values between 8 and 10 mm over eastern Emilia and Romagna, indicating a particularly humid southeasterly flow along the whole Adriatic region.

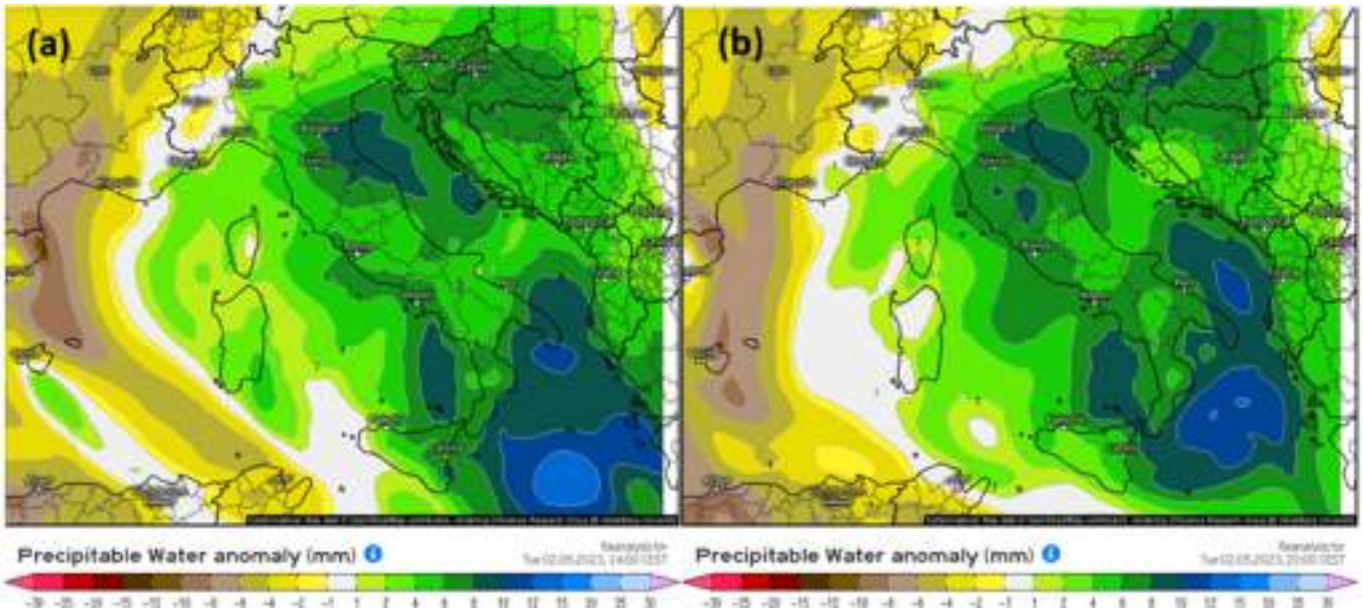


Figure 2. Anomalies in precipitable water (mm) at 12 UTC (**a**) and 18 UTC (**b**) on 2 May 2023. Source: ECMWF ERA5 Reanalisys, Plot Meteologix [12].

The anomaly values of precipitable water associated with the rise of the southeastern flow further confirmed the particularly humid and water-vapor-rich air mass. Precipitable water (PW) provides an absolute measurement of the air's water content. Anomalies above 30 mm generally indicate intense or abundant rainfall events. The meteorological dynamics formed at a synoptic scale together with some mesoscale forcings have undoubtedly contributed to increasing the rainfall on the Apennine hillside.

The northeast synoptic flow arrived in the coastal strip and the lowland areas of eastern Emilia Romagna from the Adriatic Sea (Figure 3). This flow converged with a mesoscale northwest air mass due to the Apennine chain (barrier jet). The boundary formed by this convergence, which stays stationary for extended periods, further stimulates the formation of precipitating cloud systems. This boundary, particularly active at the basis of the Apennine chain, induced more intense rainfall than in the lower plain areas, adding to the orographic component and amplifying the accumulations on the middle and lower Apennines.

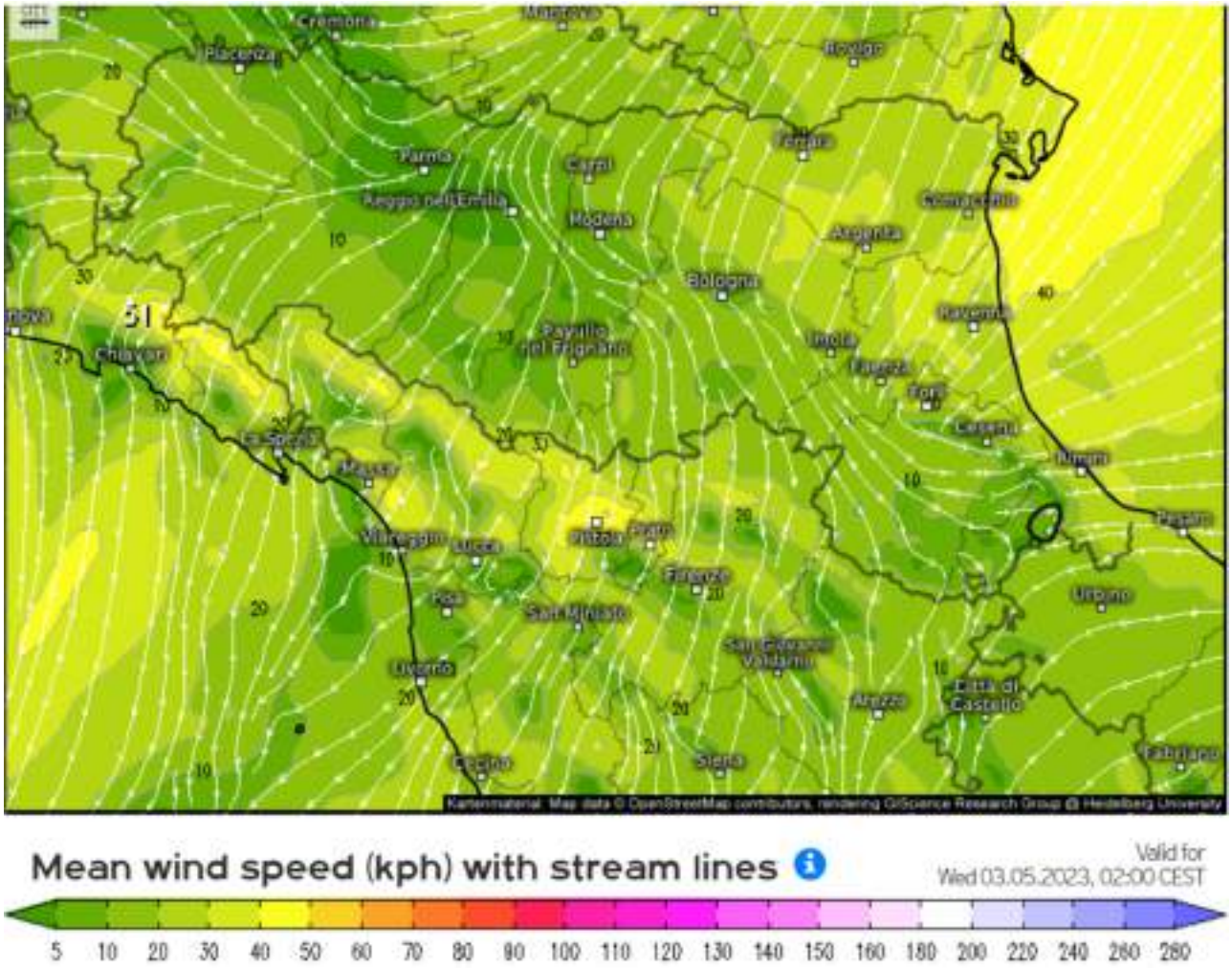


Figure 3. Wind speed and direction at 10 m in km/h at 12 UTC on 2 May 2023. Source: Europe Swiss HD Nowcast model Meteologix [13].

The radio sounding at 12 UTC on 2 May 2023, launched at San Pietro Capofiume (BO) (Figure 4), provides a detailed analysis of the following key aspects:

1. The high proximity between air temperature and dew point curves in the lower troposphere (up to the isobaric level of 400 hPa) shows a saturated or nearly saturated environment, prone to the formation of intense cloud cover and associated precipitation.
2. The surface lifting condensation level (LCL) is below 100 m, suggesting high relative humidity values with rapid saturation from the lowest layers of the rising air masses.
3. The surface-based Lifted Index is 4.5 °C, showing prevailing stability, as evidenced by the absence of storm activity. However, in the context of prolonged rainfall of stratiform origin, this stability does not necessarily limit the rainfall.
4. The CAPE (3 J/kg) and the CIN (0 J/kg) are very low, indicating low availability for convection. This aspect is more consistent with prolonged rain rather than intense thunderstorm activity.
5. The precipitable water (PWAT) shows a value of 30 mm suggesting the presence of an adequate quantity of water vapor in the atmosphere to withstand continuous rainfall.
6. The hodograph shows a wind characterized by a slight clockwise directional variation with height (veering) with weak or moderate shear. The vertical wind profile is typical for this area [14,15].
7. The southeastern flows that are distinctly cyclonic overlapped with almost saturated northeastern currents in the lower layers, including the PBL. This type of wind profile favors persistent rainfall caused by stratiform clouds. Such rainfall, typical of occluded

fronts rising across the Adriatic in the case of Mediterranean cyclogenesis, add to those induced by the orographic lifting of highly humid air over the Apennines.

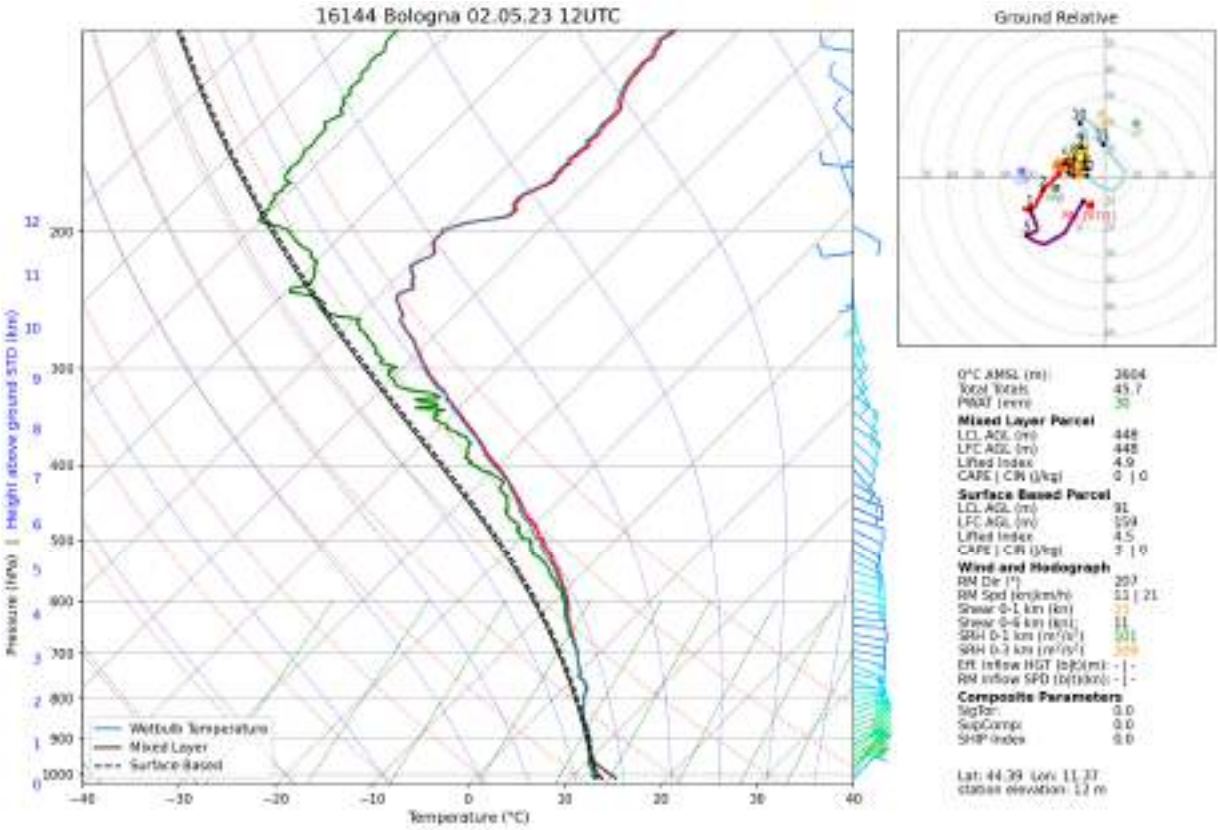


Figure 4. Radiosounding at 12 UTC on 2 May 2023, Station S. P. Capofiume (BO). Source: ARPAE network [14].

2.3. Synoptic and Mesoscale Analysis of the Event 16–17 May 2023

The second extreme precipitation event occurred between 16–17 May 2023. It was almost a "twin" to the previous one but even more intense and with a slightly different origin, where the convective component prevailed, particularly in the first phase of the event.

From 15 May 2023, the synoptic situation was characterized by an anticyclone circulation between the Atlantic Sea and the Iberian Peninsula and a strong low-pressure field from the eastern Mediterranean to northeastern Europe. A depression vortex inserted itself between the two baric structures forming a baric minimum on the ground. Meteorological Service of the Air Force called this vortex "Minerva" (European Storm Naming Program) and it caused conditions of intense instability initially in the southern regions of the Peninsula, then in the central ones, until reaching Emilia-Romagna on 16–17 May 2023.

Starting from the night between 15–16 May 2023, "Minerva", in its evolution towards the central Italian regions, triggers an intense cyclonic circulation with extremely humid currents and intense winds which impact on the coasts of the northern Adriatic.

The interaction between these air masses and the confluence of the southeastern and northeastern winds on the ground near Romagna renews, but in a more severe form, the same dynamics of 1–3 May 2023 event, causing intense rainfall, including thunderstorms, especially during the morning of the 16th.

On the whole day of 16 May and for a good part of 17 May 2023, the almost stationary depression vortex over central Italy continues to drive perturbed impulses in sequence associated with very humid air masses directed towards the Po Valley, favoring the persistence of precipitation in approximately the same areas already affected by the event at the beginning of the month.

The barrier effect of the Apennine mountains is renewed and once again concentrated rainfall on the windward side, on the hilly areas between Bologna and Romagna. The IVT, reported in Figure 5, exceeds 600 kg/m s along the Adriatic Sea. An air mass rich in water vapor flows into the Emilia-Romagna region from the east.

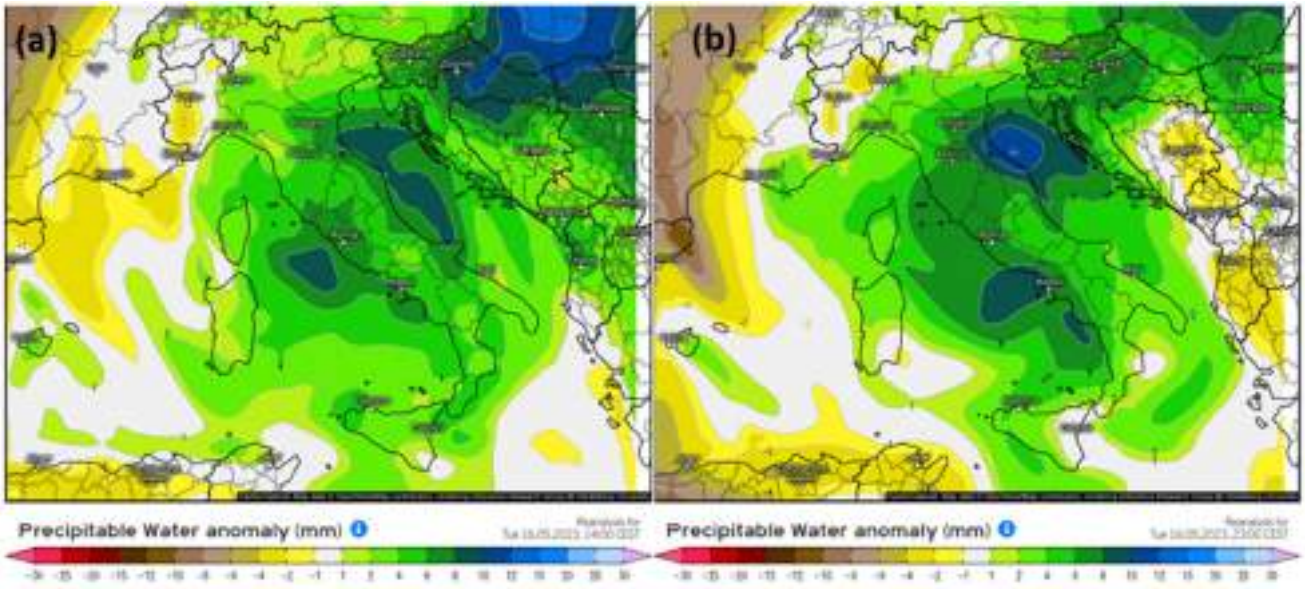


Figure 5. Anomalies in precipitable water (mm) 12 UTC (**a**) and 21 UTC (**b**) on 16 May 2023. Source: ECMWF ERA5 Reanalysis. Plot Meteologix [12].

The cyclonic vortex was much more intense than the previous one and favored insistent moderate rainfall but with showers and thunderstorms, particularly on the morning of the 16th. The persistence of the event leads to approximately 30 h of abundant rainfall with again extreme accumulations and, in some cases, even higher than those of 1–3 May 2023.

Figure 5 also shows the anomaly of precipitable water, between 12 and 21 UTC on 16 May 2023. The values, ranging between 10 and 12 mm, are particularly significant in eastern Emilia and Romagna, especially in the evening. This anomaly is primarily due to the influence of humid air coming from southeast along the Adriatic Sea.

Similarly to what occurred in the first event, a synoptic flow from the northeast is formed, transporting the highly humid air mass toward the plain of the eastern Emilia-Romagna region. At the same time, the convergence with a northwest mesoscale flow led to an accumulation of moderately cold air upwind of the mountains. Once again, the vortex stays stationary for many hours, mainly at the foot of the Apennine chain, causing intense rainfall in approximately the same areas as the previous event, adding to the orographic component. In this situation, the area involved is larger than the episode at the beginning of the month, also affecting the entire Rimini area.

Despite the failure of the San Pietro Capofiume (BO) radiosounding measurement, the pseudo-sounding through ERA-5 ECMWF reanalysis provided valuable data. This simulated survey is particularly significant as it coincides with the area of Casola Valsenio (RA), one of the most heavily affected areas (Figure 6).

The thermal profile (red curve) and dew point profile (green curve) show substantial overlap in the lower part of the troposphere, indicating high relative humidity in the lower layers, which is favorable for developing intense cloud cover associated with precipitation. The parcel trace (dashed blue curve) indicates that the lifted air remains warmer than the surrounding environment up to about 700 hPa, suggesting potential instability.

CAPE values are low (8 J/kg in mixed-layer, 12 J/kg in surface-layer), indicating a weak instability. This suggests that the energy available for air lifting is limited but still sufficient to support prolonged convection if supported by the orographic lifting.

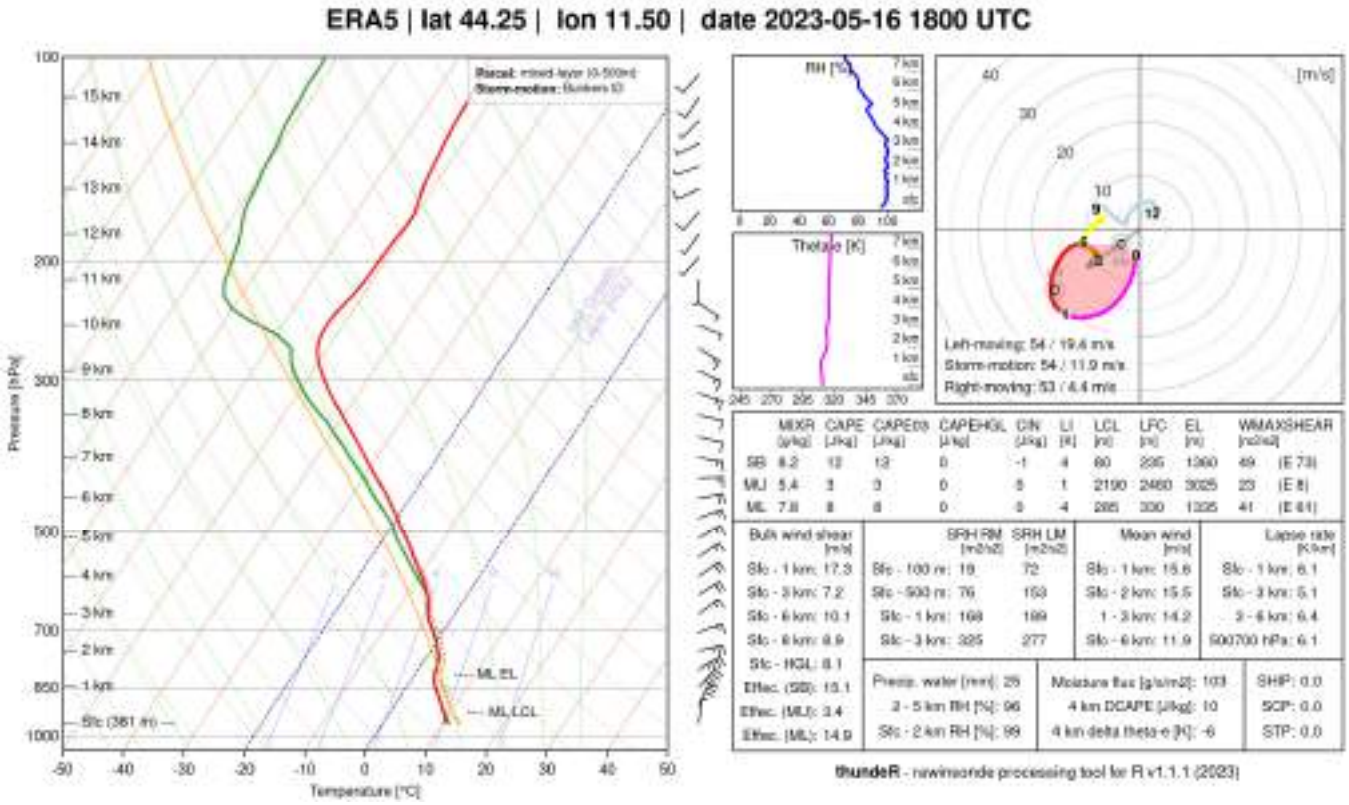


Figure 6. Pseudo-sounding 18 UTC 16 May 2023 at Casola Valsenio (RA). Source: ERA-5 reanalysis, plot thundeR [12].

The value of 25 mm of precipitable water (PWAT), not exceptionally high, indicates a good quantity of humidity available in the atmosphere, contributing to persistent precipitations. The equivalent potential temperature profile (Theta-E) is high in the lower layers, confirming warm and very humid air.

LCL is below 100 m, confirming an extremely humid air mass with rapid saturation from the lowest layers subject to dynamic and orographic lifting.

The hodograph shows a vertical wind profile characterized by a clockwise directional rotation with height (veering) and weak or moderate shear. In this case, the wind profile is also a perturbed flow due to Apennine orography. At high altitudes, cyclonic and very humid southeastern flows were formed which overlapped the northeastern currents in the lower layers (including PBL). This is a typical wind pattern observed in occluded fronts rising across the Adriatic Sea during Mediterranean cyclogenesis.

Finally, the two meteorological events were favorable to prolonged and intense rainfall in less than two weeks. The second event (16–17 May 2023) is more severe and extensive than the first one and occurred when the soil was completely saturated due to intermittent rainfall between the two main events.

3. Impacts

3.1. Impacts on River Basins and Landscape

The precipitation data reported here were collected by the Emilia Romagna Agency for the Environment Protection and Energy (ARPAE) observational network. These stations are strategically located in various river basins, ensuring comprehensive and correct data collection.

The precipitation accumulated in the two events for each location has been carefully considered. This comparison is of extreme importance as it provides a clear understanding of the variations in precipitation levels and their impact on the respective basins. (Figure 7).

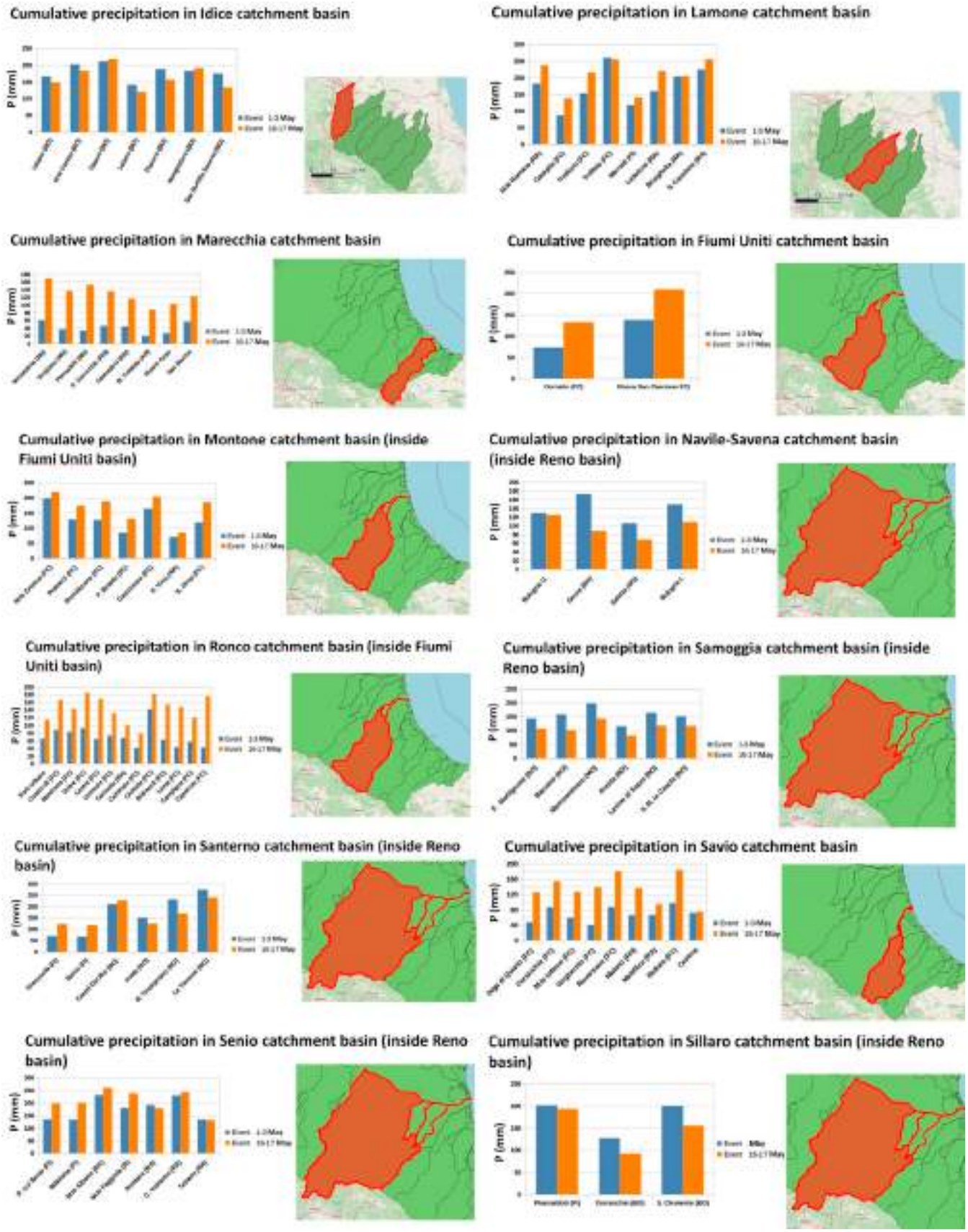


Figure 7. Cumulated precipitation in all river basins for the two extreme events (1–3 and 16–17 May 2023). Data from ARPAE hydrometeorological network [16].

The Idice basin shows cumulative rainfall over 100 mm in both extreme events, with maximums over 200 mm at Casoni di Romagna (BO, 708 m a.s.l.) and over 150 mm at Monte Ceresa (BO, 411 m a.s.l.), Pianoro (BO, 174 m a.s.l.), and Monghidoro (BO, 825 m a.s.l.). Overall, both events resulted in significant rainfall at all stations, but the 1–3 May event was generally more intense than the 16–17 May 2023 event, at least in the basin under examination. Casoni di Romagna and Monghidoro recorded the highest rainfall in both events, while there was a general reduction in rainfall between the first and second events at all stations, although the intensity of the second event remained high, with significant rainfall values. In particular, the first event shows vast rainfall accumulations from the lower hills, while in the 16–17 May 2023 event, the typical altimetric gradient of accumulations was better respected.

The Lamone basin shows cumulated rainfall over 150 mm in both events, as evident at Monte Romano (RA, 705 m a.s.l.); Tredozio (FC, 330 m a.s.l.); Trebbio (FC, 570 m a.s.l.); Lodolone (RA, 250 m a.s.l.); Brisighella (RA, 185 m a.s.l.); and San Cassiano sul Lamone (RA, 226 m a.s.l.). Specifically, at Trebbio, 250 mm of accumulation was exceeded in both events, while San Cassiano exceeded the same limit in the 16–17 May 2023 event. Extremely high accumulations were also observed in this basin from the lower hills, but unlike the Idice basin, the most important event was 16–17 May 2023. Significant variability, greater than in the Idice basin, is noted between the different stations. This dynamic variability could be attributed to local variations in weather conditions and topography. In the second event, the influence of thunderstorm activity is evident, causing even greater variability in rainfall accumulations.

As far as the Marecchia basin, the clear difference between the two events is evident, with the first causing rainfall accumulations of no more than 60 mm (Novafeltria, RN 331 m a.s.l). In the second event, accumulations exceeded 100 mm everywhere except for the Badia Tedalda station (850 m a.s.l. in the province of Arezzo and therefore less exposed to the northeastern disturbing currents), with a maximum of 168.5 mm in Novafeltria, while in Pennabilli (RN, 629 m a.s.l.), there was an accumulation of 152.4 mm. In the basin under examination, the non-excessive rainfall of the first event favored less criticalities than in other basins in the region due to non-saturated soils.

In the United Rivers basin, the most severe event was that of 16–17 May 2023. In both events, the rainfall was significantly higher at Rocca San Casciano (FC, 250 m a.s.l) than Corniolo (FC, 553 m a.s.l.), inverting the normal altimetric gradient that typically concerns accumulations from stratiform cloudiness. This is likely attributed to the highly humid air masses flowing from the lower and within the boundary layers, with compact cloudiness and rainfall from LCL at altitudes below 100 m. On Rocca San Casciano, during the event, the precipitation accumulation was over 200 mm.

In the Montone basin, rainfall was higher during the 16–17 May event compared to the 1–3 May 2023 event in all localities. The only station that did not reach 100 mm is Ponte Vico (20 m a.s.l.) located in a lowland area. In comparison, the 200 mm accumulation was exceeded at Monte Grosso (FC, 670 m a.s.l.) and Castrocaro (FC, 66 mm) in the 16–17 May event.

The Navile–Savena basin is located further west. The first event was the most intense one, with all the Navile–Savena stations showing the highest precipitation accumulations. Dozza station (BO, 42 m a.s.l.) exceeded 170 mm, while the Bologna Urban station (78 m a.s.l.) totaled over 100 mm in both events. In the remaining localities, the 100 mm accumulated was only reached in the first event.

In the Ronco basin, the higher accumulations occurred in the 16–17 May 2023 event, with many stations recording double values than the first event. Maximums of around 180 mm were reached between 16–17 May 2023 at Voltre (FC, 270 m a.s.l.), Civitella di Romagna (FC, 460 m a.s.l.), and Capaccio (FC, 295 m a.s.l.), which are located at a higher altitude. Except for the Civitella di Romagna station, the 1–3 May 2023 episode was characterized by inconsistent rainfall accumulations.

In the Samoggia basin, the 1–3 May 2023 event was more intense at all stations, with an accumulation of 198.4 mm at Monteombraro (BO, 700 m a.s.l.) and 150 mm at Bazzano (BO, 82 m a.s.l.), Lavino di Sopra (BO, 75 m a.s.l.), and San Martino in Casola (BO, 125 m a.s.l.). At the same time, the maximum for the 16–17 May 2023 event did not reach 150 mm (142.4 mm at Monteombraro). The rainfall values recorded show greater consistency, compared to other basins, with the typical altimetric gradient in rainfall where the orographic forcing is prevalent.

In the Santerno basin, there was no clear distinction between the two events, with some stations recording critical values on first event and others on the second one. The most characteristic aspect of this basin concerns the enormous rainfall accumulations observed at some stations: in the 1–3 May 2023 event, 274.4 mm was recorded at Le Taverne (BO, 486 m a.s.l.), 230.2 mm at Borgo Tossignano (BO, 98 m a.s.l.), and 210.8 mm at Castel Del Rio (BO, 183 m a.s.l.). Le Taverne station also recorded rainfall accumulation of 239 mm in the 16–17 May 2023 event, followed by 226.6 mm in Castel Del Rio, and 168 mm in Borgo Tossignano. The Santerno basin is the basin that has accumulated the most precipitation, both partial and total, in the two events and in the whole involved area

In the Savio basin, the 16–17 May 2023 event certainly appears more intense at all measurements stations, with totals of 184.2 mm at Rullato (FC, 600 m a.s.l.) and 180 mm at Roversano (FC, 175 m a.s.l.) representing the extreme peaks in the area. In the first event, none of the stations reached 100 mm of accumulation. In contrast, in the second, accumulations were exceeded everywhere except Matellica (RA, 19 m a.s.l.) and Cesena Urbana (77 m a.s.l.) for obvious reasons related to the low altimetry of the two localities.

The Senio basin is also among the most affected by heavy rainfall in both events, with a prevalence of more significant accumulations during the 16–17 May 2023 event, when 200 mm of rainfall was recorded near Palazzuolo sul Senio (FI, 500 m a.s.l.) and exceeded 200 mm at Monte Albano (RA, 480 m a.s.l., 261 mm), at Casola Valsenio (RA, 154 m a.s.l., 243 mm), at Monte Faggiola (FI, 929 m a.s.l., 237.8 mm), and at Bibbiana (FI, 858 m a.s.l., 201.8 mm). However, the 1–3 May 2023 episode was also very significant, with 231 mm accumulated at Monte Albano and 229.4 mm at Casola Valsenio. In both events, at least 130 mm of accumulated rainfall was exceeded everywhere.

Finally, the Sillaro basin was most affected by the first event as already seen for the basins located further west. Indeed, 201 mm were accumulated in Piancaldoli (FI, 500 m a.s.l.) and 199.4 mm in San Clemente (BO, 166 m a.s.l.), while the same localities accumulated 193.2 mm and 155.6 mm, respectively, in the 16–17 May 2023 event.

Summarizing, Figure 8 reports the precipitation data for all basins for the two events. Each of the two precipitation events had a variable impact depending on the geographical area involved. As can be seen, in the western basins, the most significant event in terms of rainfall accumulation is that of 1–3 May, while the 16–17 May 2023 event prevailed in the eastern basins. The Santerno basin can be considered a watershed, presenting very similar average accumulations in both events. In the Ronco, Savio, and Marecchia basins, the accumulated rainfall of 16–17 May 2023 was, on average, double or sometimes triple that of the 1–3 May 2023 period.

The most affected basins were those of Idice, Sillaro, Santerno, Senio, and Lamone, where the average of both events exceeded 150 mm, with those of Senio and Lamone presenting the greatest peaks, exceeding 200 mm on average in the 16–17 May 2023 event.

This confirms that the areas of Bologna, Ravenna, and Forlì were the ones affected by the heaviest rainfall, especially the hills starting from the lower hills, as confirmed by Figure 9. The stations, without the distinction of basin, that accumulated more than 400 mm of rainfall in the two events were considered. Two of them (Trebbio, FC and Le Taverne, BO) exceeded 500 mm of precipitation, which is an extreme value for the local climatology. Furthermore, almost all the stations with accumulations exceeding 400 mm belonged to the provinces of BO, RA, and FC, with the Idice, Sillaro, Santerno, Senio, and Lamone basins certainly the most affected.

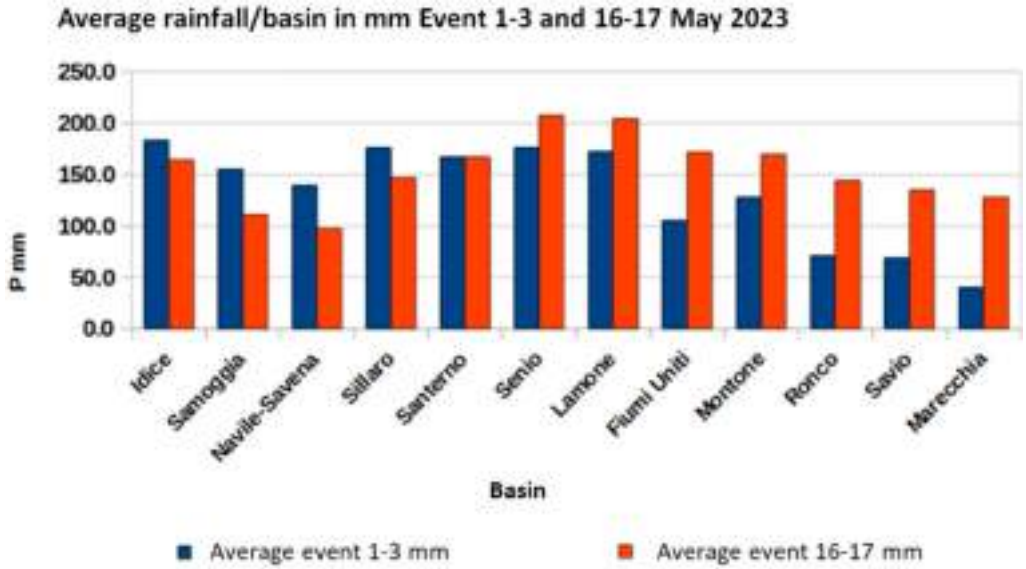


Figure 8. Average precipitation per basin; events 1–3 and 16–17 May 2023. Source: ARPAE network [16].

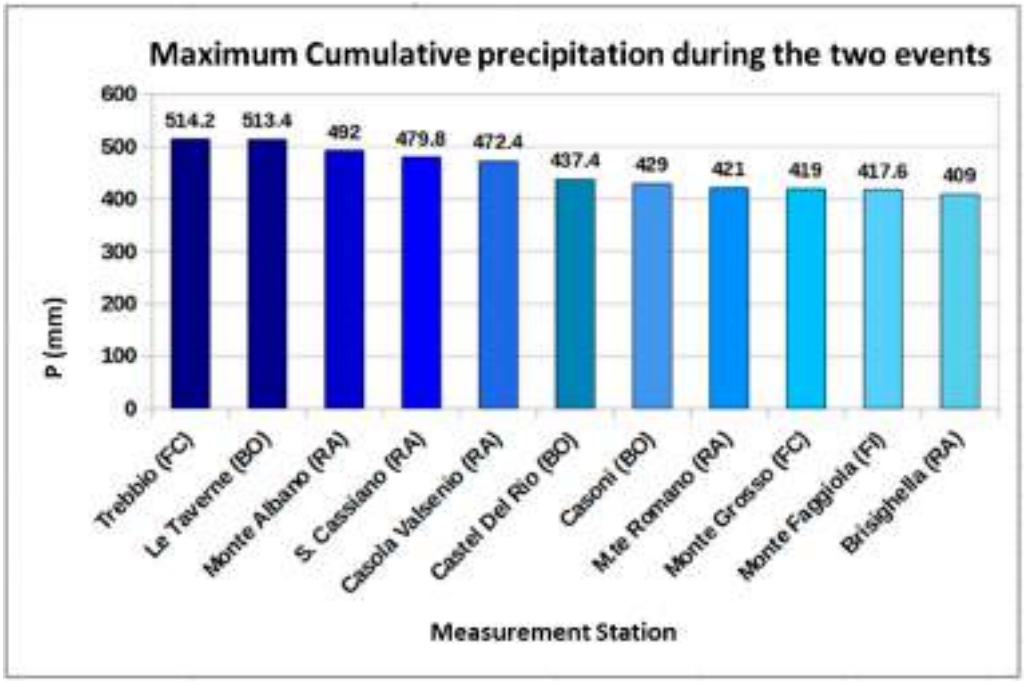


Figure 9. Maximum cumulative rainfall in mm during the two events. Source: ARPAE network [16].

In May 2023, in addition to the two main rainfall events, other lower intensity episodes occurred, bringing the rainfall accumulations for the entire month to extreme values, as seen in Table 1.

The four stations exceeded 500 mm of monthly rainfall accumulation, with Trebbio (FC) exceeding 600 mm. Based on the monthly climatological values (30-year period 1991–2020), these values are about seven times higher than the climatological mean, while the comparison with the average annual rainfall shows that the accumulated rainfall in May 2023 corresponds to 58–66% of the annual mean, with the highest peak at Trebbio (FC).

Figure 10 shows the flooded rivers and the flooded areas. Continuous floods have affected the entire area causing intense transport of material. Landslides processes and gravitational movements of the slopes transported solid material towards the plain area. The resulting impacts will have long-lasting effects on the entire territory, both environ-

mental and economic. The flooding was exacerbated by the previous months of drought conditions which dried out soils and reduced their capacity to store water. Moreover, flooding events of May 2023 occurred in provinces where the landslide index shows values from medium to high, which highlight a pre-existing territorial vulnerability, as shown in Figure 11 [1,17].

Table 1. Precipitation accumulated during May 2023 at the station with the highest values. The monthly and year climatology are also reported.

Station	m a.s.l.	Prec. May 2023 (mm)	May Mean Climatology (mm)	Year Mean Climatology (mm)
Trebbio (FC)	570	609.8	82.6	925.5
S. Cassiano (RA)	226	573.2	87.5	980.9
C. Valsenio (RA)	154	564.4	79.9	913.7
M.te Albano (RA)	480	530.0	83.3	920.8

Figure 10. (**a**) The whole Romagna basin with, in black, the rivers that flooded and in red the ones which reached an attention level. Source: ARPAE Emilia-Romagna [16]. (**b**) The flooded area on 17 May 2023. Source: Copernicus EMS [18].

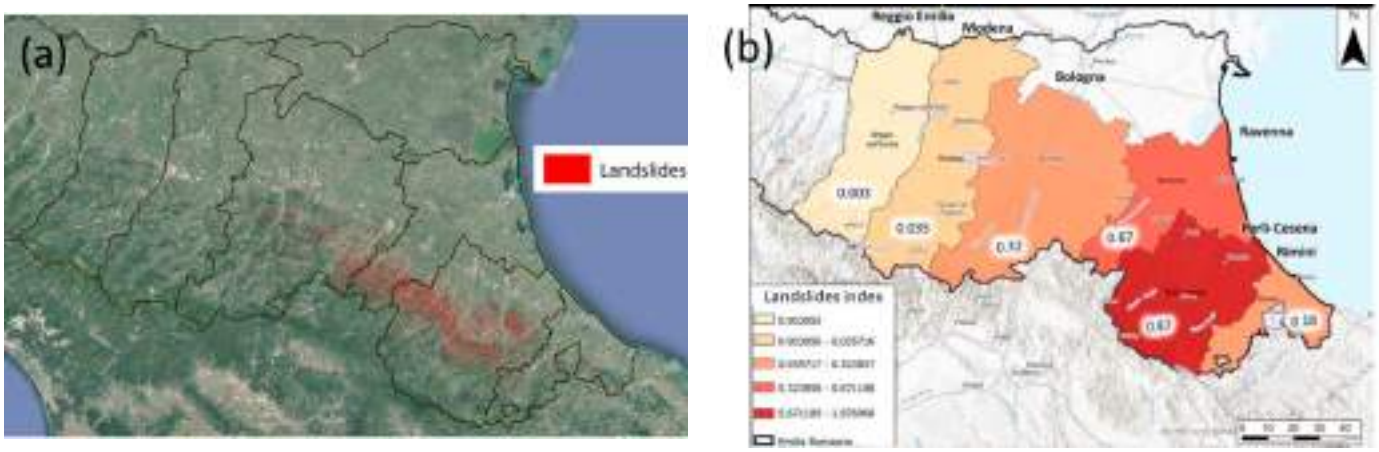


Figure 11. (**a**) Landslides (in red) and the regional border (in black). (**b**) Distribution of the landslide index by Province. Source: Emilia-Romagna Region [1].

3.2. Impacts on Agri-Food Production

Direct and indirect damage caused to the agri-food sector was considerable, as a huge portion of the orchard production areas was affected by the landslide events in May 2023

(Figure 12). The flooding was exacerbated by the previous months of drought conditions which dried out soils and reduced their capacity to store water.

On the back of ongoing damage assessments, the local authorities are anticipating economic losses to be in the billions of euros. As a protection gap exists for flood coverage, the insurance industry is likely to bear a smaller portion of the overall costs [8], but most of the restoring effect must be covered by private/regional funds. One of the main farming organizations, Confagricoltura Ravenna, made a preliminary estimate of about EUR 1.5 billion (USD 1.6 billion) for damages to crops in the Emilia-Romagna region [19].

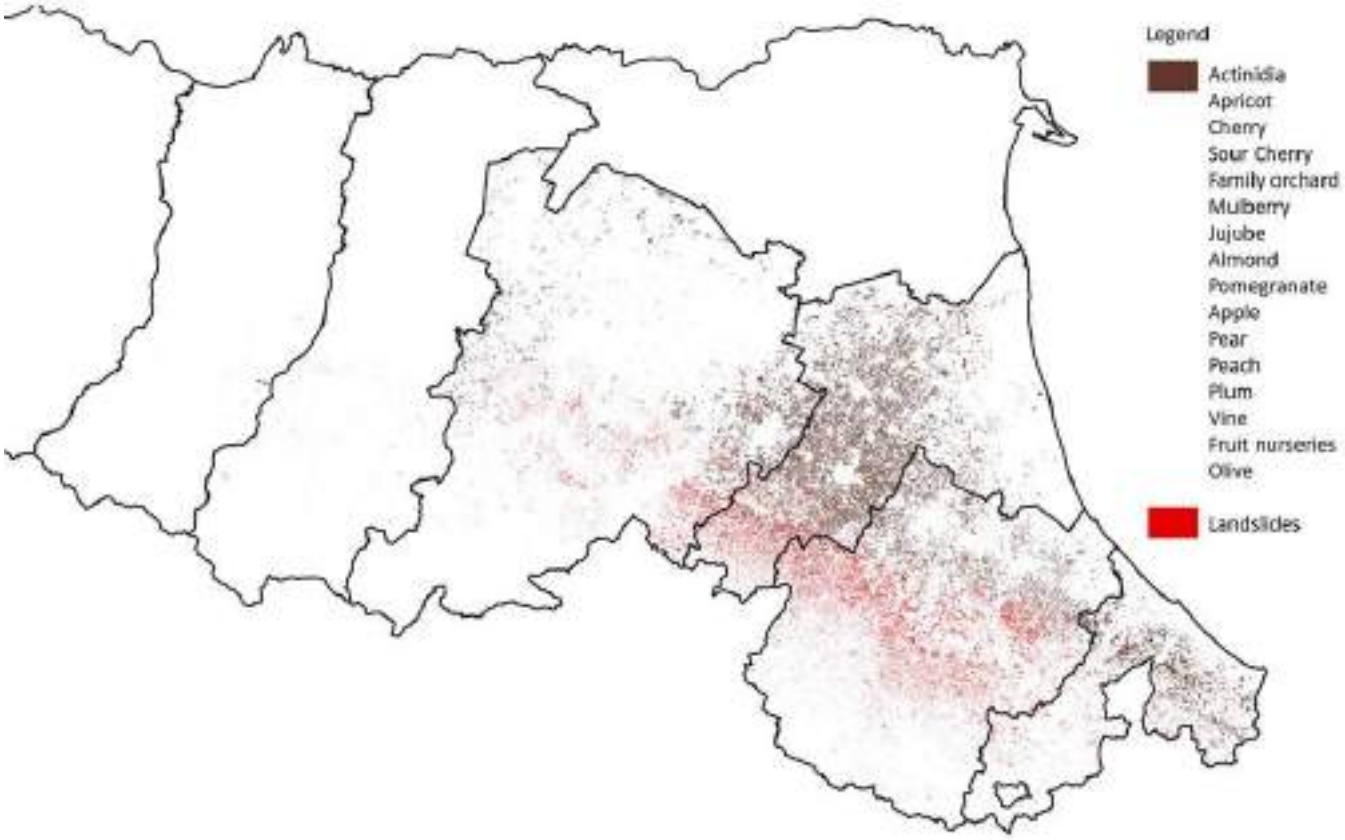


Figure 12. Distribution of the orchards systems in the flooded areas. Source: AGREA [20] (https://agreagestione.regione.emilia-romagna.it/agrea-file/UtilizziGrafici/2023/, accessed on 14 October 2024).

Due to its high traditional vocation, Emilia Romagna is one of the major contributors to Italian agri-food production, mainly fruits and fresh horticultural crops, olives, vines, nurseries, together with field crops. Large 2023 floodings and some frost events that occurred in the spring of the same year were the main meteorological–climate events that caused, after three consecutive successful years, a total economical reduction of −9%, reaching the value of EUR 5.3 B. Although part of this reduction (estimated EUR 500 M) must be attributed to Ukraine conflict, the impact due to the flooding is out of discussion in terms of productive horticultural surfaces and yield [21].

In 2023, the regional reduction of Gross Marketable Production was almost exclusively due to the 17% losses of vegetable crop production, with details for each sector summarized in Table 2.

What is not made explicit by the reported numbers are the causes of such variations. As for cereals, oil seeds, and protein crops, such reasons are exclusively linked to lower market prices; the reduction of fruit crops, oil, and seedlings is recognized to be induced by the extreme flooding events that occurred in May.

Table 2. Variation of Gross Marketable Production (GMP) in 2023 with respect to the previous year. Re-elaborated by Mazzotti [21].

	GMP 2022	GMP 2023	% VARIATION (2022/2023)
FRUIT ORCHARDS	649.62	463.75	−28.6%
WINE	388.27	440.95	13.6%
OTHERS (Olive oil, etc.)	36.9	19.16	−48.1%
CEREALS	835.36	583.54	−30.1%
POTATOES. HORTICULTURAL CROPS	598.25	685.26	14.5%
INDUSTRIAL CROPS	132.55	110.72	−16.5%
OTHERS (seedlings, etc.)	399.88	221.33	−44.7%
TOTAL CROP PRODUCTION	3040.86	2524.71	−17%
ANIMAL HUSBANDRY (TOTAL)	2839.98	2812.23	−1%

Only economic data are mentioned here as a reliable element to document the impact, as at the time of the flooding, only the short-term impacts on yield have been recorded, while the long-term impacts will arise and will be quantifiable only in the next years.

Such longer-term impacts are in fact ascribable to the need to eliminate, change destination, or eventually re-plant orchards that have been strongly damaged by water logging, being slack water and mug persisting in many fields for several days and even weeks.

Orchards, the qualifying elements of the Po Valley fruit production, largely recognized as one of the high-quality providers of the European fresh fruit supply, have proven to be vulnerable to water excess. Most rootstocks and cultivars have been, and currently are, selected to be drought resistant and low water demanding instead of flood resistant. Younger trees in many Ferrara and Ravenna areas reported serious root damage and the need to be replaced, with considerable high economic and energy expenditures, thus very credibly leading to impressive long-term effects both at farm and regional scales. Flooding is recognized to cause hypoxia (low-oxygen stress or oxygen-deficiency stress) or anoxia, depriving plants of a primary driver of many biogeochemical and microbial functions. Shifts in redox conditions have strong implications for nutrient cycling, organic matter fate, nitrogen cycling, and the bioavailability of many nutrients. Such major abiotic stress to fruit trees, that manifested in many cases and for particularly vulnerable species (peach, stone fruits, and kiwi fruits) with yield reduction, are in fact responsible for causing adverse effects on cell division, cellular metabolism, energy consumption, transcriptional regulation, mineral uptake, and physiological variables including basic life functions (water potential, photosynthesis, hormone biosynthesis, carbohydrate mobilization, and reactive oxygen species generation/scavenging) [22,23]. In addition to this, cultivated surfaces and trees carried off by the water current and the mug must be considered, making in these cases damage much more direct and heavier.

3.3. Impacts on Ecosystem Services and Urbanization

Forest and woodland cover 28.4% of the regional territory and, when compared to 1936, their surface has increased by 34% (Figure 13). Such an increase was mainly concentrated in hilly and mountainous areas, in concomitance with a gradual abandonment of dedicated agricultural destinations. This phenomenon is highlighted by the average annual working hours per hectare, which is now 18, compared to 32 in 1980 [1,24].

During extreme rainfall events, the presence of inadequately managed or abandoned forests significantly affects the movements of water into the soils: the greater competition tends to reduce mechanical resistance by weakening the stands, with significant mortality of the plant population. The large volume of uprooted stumps and the mass of debris, when transported by running water, can largely obstruct or mechanically damage the infrastructures in the area. The protection from erosion exerted by riparian forests also

becomes a missing element. Reduced maintenance of the minor hydraulic network, terraces, and man-made structures (dry stone walls) also contributes to the increase in local instability and landslides.

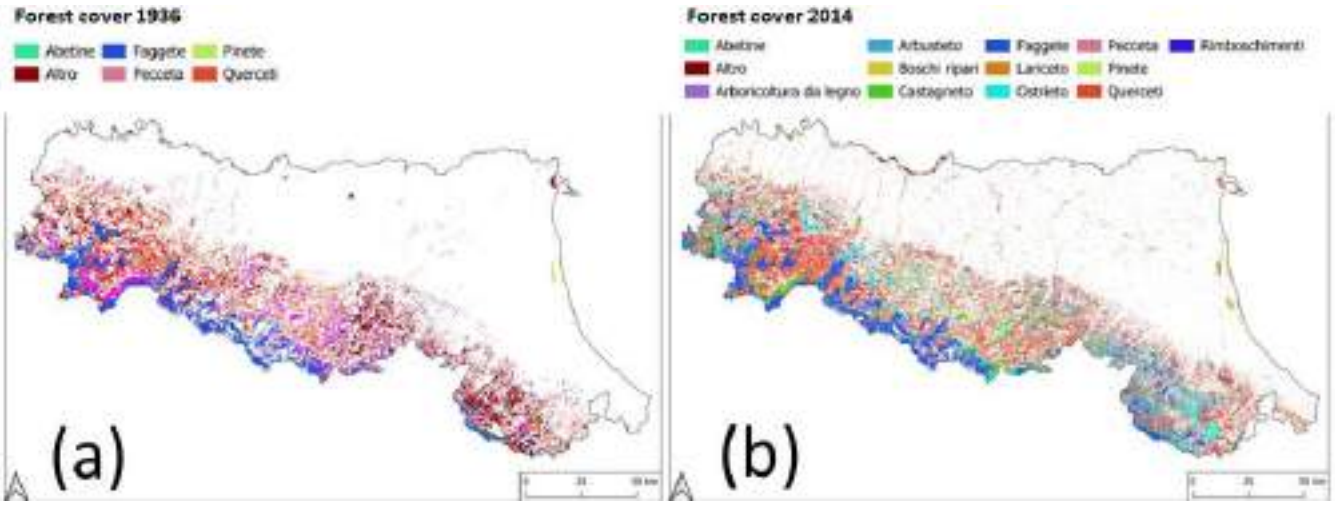


Figure 13. Forest cover maps from (**a**) 1936 and (**b**) 2014. (Regione Emilia-Romagna [1]).

The latest 2023 report on Land consumption, territorial dynamics, and ecosystem services, drawn up by the National System for Environmental Protection, reconfirms the Emilia-Romagna Region as one of the Italian regions with the highest land consumption, with concomitant impacts on the provisions of ecosystem services and landscape degradation. Net land consumption (noted as "the increase in artificial land cover assessed through the balance between land consumption and the increase in agricultural, natural, and semi-natural areas due to recovery, demolition, de-waterproofing, re-naturalization, or other actions capable of bringing the consumed soil back into a soil capable of ensuring the ecosystem services provided by natural soils") was equal to +635 hectares in 2022 compared to 2021.

Provinces and municipalities in the plain and along the Adriatic coast (Figure 14) have a density of land consumption well above the national average [25]. In addition, 45% of the regional territory is considered under hydraulic hazard (i.e., the average level of danger P2 of the three levels recognized by the respective Legislative Decree [1] with a return time of 100–200 years).

A kind of quantification of the loss of ecosystem services (in the short- and medium-term) is provided by the Charter of Ecosystem Services of regional soils [26] and the conventionally recognized indicators (Figure 15). In particular, the soil quality index "IQ4" provides a view of soil multifunctionality by summarizing the sum of four ecosystem services indicators such as water infiltration (WAR), food supply (PRO), current carbon stock (CST), and soil protective capacity (BUF). Before 2023, the plain was very fertile, while a continuous decrease of fertility towards the Apennine was observed. However, the Apennine belt, even if not performing in terms of PRO, before the time of flooding, provided large wood biomasses. The WAR service, i.e., the capability to allow rainwater infiltration by regulating the runoff and recharging the aquifers, were low, found in the low alluvial plain, and the delta part was completely unable since the first event on 1–3 May 2023, as soils were fully saturated. Then, the second event led to the collapse of the balance of many systems/ecosystems, BUF included.

The direct damage caused to infrastructure by the watercourses flooding and landslides was significant. It involved the motorway, the primary and secondary roads, and the railway network. Road infrastructures from 1950 were disrupted, i.e., 3.6% of the entire road layout of the six provinces involved. The most significant damage occurred on municipal roads (36.2% of the road sections impacted), neighborhood roads for pub-

lic use (35.7% of the road sections), and private roads (18.5% of the road sections) [1]. Fourteen landslides damaged the railway network, in particular the Bologna–Florence and Faenza–Florence lines: while it was possible to restore the first line in a few days, a long period of interruption to services to restore the latter was needed. In addition to the immediate destruction, longer-term landslides occurring in the following days due to the land settlement saturated by water continued to cause road interruptions, isolating the population.

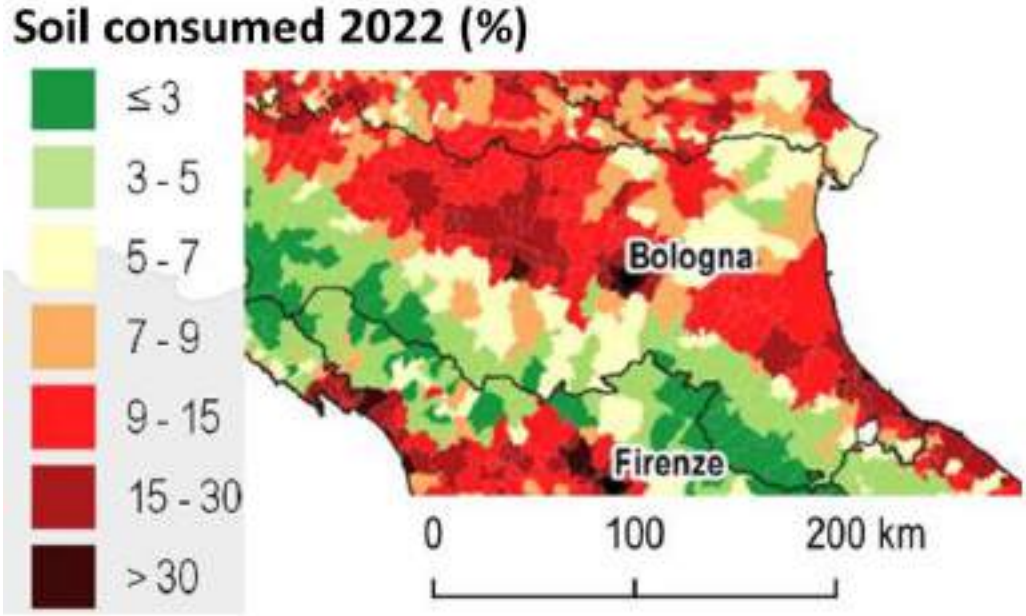


Figure 14. Land consumed at municipal level. Source: ISPRA elaborations on SNPA cartography [25].

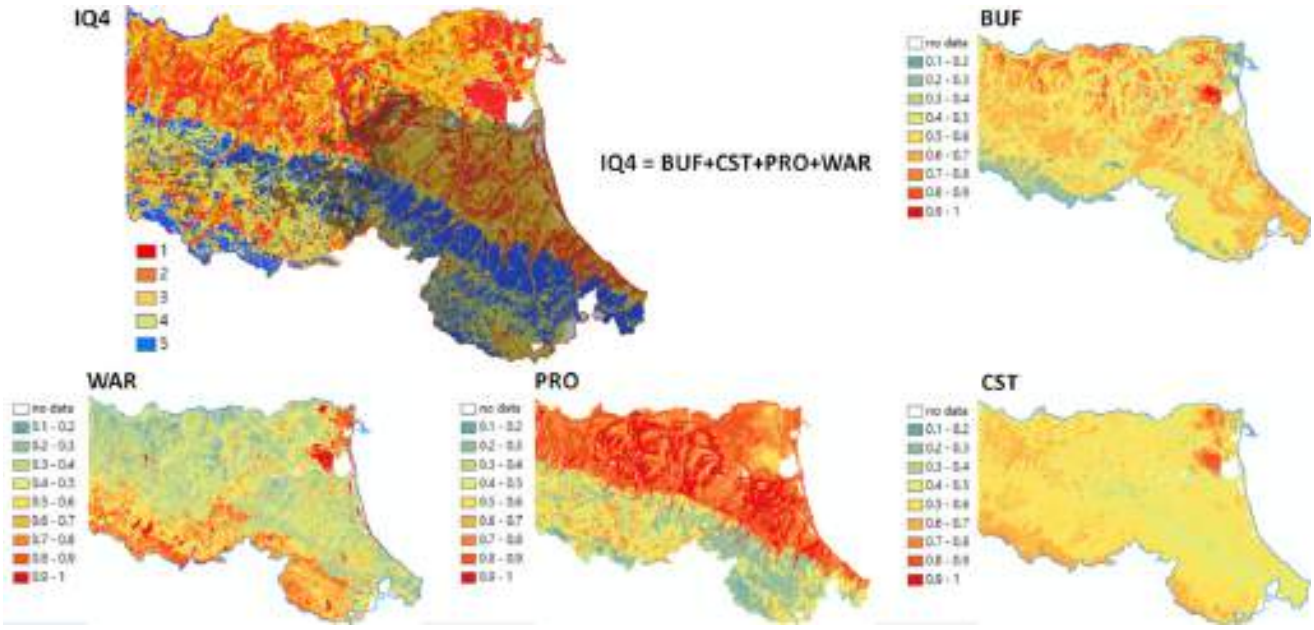


Figure 15. Representation of the IQ4 Soil Quality Index. Source: Emilia-Romagna Region [26]. The area subject to the events of May 2023 is dotted in black.

The water pouring into the inhabited centers flooded structures and buildings and generated interruptions to most services. Furthermore, sewage systems and underground services quickly saturated and filled in, causing the spreading of material contained inside. The high percentage of water-proofed surfaces characteristic of built-up areas worsened

the impacts, contributing to an increase in runoff volumes and further favoring rapid runoff, without allowing water infiltration. A problem of health risk management in areas where stagnant water persisted also emerged in a short time [27], addressed through the dissemination of a health vade mecum [28] drawn up by the regional Department of Public Health Romagna [29].

Real estate, civil and cultural, public and private heritage suffered significant damage: at least 15,000 buildings were flooded in the countryside, not to mention those in inhabited centers, which were also heavily affected. Damages concerned the buildings' structural parts, finishes, and the integrity of the buildings themselves, and were diverse in entity and kind. Basement and basement floors were the most affected, as well as ground and raised floors in some areas. Several physical causes occurred: hydrodynamic actions, due to the force and speed of water, caused damage from dragging and breakthrough. Hydrostatic actions, due to capillary upwelling and lateral hydrostatic pressure, caused damage to foundations (up to collapse) and capillary-rising phenomena and initial degradation of the building material. Erosion actions undermined foundations and consequently structural failures. The buoyancy actions acted asymmetrically on the structure, and the saturated subsoil reduced the bearing capacity of the soil and generated subsidence at the level of the foundations; cracks were created on load-bearing walls. Chemical and biological contaminating actions occurred, ranging from the pollution of flood water with industrial waste, detergents, dyes, sewage, vegetation, and microorganisms, up to the chemical aggression of materials and the formation of mold and fungi [30].

Damage to movable and immovable cultural property belonging to cultural heritage concerns losses in terms of monumental plant specimens (parks and historic gardens), archaeological sites, and monumental buildings such as libraries, museums, and churches (Figure 16), with further damage to the movable property contained therein. The Crisis Unit–Regional Coordination of the Ministry of Cultural Heritage in the Emilia-Romagna (UCCR) region created a WebGIS System to identify the damage reports [31]. UCCR specified seven damage typologies:

- Infiltration/percolation from roofs, walls, or other;
- Landslides, run-off, or erosion of land near cultural heritage;
- Fallen trees, protected or in areas of cultural interest;
- Flooding/principle of flooding in basements, ground floors, etc.;
- Flooding of archaeological sites;
- Static problems with retaining walls or structures;
- Damage or potential damage to movable properties.

Figure 16. Imola (Bo), Church of Spazzate Sassatelli. Intervention on antique furniture inside a flooded church. Source: Ministry of Cultural Heritage [31].

4. Discussion

While the meteorological causes and associated processes of extreme precipitation events may be clear, the attribution of their significancy in impacting soil and landscape is complex. It is evident that a large part of the territory lacked the fundamental resilience to protect assets and lives. Forests areas have indeed suffered high impacts, contributing to secondary effects such as river flows and flooding due to structural failures of the specific ecosystem [32]. In many cases, the debris transported by water caused the plugging of bridges, arches, or underpasses with subsequent flooding of large parts of the territories.

The abandonments of scarcely productive forests or their extensive uses led to a tangible reduction of landscape management and to missing maintenance of minor hydraulic networks. The concomitant coverage increases of forestry exacerbated the effects and impacts of intense precipitation episodes. A proper evaluation of forest management techniques, particularly in sloped areas near alluvial plains, is therefore mandatory in an adaptation perspective to climate changes.

From the atmospheric dynamics point of view, even if the events occurred are significantly out of the ordinary, there is an extensive bibliography and centuries-old case history of flooding events [33–38]. Understanding their dynamics is crucial for analyzing and interpreting the series of events that rarely have the possibility of combining, such as the co-presence of a depression system and a flow of high humidity along the Adriatic Sea. Such knowledge is key to determining whether episodes like those that occurred may be increased and exacerbated by direct links with climate change, as outlined in some publications [10,39].

One lesson clearly emerged from the events: we do not yet have sufficient capability either to exclude their reoccurrence or, also, to reasonably predict, in the case of their occurrence, the possible extent of the ecological, social, and economic impacts in the short but, mostly, in the longer-term [40]. However, there is promising potential for change, as emerged by some literature focused on the environmental impacts caused by these same events and the related metrics [41]. The indicators used to describe ecosystem services [26] can be used to represent scenarios that simulate chain events (using digital twins) to understand the impacts on the territory: areas firstly saturated can be figured out. Those that accommodate prevention works, storage, and accumulation will be more urgent.

On the topic of social differentiation, Houston et al. [41] underscored the disparities between social groups within the duration of flooding. For example, in the case of small fruit production farmers, the impacts of floods can be long-lasting, requiring the recovery of trees and then a large amount for the next yields and incomes.

With the aim to provide a helpful estimation of the damages to buildings, Martina [30] highlighted the importance of simultaneously considering the indicators of flood impact, the precautionary indicators, the building characteristics of the building, and their inhabitants. So far, only the hydrometric height, unique to the above factors, is used in the estimate. Precautionary factors concerning the building structure and the characterization of their components should also be included within the risk indicators.

The occurred meteorological events highlighted the dense and subtle network of interrelationships, from hydraulic features to the ecosystemic value of the territory to the social and economic aspects. A detailed and complete overview of hydrological risks in Emilia Romagna was provided from ISPRA (Italian Institute for Environmental Protection and Research) in 2021 [42], making it evident as a high regional vulnerability in terms of flooding, landslides, and related impacts. The weather forecast also provided reliable information about the incoming strong and intense precipitation events. Civil protection and any emergency management services effectively operated under the coordination of the regional authority. The main cause of the huge impacts to infrastructure can be attributed to inadequate temporal territorial planning. In fact, the occurrence of the return period of events characterized by such a magnitude and extension was underestimated. The increased frequency of extreme precipitation events should be therefore taken into

account to implement and improve local landscape and infrastructure planning over a return period of 200 years or more.

Active involvement of the population is crucial in understanding the actual behavior due to human presence in the territory and to foresight the implementation of adequate tailored policies. The economic consequences are profound, as families and businesses are facing restoration costs, decreased productivity, and potential closures, leading to job losses and financial negative feedback on local communities. Rebuilding efforts will require substantial investments in infrastructures and agricultural assets.

It must be remarked the open perspective offered by WMO, the leading UN organization on climate and meteorology, in relation to the Early Warning and to the Multi-Hazard Early Warning System (MHEWS) [43]. As WMO also outlines, MHEWS should be people-centered to empower those threatened by hazards to act in sufficient time and an appropriate manner, and must build on partnerships within and across relevant sectors. Advanced forecasting will also be crucial for providing early warning to populations, thereby enhancing their safety and security.

5. Conclusions

The aftermath of the 2023 flood events in Emilia Romagna were profound and multifaceted. One of the immediate consequences has been the displacement of thousands of residents from their homes, resulting in a significant strain on emergency services and resources. The economic impact of the floods has been substantial, with important losses in agriculture, infrastructure, and business. Several bridges, roads, and buildings have been severely damaged, disrupting crucial transportation networks and hindering access to many services. The agricultural sector has suffered significant losses with flooded fields, missing yield, needs for plant replacement, and suffering to livestock affecting the livelihoods of many farmers. Impacts on Po Valley fruit production will persist in the incoming future, while research and innovation (besides economic compensation put on place by local administration, EC contribution, and Common Agricultural Policy actions) are working to produce more resistant genotypes, and suitable management techniques able to match with a wide range of water availability, unfortunately ranging from drought to flooding. Large strategical expectancies are reserved for adaptation, with cisgenic breeding, varietal selection, water containment, and regulation tools as early warnings for locally tailored smart crop management and, in the longer-term, to improve the mitigation capacity of agricultural productions.

The environmental repercussions were also severe, with widespread damage to ecosystems, wildlife, and water quality. The psychological impacts on individuals and communities also cannot be understated. Besides the immediate attention to the event and declarations about the mitigation actions to be undertaken to reduce most of the impact, an intrinsic fragility of the territories emerged substantially, as two consecutive new floodings occurred in September 2024 in a large part of the same regional areas.

This paper can be therefore considered as a description of a worst case to show how extreme events, exacerbated everywhere by new climate dynamics, may be dangerous, and to alert about the urgency to put in place timely, appropriate, tailored mitigation and adaptation actions.

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Agency (REA.B—Green Europe), B.2-Farm to fork, Communities Development and Climate Action. Website: https://optforeu.eu/, accessed on 14 October 2024.

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