https://doi.org/10.5194/egusphere-2025-4405
Preprint. Discussion started: 24 September 2025

The 15 September 2022 floods in northern Marche (Central Italy): disaster analysis, case studies and mitigation strategies for geomorphological- hydraulic risk

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Abstract. On September 15th and 16th, 2022, a large area of the Marche region in central Italy experienced an exceptionally heavy rainfall event, with nearly 420 mm/m² of rain falling in just six hours. The intense rains, in addition to causing 13 fatalities, triggered a large number of landslides in the mountain areas and flood events, mainly concentrated along the valleys of the hydrographic basins of the Metauro, Cesano, Misa, and Esino Rivers. The physiographic setting of the territory and the poor maintenance of both the main and secondary hydrographic network, often insufficient or entirely absent, exacerbated an already exceptional event. Although extraordinary, the natural event affected an area already hit by intense meteoric events in the past, the most recent of which occurred just eight years earlier, in 2014.

This study presents the results of the systematic and detailed surveys conducted in several sites affected by the storm, also providing detailed case studies. These surveys highlighted the critical issues detected during the disaster and identified appropriate intervention measures for reducing hydraulic risk in the Region. Many of these measures are innovative and will serve as guidelines for future land-use planning and for improving public education and awareness in flood-prone areas.

1 Introduction

Floods represent one of the most destructive natural phenomena in Europe, with estimates indicating that approximately 500,000 people are affected by flood events annually (European Environment Agency [EEA], 2020). In recent decades, floods have been responsible for over 60% of the damage caused by natural events, with associated economic costs increasing significantly from around 5 billion euros per year in the early 2000s to approximately 12 billion euros from 2010 onwards (EEA, 2020). Among the most devastating events are the 2002 floods in Germany and the Czech Republic, the 2010 floods in Bulgaria and Romania, as well as the tragic 2021 floods in Belgium and Germany, which resulted in over 200 fatalities and billions of euros in damages (Jongman et al., 2014; EEA, 2021).

In response to the growing frequency of these events and their devastating impacts, the European Union adopted the Flood Directive 2007/60/EC, aimed at reducing flood risks. This directive requires Member States to identify vulnerable areas, develop flood risk maps, and establish flood risk management plans (European Parliament and Council, 2007). The Directive

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represented a key step towards proactive flood risk management, encouraging policies for prevention and adaptation to climate change, emphasising protecting people, the environment, and infrastructure (Barredo, 2009).

However, despite legislative and policy efforts, floods continue to cause significant damage. The case of the flood that affected the Marche region on September 15, 2022, highlights the need to further strengthen flood risk management by improving monitoring, forecasting, and intervention strategies at local and regional levels, in line with the objectives of Directive 2007/60/EC.

Analysing the conformation of the Italian territory from a physiographic point of view, it is not difficult to understand why this Country registers a large number of landslides and flooding events during intense storms each year. This is mainly because the Italian peninsula is elongated from North to South, it is northward bounded by the Alps and longitudinally crossed by the Apennines. This mountain ridge can easily reach 3000 meters above sea level and the Alps, in some cases, can abundantly exceed even 4000 meters.

The definition “geomorphological-hydraulic risk” used in the title refers to the interaction between geomorphological processes (such as landslides, erosion, and soil instability) and hydraulic dynamics (such as flooding and surface runoff).

The hydrogeological-hydraulic risks increase if we consider that most of the anthropogenic settlements have developed right along the river floodplains, increasing the "exposure factor” to the point of potentially involving 6.8 million inhabitants living in flooding areas, more or less 11% of the entire population (ISPRA report 2021). This is mainly because, during the time, the river was deprived of its flood plain, which was firstly used for agricultural purposes and, in recent decades, for urban purposes (infrastructures, industrial areas, new urbanisation, shopping malls, etc.). Therefore, during a flood, rivers are not free to meander, dissipating their energy in an open land, but they employ their erosive potential, causing destruction along the entire watercourse. And this implies the need and the duty to manage the hydrogeological-hydraulic risk.

The hydraulic hazard increases exponentially if we consider that anthropized (impervious) surfaces have increased from 2.7 % in the 1950s to 7.11 % in 2020 and, at the same time, the progressive abandonment of rural mountainous and hilly areas resulted in a neglect of the territory, increasingly deprived of its garrisons. Current climate change is also leading to an increase in the frequency of intense rainfall events and, consequently, an increase in the frequency of surface landslides, debris flows and flash floods (ISPRA report 2021). All these natural phenomena occurred during the extreme weather events of September 15^{th} and 16^{th}, 2022, in the Marche region.

The configuration of the hydrographic network, together with the presence of obstacles along the rivers (hydraulic crossings such as undersized bridges, lifelines, footbridges, or piers and other obstacles in the riverbed) are some of the main elements that can predispose sudden meteorological events. During an intense storm, in fact, the fluvial stream eradicates tree trunks, branches, bushes, sediment and other material from the riverbed, accumulating it in the first “bottleneck” encountered along the way (often represented by undersized bridges). The anthropogenic crossings resist until critical pressures are exceeded, causing the failure of the barrier of material that served as a dam or, even, the collapse of the structure itself. This triggers the “dam break” effect, which causes all the water collected upstream of the obstruction to go downstream, giving rise to a “wall of water" (it is often described in this way by witnesses) as high as many meters pouring abruptly downstream, so much so that they are called "flash floods".

It starts from here, the need for a proper maintenance of waterways intervening, where it is impossible to delocalize, through cleaning riverbanks of vegetation and surface water regulation works. In the last decades, most of these actions were neglected or unacted, due to the gradual abandonment of cultivation and mountain areas (farmers used to be very good maintainers of the land), together with a widespread lack of attention by the deputed Administrations.

During the 15th of September 2022 events, most of the rain fell in the mountainous interior territory of the region and, in a few tens of minutes, it was channelled through the hydrographic network to the main watercourses, swelling hydrometric levels and causing scattered flooding along the entire river valleys. Unfortunately, in addition to bringing about two billion euros in damage to the anthropic heritage, this event also recorded the loss of thirteen human lives and fifty injuries.

After this natural disaster, the geomorphology research group of the Geology Division of the University of Camerino (MC) conducted field surveys to identify the main critical issues, mapping them from a hydrogeological and hydraulic point of view. The situations of hazard have been detected both in mountain and valley environments (in this paper, the most affected and representative situations were treated in detail), also using lidar survey using drone and numerical modelling for the prediction of the maximum level of water reachable during a flooding event with different return times. This work focused on disaster analysis from a geomorphological and hydraulic perspective, following detailed on-field surveys conducted along the most damaged areas of the 15th and 16th September 2022 rainfall event in the Marche region. After this study, mitigation actions have been suggested for each situation. The magnitude of the event (intensity of precipitation, water discharge, debris and solid transport) and the subsequent impacts were far more severe and extended than previous flood events in the same area, thus calling for a radical change in current flood risk management practices (Dottori et al., 2024).

2 Materials and Methods

The Marche region shows a distinctive physiographic setting, with an internal Apennine ridge and streams branching off from it, from west to east up to the Adriatic Sea, with a comb-like arrangement orthogonal to the structure (fig 1), with an altitude trend generally decreasing from West to East.

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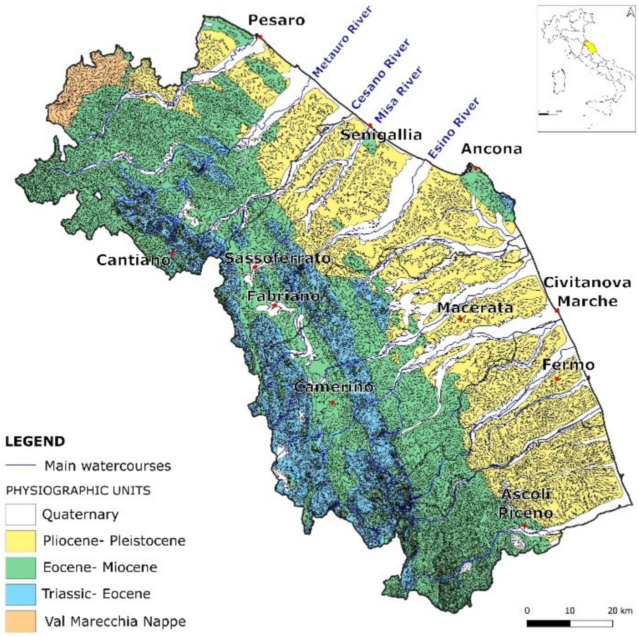

Figure 1: Physiographic setting of the Marche region (Farabollini & Bendia, 2022, modified) with elevation contour lines, main watercourses, and provincial boundaries. Cartographic layers from Regione Marche, n.d.

This geomorphological setting contributed to distinguishing two main different environments, with two different dynamics, each one with different accumulation/erosion processes and, therefore, different hydraulic criticalities, responses and damages. In the mountainous area, the first noticeable element in the landscape is the large number of landslide phenomena that occurred (fig. 2a) caused by the saturation of soils or sometimes triggered by the erosion at the base of the slope, caused by rivers.

Along the waterways, the flood caused large erosion phenomena at banks and scours at piers and abutments of bridges and, anyway, where the water flow encounters man-made works. This resulted in damage and failures due to the collapse of the structures due to geotechnical instability. These processes occur slowly under normal conditions, but very quickly and dangerously during flood events. The presence of bridges and, more generally, hydraulic crossings involved by the flood may trigger water vortexes in the proximity of the structures, able to create pervasive erosions and destabilizations of the structure and its surroundings.

Along the slopes, at the outlet of the incisions, incision phenomena were mainly channelled into gullies and accumulation processes have been recorded at their outflow, in particular debris flow fans. The retaining structures along the watercourse- such as walls, gabions, and weirs- were often inadequate and, in many instances, were damaged or destroyed by floods.

The foothill area registered extensive floods, which mainly covered infrastructure underpasses and underground floors (causing, moreover, several fatalities). In this portion of territory, the man acted by channelling the river to subtract its useful surface for cultivation and construction. The fluvial landscape appears constrained within anthropogenic earthen embankments, very often undersized and unmaintained.

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The level of water caused embankment overflow or riverbank erosion, often triggering the collapse of the same structure through piping, with the result of flooding the territory around it.

In the town, the critical issues have been additionally unpleasant because, over the past century, many sections of the river have been channelled and buried. In response to the hydrodynamic pressures of the flood, they have frequently experienced cover collapse.

During the events of the present study, along the mountain territories, very intense erosion phenomena were recorded along the slopes, with erosion gullies concentrated where surface runoff was most intense and the triggering of many gravitational events (see also Donnini et al., 2023; Santangelo et al., 2023). The geomorphological conformation of the Apennine territory predisposed the formation of different typologies of landslides. In many cases, the presence of an elevation gradient sometimes even of one thousand meters, the stratigraphic condition of the material and the disruptive action inferred by the meteoric processes, acted originating a large quantity of debris flow phenomena (fig. 2 a, b), involving coarse-grained material with gravel sizes ranging from cobbles to boulders, according to Udden, 2014 and Wentworth, 1922.

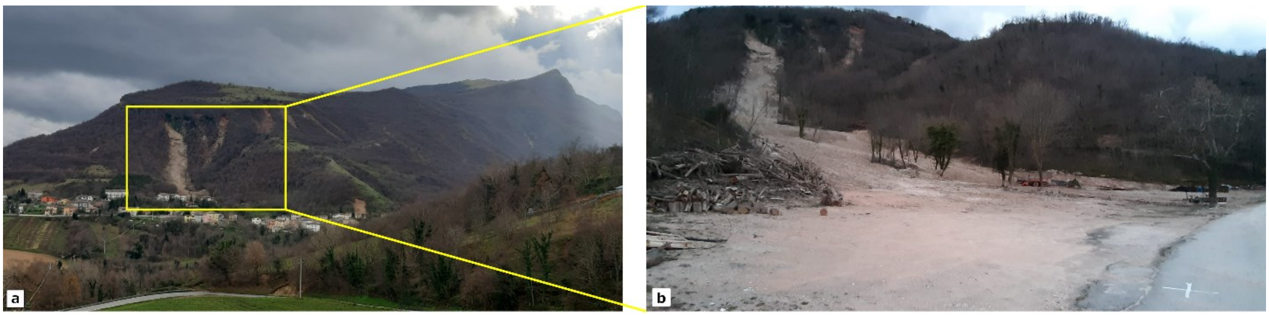

Figure 2: a) the scars of landslide events along the northern slopes of Mt. Calvello, activated during the rainfall event in question and involving the hamlet of Leccia, municipality of Serra Sant'Abbondio (PU); b) detail of the frame in picture a).

2.1 Meteorological analysis of the flood event of September 15th and 16th, 2022 in the Marche region of Italy

The extreme meteorological event of September 2022 in the Marche region has been extensively analyzed from a meteorological point of view (Civil Protection of the Marche region, 2022; Gentilucci et al., 2023; Torcasio et al., 2023), also considering the important contribution coming from the use of satellite data (Pulvirenti et al., 2023). On September 15th and 16th, 2022, after a long drought period, the Marche region was affected by a very intense self-healing thunderstorm, which mainly involved the provinces of Pesaro Urbino, Ancona and, on the following day and even if in a minor part, Macerata (Tognetti D., 2022). The magnitude of the event was so extraordinary that, on September 16th, 2022, through two resolutions the Council of Ministers of the Italian Republic declared a “state of emergency”, a legal status that can be enacted by the national Government after the occurrence or in the imminence of exceptional events, such as extreme natural events like earthquakes, floods, volcanic eruptions, drought, pandemics, etc. (Donnini et al., 2023; Lodi et al., 2023). One of the first actions identified by the Italian Prime Minister was to delegate post-event management to an Extraordinary Commissioner to

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manage the emergency phase, support rescue efforts, accommodate displaced people, implement residual risk mitigation in the damaged territories, bestow financial assistance for affected citizens and businesses activities, reconstruct the damaged building stock (structures and infrastructure), and reestablish the connection between the riverine and urbanized environment. From a meteorological point of view, a convective system generated by low pressure over the Atlantic and high pressure over northern Africa resulted in the formation of a stationary, self-healing thunderstorm, as it transited from West to East over the north of the Tyrrhenian Sea (Gennari et al., 2023; Gentilucci et al., 2023). This typology of the storm is called "V-shaped" because of its geometry, well recognizable in plain view (fig. 3). In general, V-shaped thunderstorms are not uncommon over Italy, especially in the summer (Torcasio et al., 2023) and not all V-shaped thunderstorms result in floods or flash floods, as their duration is short. However, when V-shaped thunderstorms are stationary for several hours over a specific area, they very often result in floods or flash floods (Federico et al., 2019). The vertex of the V-shaped (sting) is the point where the fresh new storm cells are continually regenerating, and it is there that the phenomena can take on an extraordinary character in terms of rainfall and lightning. Geographically, during the event, this position was the inner territory of the Marche region, between Pesaro Urbino and Ancona provinces. Comparing fig. 3 and 4, in fact, it appears clear the superimposition between the location of the sting and the areas with the highest recorded rainfall.

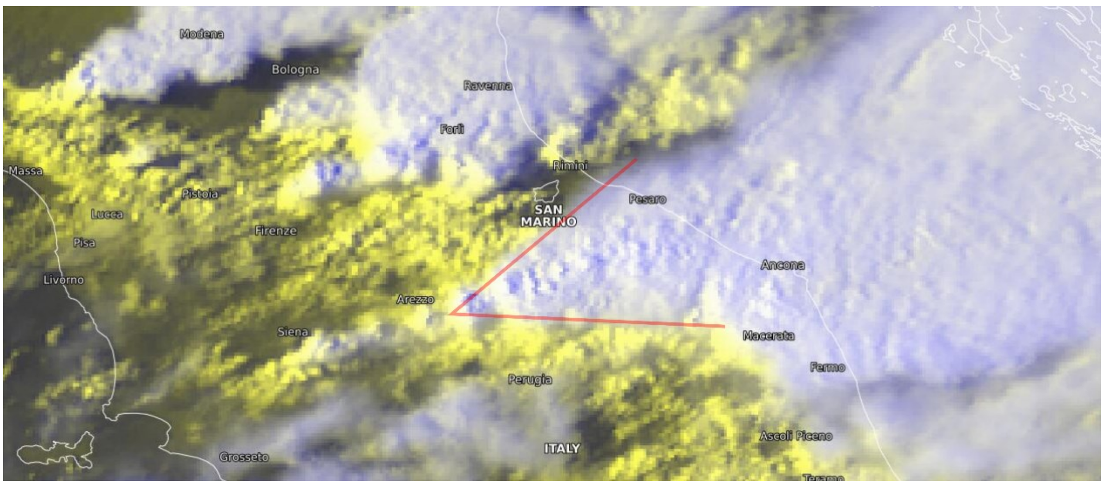

Figure 3: The Central Italy satellite view of the thunderstorm at 3:00 pm UTC on 15th September 2022. MSG-SEVIRI HRV cloud composite with the characteristic and well-recognisable V-shape (drawn in red). Copyright Eumetsat. Image from https://view.eumetsat.int/productviewer?v=61314 (last access 10.18.2024).

2.2 Hydrologic analysis of the event

From the regional rainfall map (fig. 4), it is possible to recognize the areas most affected by rain during the meteorological event, such as the western Apennines area of the province of Pesaro Urbino and a large portion of Ancona province.

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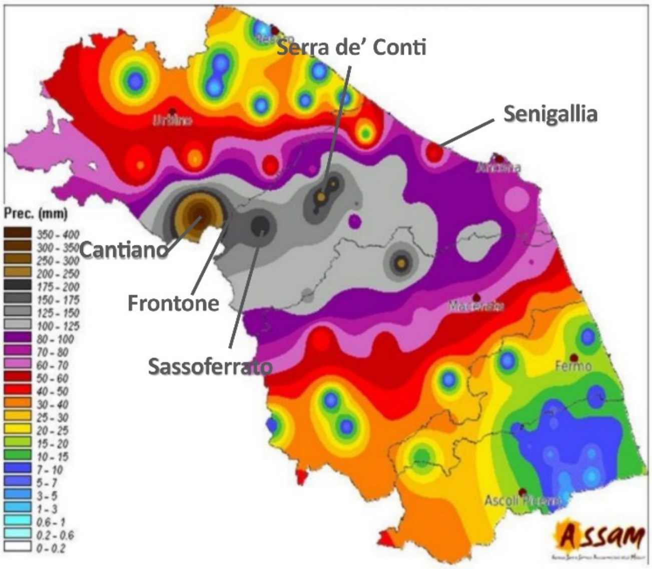

Figure 4: Cumulative rainfall distribution during the entire day of 15th September 2022 in the Marche region, modified, indicating the most represented localities treated in this work (Regional Agro- meteorological Service of AMAP Regione Marche, 2022; modified).

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The hydrographic basins involved were those of Metauro, Cesano, Misa, Esino and Potenza Rivers, although the last (southern) one was affected to a lesser extent (fig. 5).

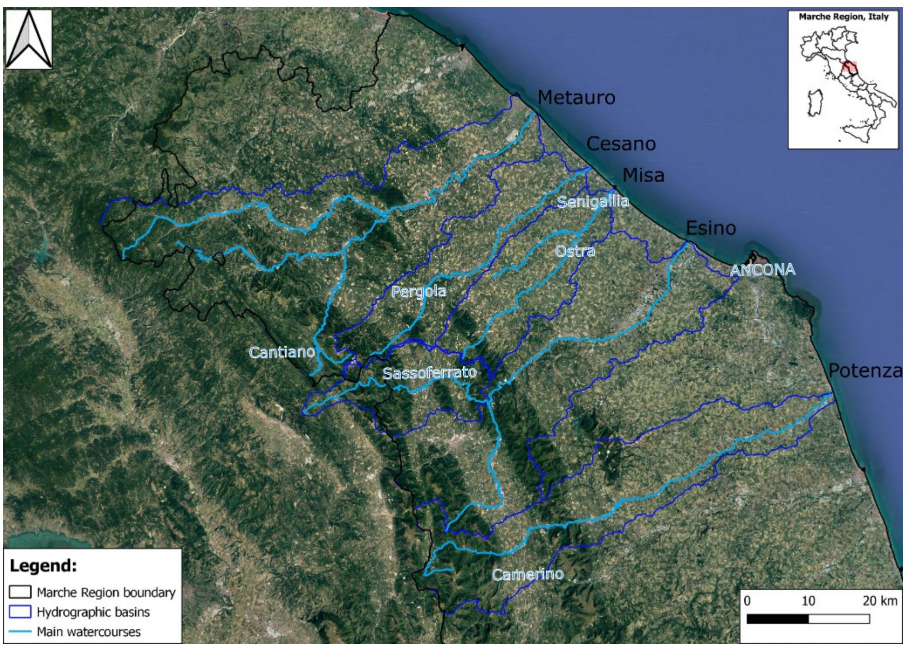

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Figure 5: The northern portion of the Marche Region with the hydrographic basins involved by the flood and the main watercourses. Cartographic layers from Regione Marche, n.d.

It should be noted that this work is based on cumulative rainfall data acquired through different regional agencies responsible for data acquisition, named SIRMIP, 2022 and the Regional Agro- meteorological Service of AMAP Regione Marche, 2022. SIRMIP is the acronym of "Sistema Informativo Regionale Meteo- Idro- Pluviometrico", it means the regional meteorological-hydro- pluviometric information system. Important pluviometric differences were noted in the towns of Sassoferrato and Arcevia. The most representative stations for this analysis were considered and collected (tab. 1) for the sake of the record.

Station	**SIRMIP (2022)**	**Civil Protection of the Marche Region (2022)**	**Regional Agro-meteorological Service of AMAP Regione Marche (2022)**
Cantiano (PU)	419 mm/m2	419 mm/m2	not available
Frontone (PU)	384 mm/m2	384 mm/m2	380 mm/m2
Serra Sant'Abbondio (PU)	373 mm/m2	373 mm/m2	not available
Arcevia (AN)	128 mm/m2	178 mm/m2	128 mm/m2
Sassoferrato (AN)	100 mm/m2	100 mm/m2	197 mm/m2
Senigallia (AN)	not available	15.6 mm/m2	not available

Table 1: Comparison of cumulative rainfall between different regional agencies responsible for data acquisition.

According to our analysis, the discrepancies between the two sets of data may be due to the presence of two different rainfall station networks with different coordinates and elevations and, sometimes, with two different rain gauge installation methodologies. For example, the town of Sassoferrato has three rainfall sensors, two of the SIRMIP pluviometric network (sensors n. 2073 and n. 2992) and one of AMAP (sensor ST59). Rainfall sensor n. 2073 didn't work during the event. Rain gauge sensor n. 2992 recorded a cumulative rainfall of 100.4 mm/m2 and AMAP recorded a cumulative rainfall of 197 mm/m2 from 3 pm to 11 pm. This is probably because, in some cases, the modalities of installation of rain gauges may differ between the two monitoring networks (rainfall sensors set up near watercourses with trees that, growing in height with time, could shelter the rain and could affect, even considerably, the final result).

From a hydrological point of view, the largest amount of the rain fell in the area around Mount Catria (1702 meters a.s.l.), thus first involving the surrounding villages of Cantiano (province of Pesaro Urbino, Metauro River basin), Frontone (province of Pesaro Urbino, Cesano River basin) and then spilling down into the valleys of Sassoferrato (province of Ancona, Esino River basin), Pergola (province of Pesaro Urbino, Cesano River basin), to finally arrive in the towns of Ostra and Senigallia (province of Ancona, Misa River basin), close to the Adriatic coast. Just to have an idea of the magnitude of the event, from 2:30 to

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09:45 pm on September 15th, 2022, the sensor n. 2972 of the rain gauge of the town of Cantiano recorded the highest rainfall during this extreme event, with a cumulative of 419 mm/m2 and almost all of this rain fell in the first 6 hours (fig. 5 and tab. 2). During the same time, the sensor 3294 of Mt. Acuto (Frontone) registered 380.08 mm/m2 (SIRMIP, 2022). The largest part of the rainfall was mainly concentrated between 3:00 and 7:00 pm time window and it decreased going from the mountains to the sea; therefore, almost no rain fell in Senigallia. The rainfall data for each considered time interval acquired from rain gauges in the most representative localities of the meteorological event were collected and summarised in tab. 2.

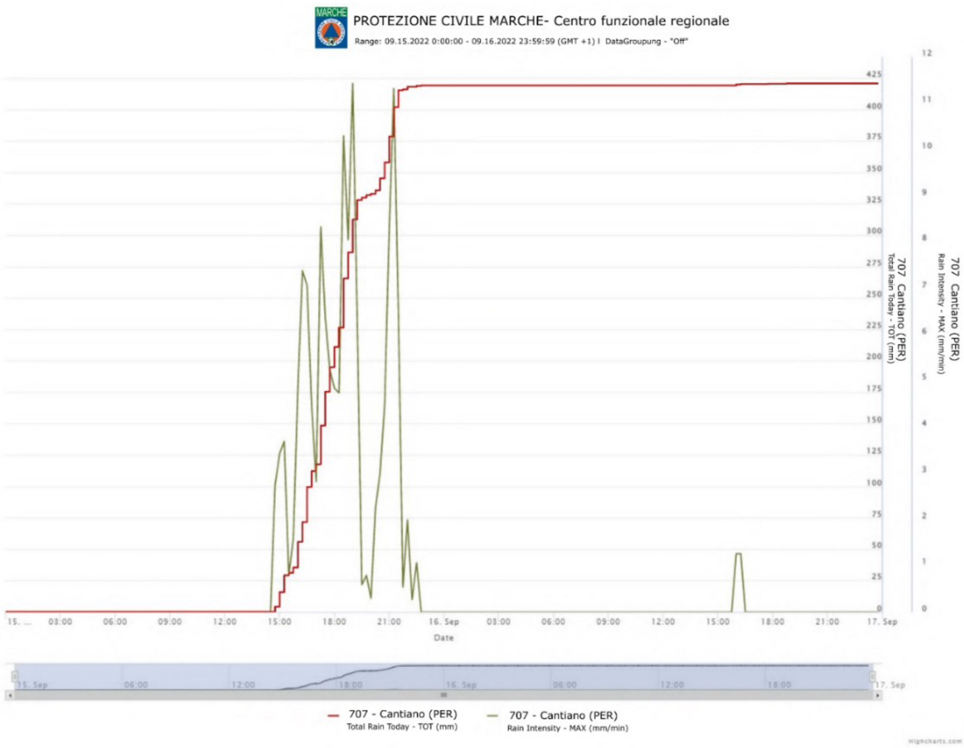

Figure 6: Cumulative and intensity of precipitation recorded by the rain gauge of Cantiano (redraw from Civil Protection of the Marche region, 2022). Times in the graph refer to standard time.

Rain gauge station	**Hydrographic basin**	**Cumulative rainfall September 15-16, 2022**				**Return time (years)**			
		Max 3h	**Max 6h**	**Max 12h**	**Max 24h**	**3h**	**6h**	**12h**	**24h**
Cantiano	Biscubio	256.6	384	419	419	>1000	>1000	>1000	>1000
Frontone (Mt. Acuto)	Cesano	248.4	343	384.2	384.4	>1000	>1000	>1000	>1000
Arcevia	Misa	94.8	117.8	128.8	129.2	>1000	>1000	910	200

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Barbara	Misa	111.4	121.2	127	127.2	>1000	>1000	>1000	140
Colle	Misa	162.4	186.4	204	204	>1000	>1000	>1000	>1000
Sassoferrato	Sentino	62.8	99.8	99.8	100.4	130	600	120	30
Colleponi	Sentino	68	122	122.2	122.6	230	>1000	750	150
Mt. San Vicino	Musone- Esino	108.2	120	192.8	193.6	>1000	750	>1000	>1000
Cingoli	Musone	160.4	184.6	247.2	247.6	>1000	>1000	>1000	>1000

Table 2: Estimation of the return time of rainfall recorded by some significant rain gauges for the event using the procedure given in the document on the Regionalization Study of Heavy Rainfall defined within the agreement between the Commissioner delegate bad weather May 2014 and the CIMA Foundation, "Centro di Competenza del Sistema di Protezione Civile nazionale per il settore idrometeorologico" (Civil Protection of the Marche region, 2022)

The magnitude of this event significantly surpassed the literature Intensity-Duration-Frequency curves (Fig. 7), categorizing it as an "outlier event," likely triggered by the ongoing climate change across the Mediterranean climate "hot spot" (Corti et al., 2024).

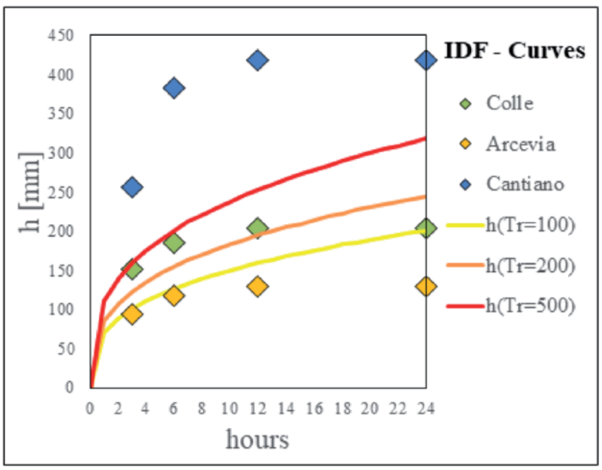

Figure 7: Intensity-Duration-Frequency (IDF) curves calculated for the Marche area compared to Colle, Arcevia and Cantiano station rainfall values during the event. As can be appreciated, the Cantiano station showed extreme rainfall amounts with respect to the others (Mattavelli, 2023 modified by Corti et al, 2024)

The hydrometric analysis for the municipality of Cantiano (Fig. 8) confirms the testimonies collected from residents who narrated about two flood waves that affected Luceoli Square: the first, smaller, inundated the square with about 50 centimetres of water and the second, more extensive, reached a height of 2.35 meters. This is well recognizable in the two peaks corresponding to the two flood waves that reached Luceoli Square at 7:30 p.m. and 9:30 p.m.

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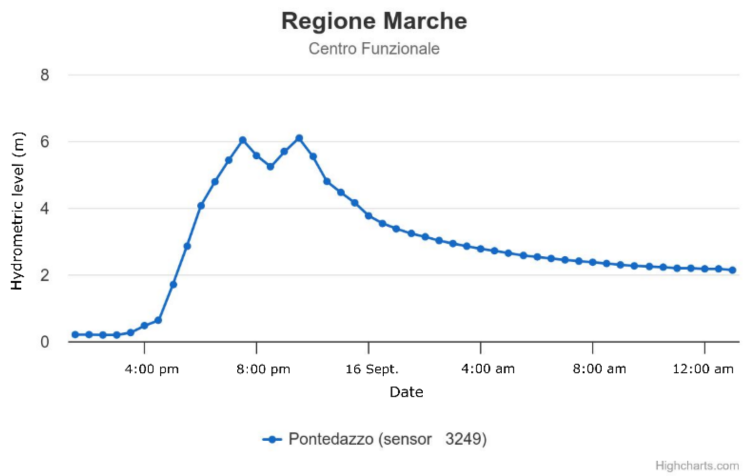

Figure 8: The hydrometric graph of sensor 3249 Pontedazzo about one km downstream of Cantiano from 1:00 p.m. of Sept. 15th, 2022, to 1:00 p.m. of Sept. 16th, 2022, Italian time (SIRMIP 2022).

Analysing the hydrometric graphs (Fig. YYY) along the catchment area of Metauro River from Cantiano (hamlet of Pontedazzo) to Fossombrone (PU) it is possible to recognize the two main peaks inherited from the Cantiano floods also reflected in the downstream municipality of Cagli (PU), which is another locality studied for this work. After the rain gauge in Cagli (Cavour Bridge of Flaminia Street), the Burano River reaches the water contributions of Bosso River, further on, those of Candigliano River and, further on, in proximity of Fossombrone, those of Metauro River. It is precisely for these contributions that, from the town of Cagli on, we don't find the double peak in the flow. The downward trend in hydrometric levels is because the Metauro River has a SW-NE direction while the storm has moved to the south-east.

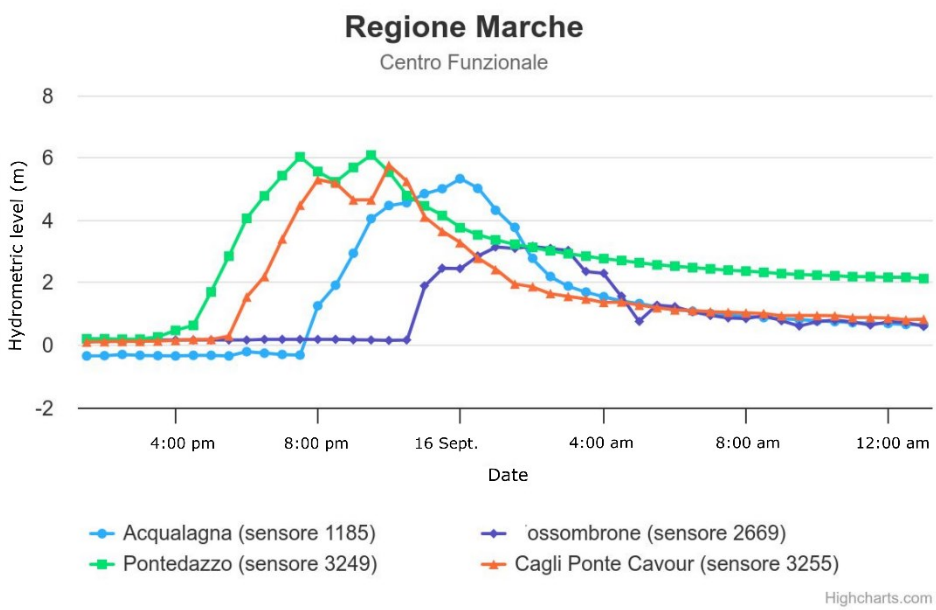

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Figure 9: The hydrometric levels of the mountain portion of the Metauro River basin from Pontedazzo (Cantiano) to Fossombrone, from 1:00 p.m. of Sept. 15th, 2022, to 1:00 p.m. of Sept. 16th, 2022. Italian time (SIRMIP 2022).

Looking at the hydrometric comparison between the hydrometers along the catchment area of the Misa River, it is immediately apparent how the hydrometers of Serra de' Conti, Corinaldo, Passo Ripe and Pianello di Ostra stopped because they were broken, temporarily disabled, or washed away as the flood arrived. The difference between Bettolelle (municipality of Ostra) sensor 1112 and, downstream, Ponte Garibaldi sensor 3147 (Senigallia city centre). From Serra de' Conti in the mountain area to Garibaldi Bridge in Senigallia, the peak of the flood wave took presumably about three hours and a half.

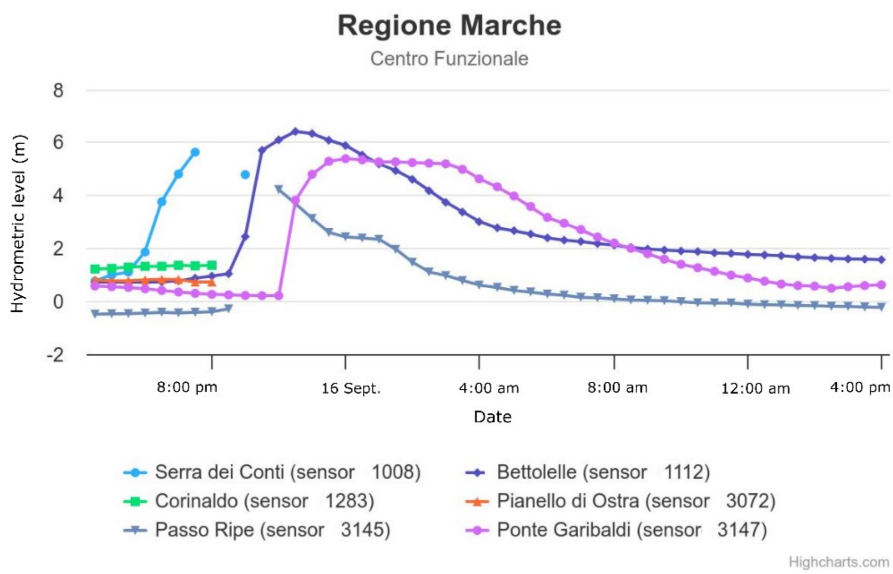

Figure 10: The hydrometric levels of the Misa River basin between Serra de Conti (AN) and Senigallia (Garibaldi Bridge), from 4:00 p.m. of Sept. 15th, 2022, to 4:00 p.m. of Sept. 16th, 2022. Italian time (SIRMIP 2022).

To get an idea of the uniqueness of the event, an online blog of hydrogeology (Idrogeologia Polito, 2022) provided an interesting historical series of annual precipitation maxima for 5 different durations (1, 3, 6, 12 and 24 hours) of the Cantiano rain gauge (fig. 11).

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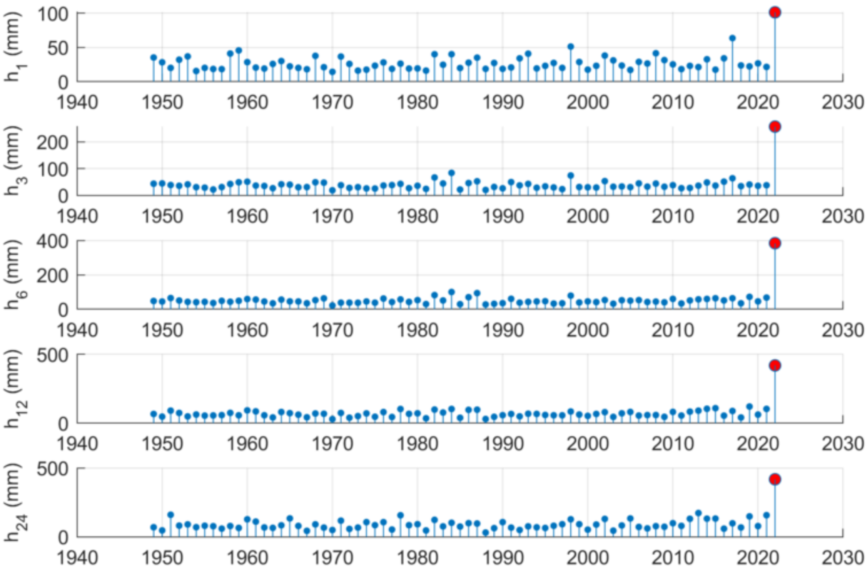

Figure 11: Historical series of annual precipitation maxima for 5 different durations (1, 3, 6, 12 and 24 hours) of the Cantiano rain gauge, showing the extremes recorded during the September 15th, 2022, event (Idrogeologia Polito, 2022).

The statistical analysis of the extreme and rare event object of the present paper reports very significant return levels (Gentilucci et al., 2023) and return times in terms of rainfall. Some authors suggest that, for the Frontone weather station, a quarter of the average annual rainfall fell in only nine hours (Regional Agro- meteorological Service of AMAP Regione Marche, 2022). Civil Protection of the Marche region, 2022, reports return times of more than a thousand years for some (Cantiano, Frontone) of the most affected localities (tab. 2). Other authors (Guglielmo & Verdicchio, 2022) calculated return times for 24 hours included between 2000 and 3000 years and greater than 3000 years for durations up to 12 hours.

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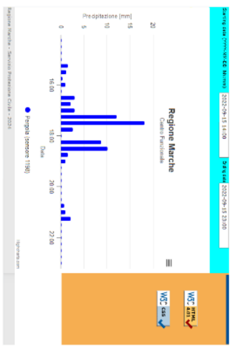
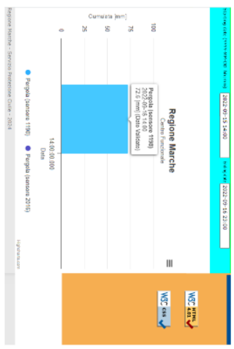
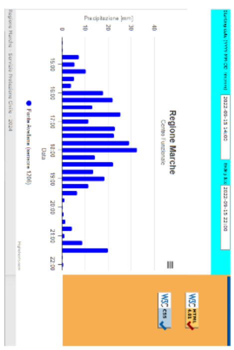
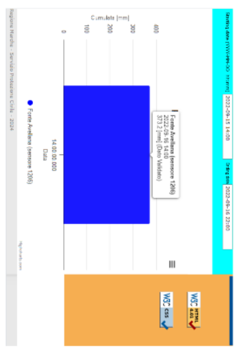
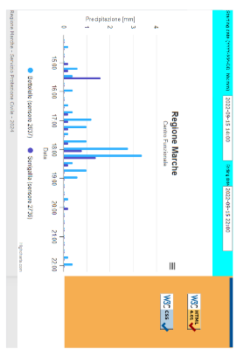
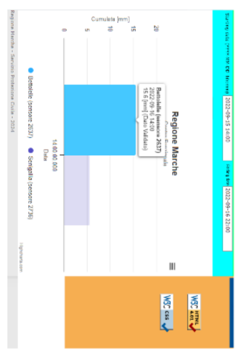
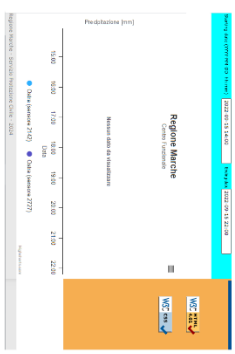
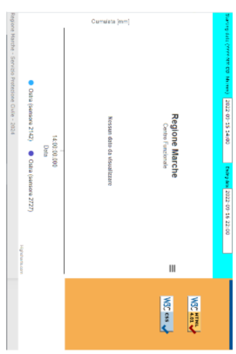
Validated rainfall data (mm/m^2)	Cumulative rainfall (mm/m^2)	
		Pergola
		Serra Sant'Abbondio
		Senigallia
		Ostra

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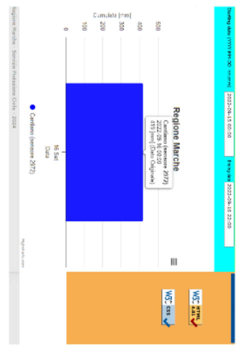
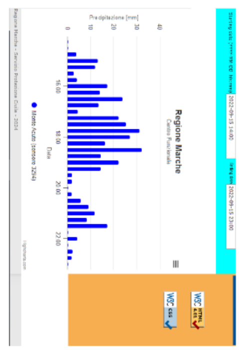
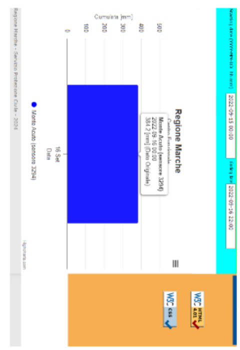
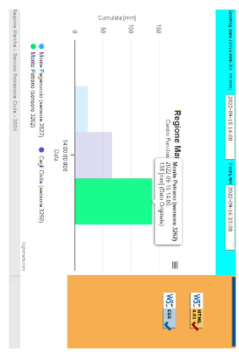
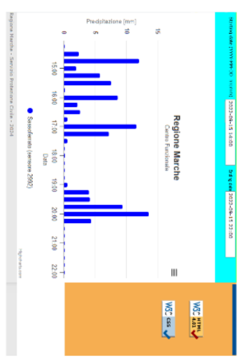
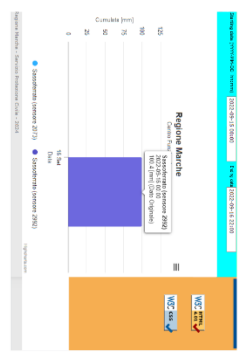
		Cantiano
		Frontone
		Cagli
		Sassoferrato

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Table 3: Comparison between cumulative rainfall and rainfall measurements (with 15-minute time intervals) in the most representative localities of the meteorological event (SIRMIP 2022). Accessed 30 December 2023.

This work follows an agreement where the Marche Region Administration, through the Commissioner delegated by the National Government for the management of the Marche 2022 flood, conferred to the geology division of the University of Camerino (MC) and the civil engineering division of Marche Polytechnic University of Ancona (AN) studies to identify priority interventions to mitigate risk in flood-affected areas. The present study, in addition to providing a complete examination of the event, is based on geomorphological field surveys aimed at disaster analysis, by investigating the critical issues found along the main damaged watercourses and localities, differentiating between mountain and foothill environments. It is considered to have a great impact at the social level because it has been functional for mapping all the critical issues detected and for the subsequent proposals of intervention aimed at risk mitigation. It is furthermore an extraordinary example of synergy between institutions where the academic knowledge of geologists and engineers, enhanced by modern and innovative technologies, is made available for the territory and the society.

The first part of this work consisted of a cartographic recognition conducted through the predisposition of a Geographic Information System (GIS) database, where all cartographic elements considered useful were collected:

- Topographic map of Istituto Geografico Militare "IGM" (scale 1:25,000),
- Regional Technical Map (C.T.R.) of the Marche Region (scale 1:10,000),
- Detailed municipal topographic survey (scale 1:2,000),
- Cartography maps of hydrogeological and hydraulic hazard and risk ("Piano di Assetto Idrogeologico", P.A.I.),
- Archive of Italian Vulnerated Areas (A.V.I.),
- Gregorian historical cadastre (year 1835) to understand the hydrographic network modification interventions conducted in the past,
- Historical images retrieved from archives online,
- Satellite data of post-event (Copernicus Emergency Management Service, 2022),
- LIDaR digital elevation model acquired through drone surveys,
- Geological and geomorphological cartographies (CARG project, scale 1:10,000),
- Post-event cartographies drawn up by the technical offices of the interested municipalities and Civil Protection.

All this information was catalogued in a GIS database (fig. 12), useful in supporting the indispensable on-field geomorphological surveys. All the findings were subsequently implemented with the technical innovation provided by new instruments and software, such as drones, QGIS software, QField mobile app and numerical models for hydrologic and hydraulic predictions HEC-HMS and HEC-RAS.

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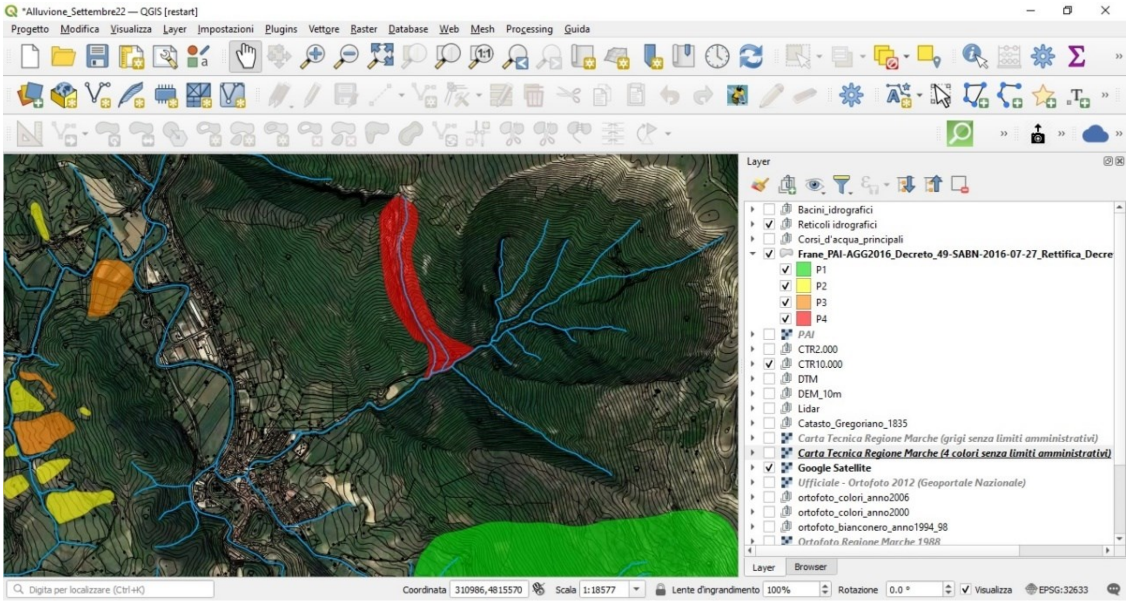

Figure 12: The QGIS project with all the cartographic information collected. Cartographic layers from Regione Marche, n.d.

The availability of satellite data from the Copernicus European project, consultable in real-time, was acquired during and in the immediate aftermath of the event (fig. 13). For each locality has been produced a map capable of investigating and defining the extent of the phenomenon and the expected level of damage through remote sensing techniques.

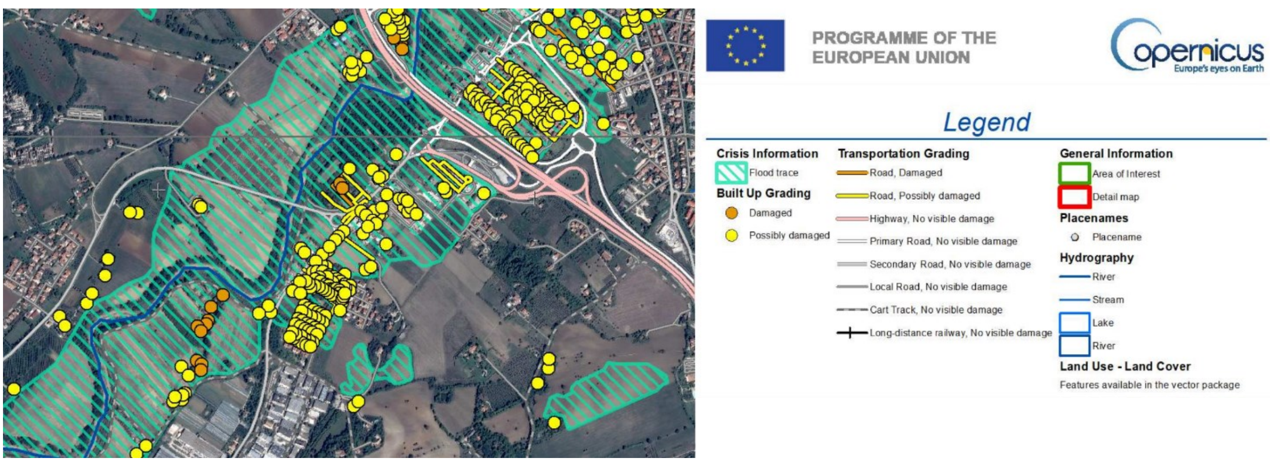

Figure 13: An excerpt, modified, of Copernicus satellite mapping in the immediate aftermath of the Marche floods, with the well-recognisable flood trace and the damaged and possibly damaged buildings. South-West of Senigallia. Original image from https://emergency.copernicus.eu/mapping/list-of-components/EMSR634 (Accessed on 12.16.2024).

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2.3 Case studies

The surveyed localities correspond to the most affected towns: Cantiano (PU), Cagli (PU), Serra Sant'Abbondio (PU), Pergola (PU), Sassoferrato (AN), Serra de' Conti (AN), Ostra (AN) and Senigallia (AN) (fig. 14).

Figure 14: the surveyed locations in the provinces of Ancona and Pesaro Urbino, with the effective surveyed areas superimposed to the @Google Earth image and highlighted in orange.

The on-field surveys detected all the critical issues encountered along the watercourses, according to the datasheets provided by the "Consorzio di Bonifica delle Marche", the public agency that manages the hydrographic basins of the region. This paper aims to illustrate some case studies depicting the most representative situations encountered, both in mountain and valley floor environments. In each one of them, meteorological processes resulted in substantial differences in hydro- hydro-geomorphological dynamics and processes and in the hydraulic response of the watercourses.
Based on the differences in different environments, it is possible to subdivide the most representative situations encountered, described in detail in the following lines.

2.3.1 Case study 1 (mountain context): the Mt. Tenetra River valley (Cantiano, PU)

Tenetra River valley (fig. 15) is about 1500 meters long and is represented by a narrow valley located around an altitude of 430 meters a.s.l. elongated in a N/NE-S/SW direction and bordered to the northeast by the morphological amphitheatre of Mount Tenetra (1242 meters above sea level) with a still debated morphogenesis. It is not excluded that the area was involved in the past by glacial processes, present in the bibliography (Savelli et al., 1995), later resumed and amplified by karstification and other erosional phenomena, conferring the suggestive landscape forms visible today. The southwestern foothill of the hydrographic basin ends, valley-side, with two distinctive morphological structures called flatirons of Pontedazzo and Mt. Alto. The steep slopes of these elements, inherited from the interaction between the stratigraphic-structural setting and the erosive processes that acted above it, end up imposing rocky buttresses on either side of the ditch, which therefore sees its

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section drastically reduced near the hamlet of Tenetra. In the historical centre of Cantiano, the Tenetra Stream flows into the Bevano Creek coming from the south.

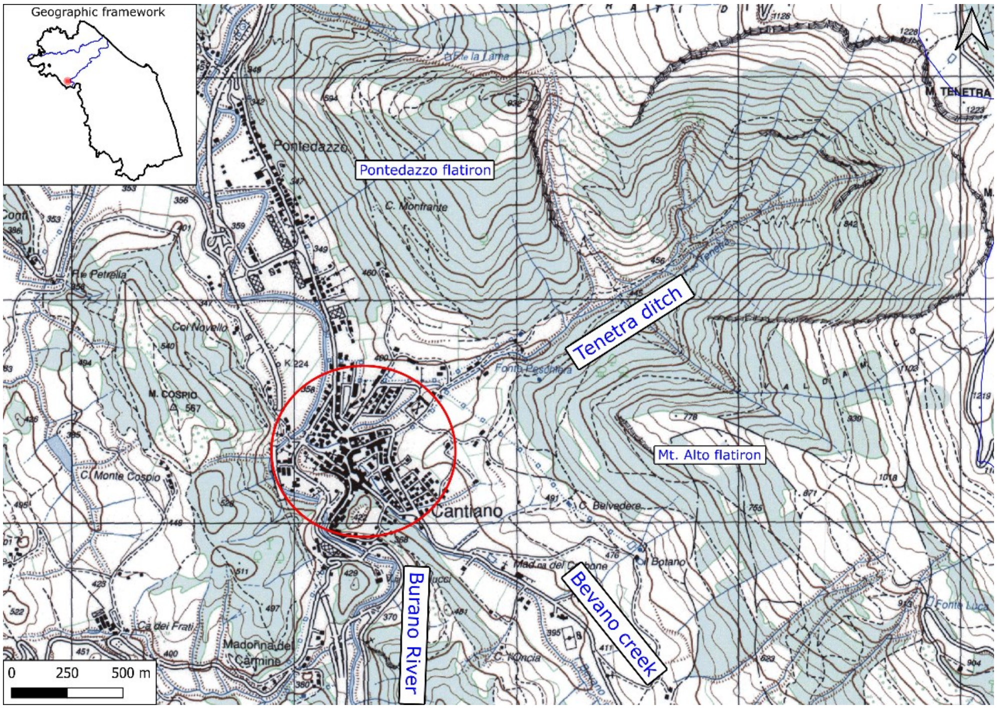

Figure 15: Topographic map of the town of Cantiano (IGM 1:25,000) with the well-recognisable form of Mt. Tenetra amphitheatre and the three main watercourses. In the extent rectangle, the Marche region, the hydrographic basin of the Metauro River in blue and the town of Cantiano in red. Cartographic layers from Regione Marche, n.d.

2.3.1.1 Geomorphological setting

The geologic-stratigraphic succession outcropping in the Tenetra basin results arranged according to a dip-slope giacitural relationship with an inclination also sometimes complementary to that of the western flank of the homonymous relief. The stratigraphic succession is constituted from limestones, marly-limestones, limestone- marls and cherty-limestones sediments of the Jurassic Period (at the core of the Tenetra morphological amphitheatre) to the hemipelagites in the vicinity of Cantiano (referable to the Middle Miocene). The outcrops are arranged with a periclinal setting defined by less sloping dips on the western flank, with older lithotypes found at the core of it, sub-horizontal bedding near the summit plateau of M.te Tenetra-M.te Morcia that finally bends on the eastern flank of the orogen, where they have a more sloping dipping axis.

Locally, the geological bedrock is in general weakened by the presence of widespread tectonic lineaments that have involved the area and it is therefore characterized by wide fractured portions that degrade the rocks, also favouring the meteoric alteration phenomena with consequent triggering of associated gravitational movements. The presence of the "Rosso

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Ammonitico Formation" and "Marne a Fucoidi Fm.", characterized by a very low permeability and therefore capable of acting as aquicludes, in addition to having sculpted the landscape in a very incisive way, has permitted the setting of multiple water venues, variously scattered along the basin itself. The stratigraphic succession of the area ends upwards with the presence of Quaternary deposits characterized by slope debris and landslide deposits and, in the Tenetra valley, alluvial deposits with interdigitated presumable lacustrine episodes.

From a geomorphological point of view, the Tenetra ditch has a mostly straight course, with a N/NE-S/SW direction on which several tributaries are laterally connected. These are orthogonal to it on either side of the valley floor, while those set within the amphitheatre itself locally show a centripetal arrangement. The general anti-Apennine trend of the Tenetra suggests a plausible tectonic control over it. At the historic centre of Cantiano, the water lineament converges to the Bevano Creek and then both flow into the Burano River. The extent of the valley is variable, with a width of around 20-30 meters in the upstream section and up to 140 meters in the intermediate section, which has large and cultivated areas. Downstream, near the locality of Tenetra, the valley suddenly narrows due to the closure of the sides of the two flatirons.

2.3.1.2 Critical issues detected

As widely mentioned, on Sept. 15th, 2022, the rainfall sensor "2972 Cantiano" recorded a cumulative rainfall of 419 mm/m^2, almost all of it concentrated in just over six hours (fig. 4, 5; and tab. 1, 2). The amphitheatre-type shape of the western flank of Mt. Tenetra, together with its high relief energy (fig. 16a), channelled all the surface runoff towards the homonymous ditch. From a geomorphological-hydraulic point of view, this resulted in different landslides recorded along the flanks of the relief with the consequent removal, transportation and deposition of a huge quantity of coarse-grained material along the waterway itself, with rock blocks as large as several meters. In many cases, the watercourse has cut so deeply into the riverbed as to expose the underlying local calcareous bedrock, which in the past was covered during time by alluvial and colluvial sediments. In many observations, along the slopes, the same channels have been filled with this coarse-grained sediment and subsequently incised during the tail of the event, remaining debris flow deposits in the form of embankments lateral attributable to a lateral overflow of the flow front (Johnson & Rodine, 1984) (fig. 16b). After the extreme event many deposits at the foot of the slopes (fig. 16c) and throughout the valley were recorded. The shape of the valley, in fact, resulted in steep slopes and a flat bottom filled with sediments (fig. 16d), spreading as flat blankets on alluvial fans (Aulitzky, 1980), indicating the overflooding condition of the same.

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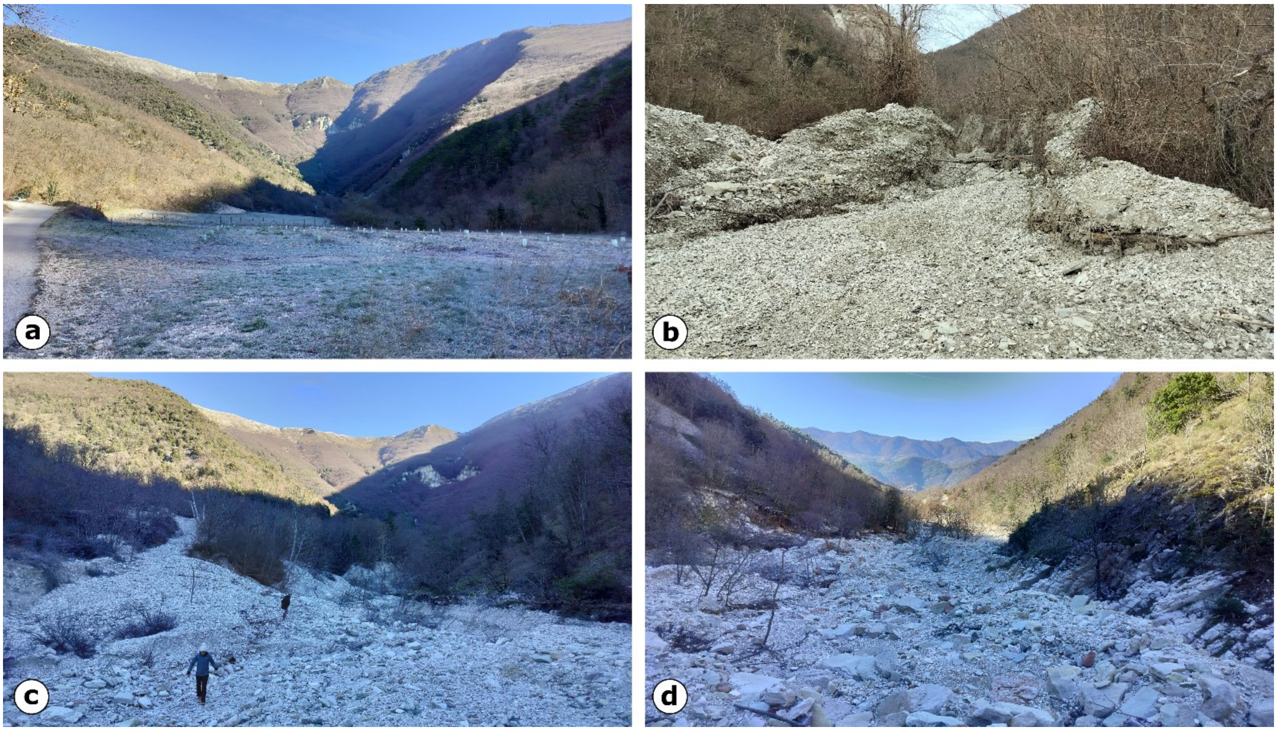

Figure 16: geomorphological criticalities detected along the Tenetra valley in the municipality of Cantiano: a) panoramic view of the valley seen from downstream; b) debris flow channel in the hydrographic right portion of Tenetra ditch; c) debris flow deposits of the channel in picture b) in the valley bottom side; d) the flat bottom of Tenetra Stream valley seen from upstream filled with debris flows sediments.

The on-field survey mapped different criticalities, also from the anthropic point of view. Along the watercourse, three hydraulic weirs were present, and they were entirely filled (fig. 17a) and damaged (fig. 17b) by the event, compromising their functionality. Some riverbank protection works were also damaged, such as the gabion wall (fig. 17c) protecting the municipal road. Another criticality was represented by the undersized bridge in the hamlet of Tenetra (fig. 17d), which was obstructed and overtopped during the flood so much that it separated the two dwellings on either side of it.

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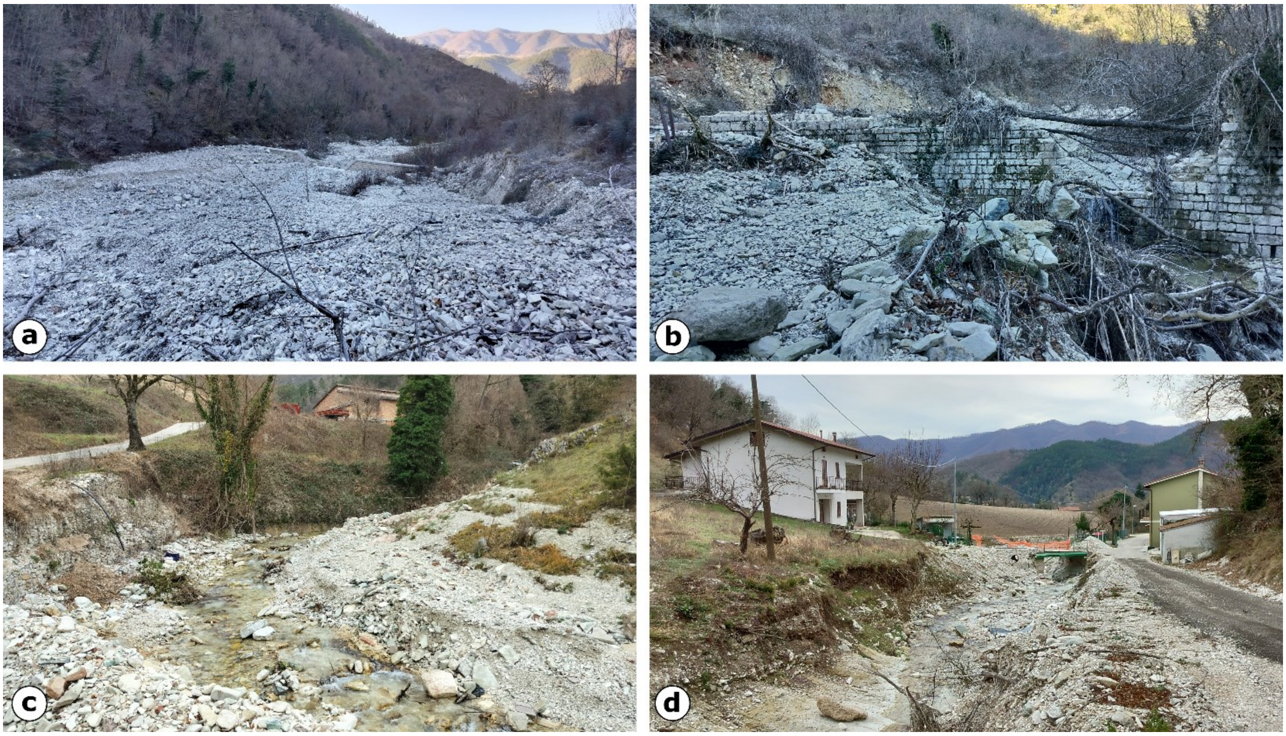

Figure 17: Critical issues represented by the anthropic structures: a) filled and buried hydraulic weir seen from upstream; b) damaged hydraulic weir; c) damaged gabion wall; d) undersized bridge in the hamlet of Tenetra.

2.3.1.3 Restoration works and mitigation of hydraulic risk

The main goal of our research group was to identify critical issues along the hydrographic basin useful to suggest remediation interventions for the reduction of hydraulic risk. This led to the production of two different cartographies: a map of critical issues detected during the on-field survey (fig. 18) and a map of the suggested interventions (fig. 19).

The area of the western offshoots of Mt. Tenetra is not too much anthropized, but the Tenetra stream represents a very important watercourse because a few hundred meters downstream it reaches the historic centre of Cantiano, adding its waters to those of the Bevano Creek, which, still in the historic centre, converges into the Burano River. This double confluence of three watercourses within the built-up area caused the sum and concentration of surface runoff, resulting in a sudden water level rise. The implementation of interventions along the Tenetra sub-basin is considered strategically important for managing water flow volumes and solid transport within Cantiano.

Therefore, starting from the upstream section, the following interventions have been identified and proposed:

- the lateral flatirons of Pontedazzo and Mt. Alto engrave the western slope of Mt. Tenetra by channelling possible debris flow events (fig. 16b, 16c), which are triggered quite frequently in this area due to the high slopes often not covered by vegetation and litho-structural conditions of the rock masses, which present discontinuities and fractures

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because highly tectonized. Containing this material along the slopes is necessary to prevent debris flow phenomena from reaching the watercourse and the anthropogenic structures downstream. For this reason, the installation of anti-debris flow barriers has been proposed to contain the material along the slopes, thus preventing the filling of the weirs with sediment (and therefore their function),

- removal of dead or eradicated vegetation present in the riverbed and the hydraulic weirs,
- restoration of weirs and removal of debris fill sediments (fig. 17a, 17b) and possible installation of a new hydraulic weir,
- restoration of the original fluvial section of Tenetra stream by removal of over-flooded sediment, capable of narrowing the flow section (fig. 16d, 20),
- reinforcement of the embankments and installation of gabions on the eroding banks (fig. 17c),
- demolition and reconstruction of the bridge by enlarging its hydraulic section (fig. 17d).

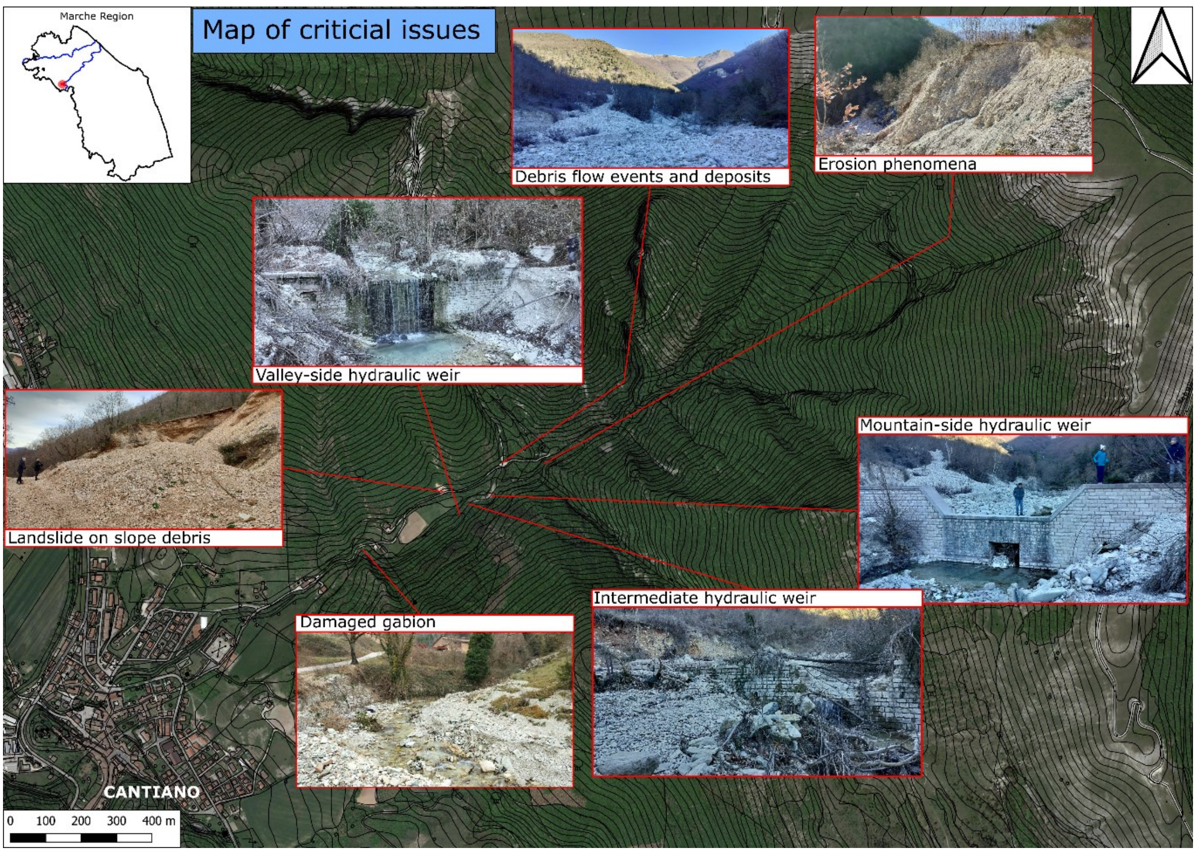

Figure 18: Map of critical issues in the Tenetra valley. The extent rectangle shows in black the boundaries of the Marche Region with Cantiano (in red) and the catchment area of the Metauro River (in blue). Cartographic layers from Regione Marche, n.d.

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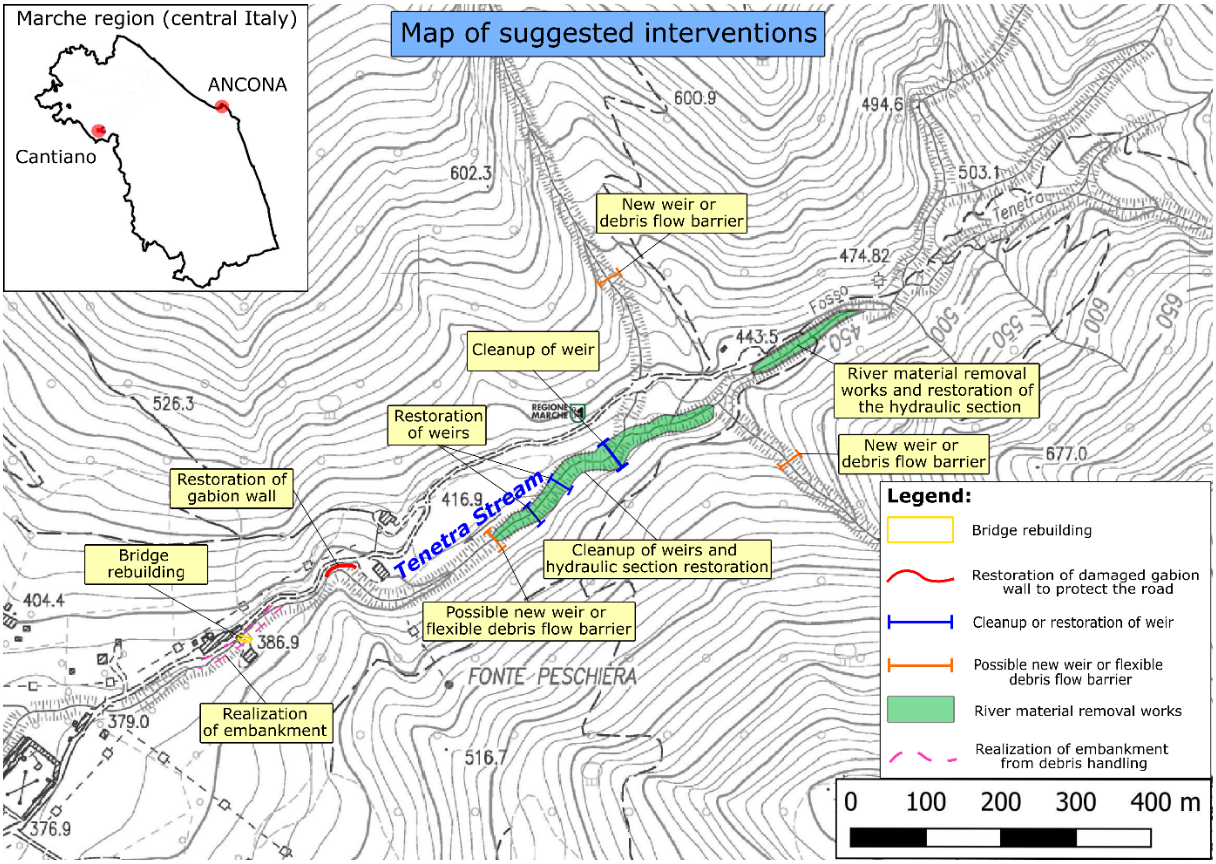

Figure 19: map of the suggested intervention in the Tenetra Valley. The extent rectangle shows in black the boundaries of the Marche Region with Cantiano (in red) and the catchment area of the Metauro River (in blue). Cartographic layers from Regione Marche, n.d.

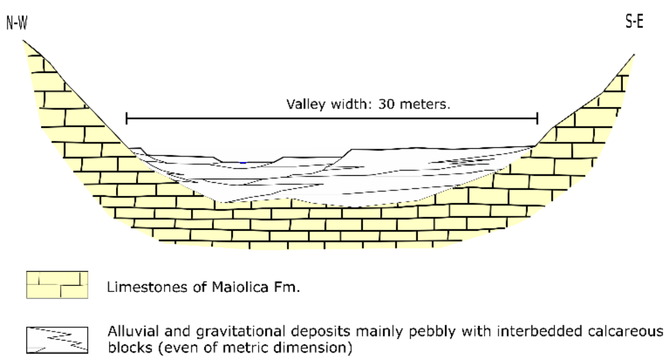

Figure 20: Representative hydraulic and stratigraphic section of the Tenetra Valley around 450 m. asl.

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2.3.2 Case study 2 (urban context): the historical centre of Cantiano (PU)

The town of Cantiano is in the north-western portion of the Marche region, along an alluvial plain situated around 360 meters of altitude in the mountain portion of the hydrographic basin of the Metauro River, an Apennine watercourse with a predominantly torrential behaviour. With a cumulative rainfall of 419 mm/m2 in just over six hours (tab. 1, 2, 3) and a maximum cumulated rainfall in 1 h (Emax1h/mm) of 101.4 mm/m2 (Donnini et al., 2023), Cantiano is the location which recorded the most abundant rainfall during the extreme weather event of September 15th, 2022. With 48 landslides on a territory of 84 square kilometres, 22 compromised artisanal activities (some with zero production capacity), 28 businesses destroyed by the flood (bars, restaurants, shops, offices, etc.), six locations of recreational/cultural associations destroyed, the town of Cantiano paid one of the highest prices of all the affected communities.

2.3.2.1 Geomorphological setting

From a hydrographic point of view, the town of Cantiano falls along a narrow alluvial valley interposed in the Miocene Umbria-Marche ridge of the northern Apennines and the town precisely falls at the confluence of three watercourses: Burano River comes from the South and in the historic city centre, it receives important water inputs from Bevano and Tenetra streams, respectively coming from SE and E (fig. 21a, 21b). These two latter watercourses show a mostly straight direction, with confluences of tributaries often orthogonal to them. These characters indicate a strong control by the litho-structural setting over the hydrographic network, able to condition its flow. The geomorphological setting conditioned the main drainage axis, which, during the extreme events object of this study, acted by summing the effects of water contributions from ditches and channels coming from the steep slopes around Cantiano. In particular, the calcareous ridge of Mt. Tenetra- Mt. Acuto- Mt. Catria shows concave forms and deposits attributable to glacial valleys (Savelli et al., 1995 and Valentini et al., 2023).
The geomorphological analysis indicates that the Tenetra ditch conveys water captured from the natural amphitheatre by directing it through a valley narrowing imposed by the conjunction of two triangular facets (so-called flatirons of Pontedazzo and Mt. Alto), resulting in an extensive alluvial fan on which, in part, the town of Cantiano has been built over time.

2.3.2.2 Critical issues detected

Cantiano and its surroundings registered many landslides during the considered event, because of the condition of lithotypes (very fractured, due to the tectonic evolution and to intense weathering at these altitudes) and because of the geomorphological-structural setting, with high reliefs, alternating with valleys. On the 15th of September 2022, the South-Western slope of Mt. Tenetra released different debris flows (fig. 16b; 16c) along the pre-existing channels, in some cases stopped along the slope, in other cases able to reach the Tenetra mainstream at the bottom of the valley. Very likely, the presence of three hydraulic

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weirs (resulting damaged and filled) placed upstream with respect to the town counteracted the erosive potential of the stream, preventing major damage to downstream structures.

During the time, in fact, anthropic efforts were applied to manage the watercourses. In Cantiano, rivers were channelled (fig. 21), diverted, or even, buried under reinforced concrete structures, mostly in the city centre. But, surely, the most sensational practice was conducted in 1928 (Morelli et al., 2023) to force Burano River to jump a meander, anticipating its curvature and diverting it below a rocky ridge with a tunnel of about 65 meters (fig. 22). In this way, the river was supposed to abandon its floodplain, allowing humans to cultivate it and, in recent decades, create a parking space above it. This practice certainly proved to be a gamble because, during the flood of September 15th, 2022, Burano River in the proximity of Fiorucci Street was able to overflow above the artificial embankments built for its channelization (fig. 10), flooding the entire floodplain, the parking, Fiorucci street and to arrive at the historic city centre inundating all Luceoli square (fig. 23) with two main events, at 7:00 pm with a water level of 0.5 meters and at 10:00 pm raising 2.35 m. (hydrometric levels recorded in front of the town hall). Effectively, the Bevano Creek originally flowed through Luceoli Square, as evidenced by the Gregorian cadastre cartography of 1835 consulted as an indispensable tool supporting the present work (fig. 24). Even the most significant contribution was provided by the Burano River, the main responsible for the flood, also for its higher flood discharge. The swollen watercourses merely occupied and reclaimed their original spaces. For this paper, a map was produced showing the anthropogenic interventions that have forced the watercourses over time (fig. 12) greatly affecting the surface hydrological regime.

The culverts were undersized, both in size and construction details, because the covers did not withstand the hydraulic pressures set below them and they literally collapsed (fig. 25a and 25b). Moreover, during the on-field surveys, other critical issues were detected: undersized bridges with a limited height between intrados and riverbed (fig. 25c), partially occluded arches of the bridges (fig. 25d), absent river maintenance with the presence of vegetation and sediment that can reduce the hydraulic section during flood events.

Figure 21: a) the Tenetra ditch channelled below a dwelling in the historical centre of Cantiano; b) the confluence between Tenetra (left) and Bevano creeks (right) in the historical centre of Cantiano with the channelled watercourses.

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Figure 22: The 65-meter tunnelling of the Burano River below the calcareous mountain ridge, with the anthropogenic embankment behind which the alluvial plain, the parking and the historical centre are recognizable.

Figure 23: The entirely flooded Luceoli Square in the historical centre of Cantiano during the afternoon of 15th September 2022. Image from https://www.vivereurbino.it/2022/09/16/alluvione-cantiano-intere-zone-isolate-impraticabili-le-statali-flaminia-e-della-contessa-scuole-chiuse/2100257772/# (accessed on 09.09.2024).

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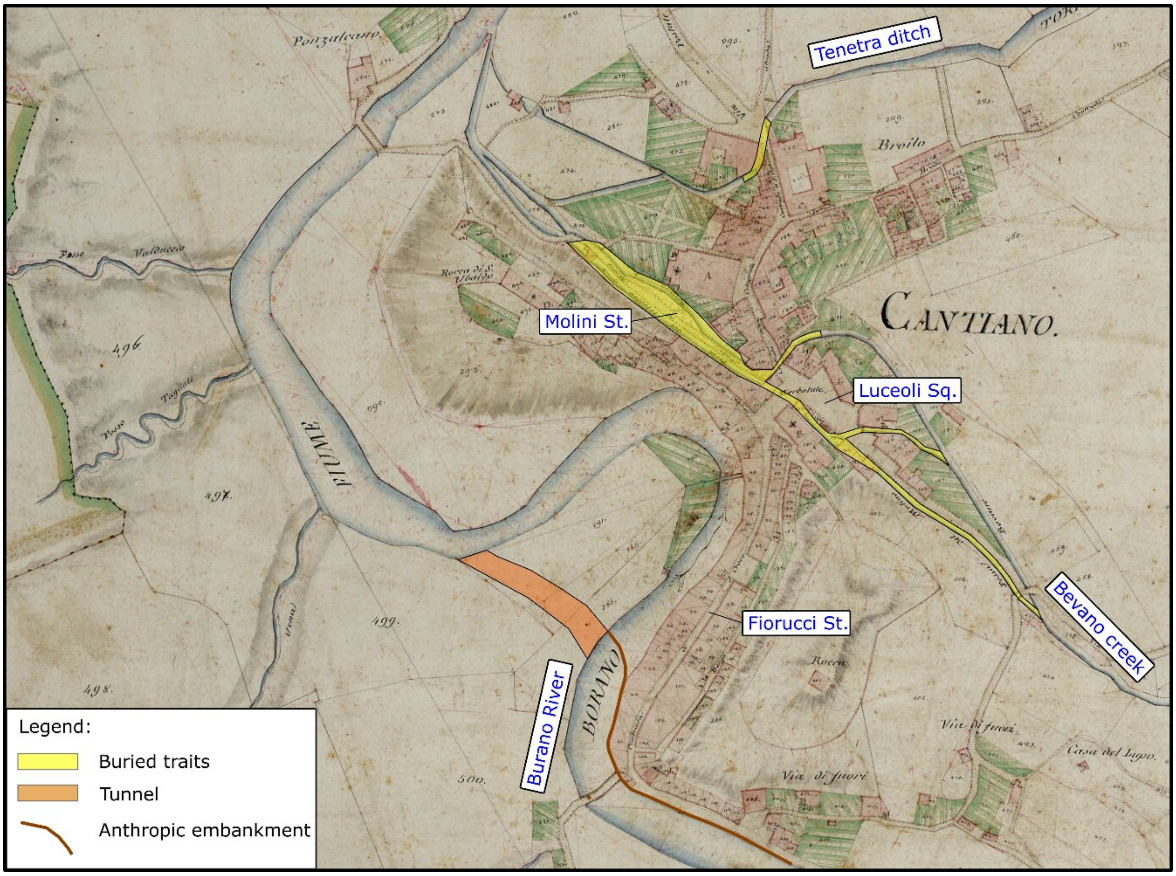

Figure 24: schematic map of the main anthropogenic surface water regulation interventions superimposed on the Gregorian cadastre (Archivio di Stato di Roma, n.d.). It is easily recognisable that the abandoned meander is destined for human use.

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Figure 25: a) collapse of the tombed sections in Tumiati Street, Tenetra Creek; b) explosion of the buried sections in Fiorucci Street, Bevano Creek (courtesy of National Fire Department); c) undersized footbridge reached by the water level, subsequently washed away, Burano River; d) narrowing of bridge arch partially occluded by sediment and anthropogenic material, Bevano Creek.

2.3.2.3 Restoration works and mitigation of hydraulic risk

The surveys focused on producing a map for each locality that indicated the critical issues and the suggested interventions for reducing hydraulic risk. Seeing the impossibility of giving back to the river its floodplain, the main interventions for the mountain environment identified a widespread need for:

- removal of dead or eradicated vegetation present in the riverbed and stacked near bridges,
- restoration of the original fluvial section by removal of over-flooded sediment, capable of narrowing the flow section,
- raise the embankment level before the tunnel,
- reinforcement of the embankments and installation of gabions on the eroding banks,
- cleaning the intubated sections with a proposal to restore the watercourse without anthropic coverings.

2.3.3 Case study 3 (mountain and urban context): Sassoferrato (AN)

Another explanatory example relating to the urban fabric response during flood events is represented by the situation of Sassoferrato (AN), located in the inner portion of the Marche region along an intra-Apennine valley, bounded by reliefs with

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elevations reaching more than 1300 m. With a cumulative rainfall of about 197 mm/m^2 fell in just over 6 hours (Regional Agro- meteorological Service of AMAP Regione Marche, 2022) Sassoferrato represents one of the locations which recorded the highest rainfall during the extreme weather event on September 15th, 2022, and its territory was widely damaged.

2.3.3.1 Geomorphological setting

The study area is contained within the catchment area of the Sanguerone Stream, and it can be distinguished into two different portions: a hilly-mountainous and an urban one. The first critical situation encountered starting from the mountainside is represented by Monterosso Stazione, a hamlet of Sassoferrato, where the Sanguerone Stream flows at around 380 meters altitude. In this portion, the watercourse flows along a syncline set at the lithostratigraphic transition between the more calcareous and calcareous-marly Scaglia Rossa and Scaglia Variegata lithotypes on which the Mt. Romano- Mt. Rotondo- Mt. Castellaro ridge is structured (with elevations between 600 and 800 m.) and the hemipelagites with more marly and marly-clay content of the Scaglia Cinerea, Bisciaro and Schlier. These sediments, characterized by a greater aptitude for degradation by erosion, border the slope on the hydrographic right of the Sanguerone, which is therefore characterized by more gentle morphologies and less steep slopes. The stream in this mountainous section presents a rather regular course, partly because it flows embedded within the geological formations it crosses.

The valley is quite wide, with an amplitude of even hundreds of meters, mainly thanks to its sharing with other streams coming from the hydrographic right (Piantonate ditch and, in the south, two other unnamed ditches), one of which in this stretch flows parallel to it. All the above come from the eastern slopes of Mount Strega, and the two unnamed ditches flow into the Sanguerone near the automobile repairs workshop at Piano di Monterosso Stazione, factors that undoubtedly acted to concentrate runoff in this area. On the hydrographic left, the Sanguerone Stream receives tribute from other ditches orthogonal to it (Pontiglio ditch and two unnamed ditches) located along the steep southwest flank of Mount Castellaro. In this portion, there was a round-arched bridge since Roman times (fig. 26a, b, c), over time hidden by vegetation so that it was no longer visible and whose presence became unknown even to residents.

2.3.3.2 Critical issues detected

The examples of Monterosso Stazione and Sassoferrato represent a key point to observe and understand the hydraulic behaviour and influence of some structures during a flood. During the flood, the Roman bridge was filled with tree trunks, branches, bushes and other material until its obstruction. It acted as a dam, limiting almost to the point of inhibiting the outflow of the watercourse and thus allowing the setting of a lake upstream of the barrage. As hydraulic pressure increased, the abutments of the Roman bridge (never maintained or restored over time) did not hold the hydrodynamic forces and collapsed (fig. 26c), causing the “dam break effect” and triggering the downstream release of the entire volume of stored water: a flash flood event that saw a wall of water invade the hamlet.

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After the flooding, the watercourses released their solid transport in the portions where hydraulic affinity allowed this. The riverbed of the unnamed ditch coming from the south behind the automobile repairs workshop was filled with gravel and raised about two meters (testimony from residents) compared to the pre-event situation (fig. 26d). This resulted in repeated new flooding of the forecourt of the building at each new rainfall event. This represented an important critical issue which required the emergency restoration of the original section of the watercourse.

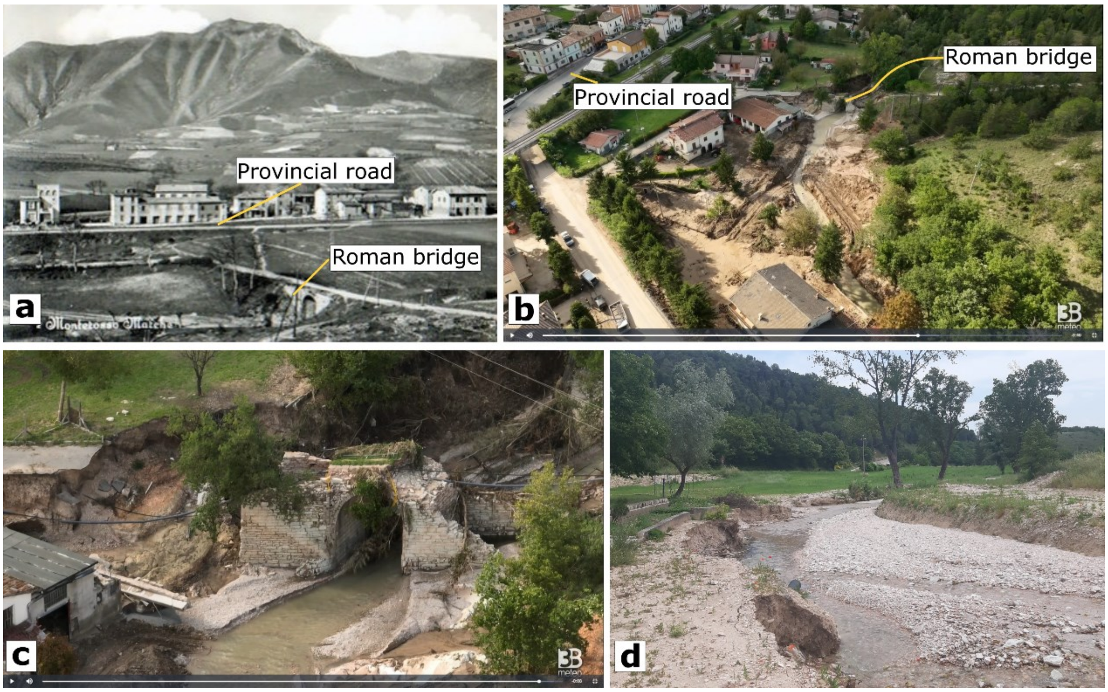

Figure 26: a) the Roman bridge at Monterosso Stazione above the Sanguerone Creek in a historical photo, with the eastern foothills of Mt. Strega in the background (scanning from a postcard, then modified); b) the post-event situation for comparisons with image a (also related to urbanisation). Note that in the past, the alluvial valley was not urbanised; c) the Roman bridge after the event viewed from downstream, with the collapsed abutments; d) the unnamed ditch in Sassoferrato Stazione after the flood, with the waterbed filled with gravel and raised about two meters compared to the pre-event situation. Images b and c come from https://www.3bmeteo.com/giornale-meteo/cronaca-meteo-alluvione-marche---monterosso-stazione-dal-drone--ponti-crollati-e-gravi-danni---video-643860 (accessed on 10.18.2024).

About seven kilometres downstream, the Sanguerone Stream reaches the town of Sassoferrato, where it flows between 280 and 290 meters above sea level with an approximately N-S direction (fig. 27). The watercourse flows through the lithostratigraphic transition between the eastern more calcareous and marly-calcareous lithotypes on which the historic centre of Sassoferrato was built, and the western hemipelagites with a more marly and marly-clay content. These sediments, characterized by a greater aptitude for degradation by erosion, border the slope on the hydrographic right of the Sanguerone, which is therefore distinguished by gentler morphologies and less steep slopes.

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The Sanguerone Valley, upstream of the confluence with the Sentino Creek, presents a rather curvilinear course, with a variable width of about 30- 50 linear meters. This amplitude is drastically reduced when the watercourse meets the Garibaldi Street Bridge.

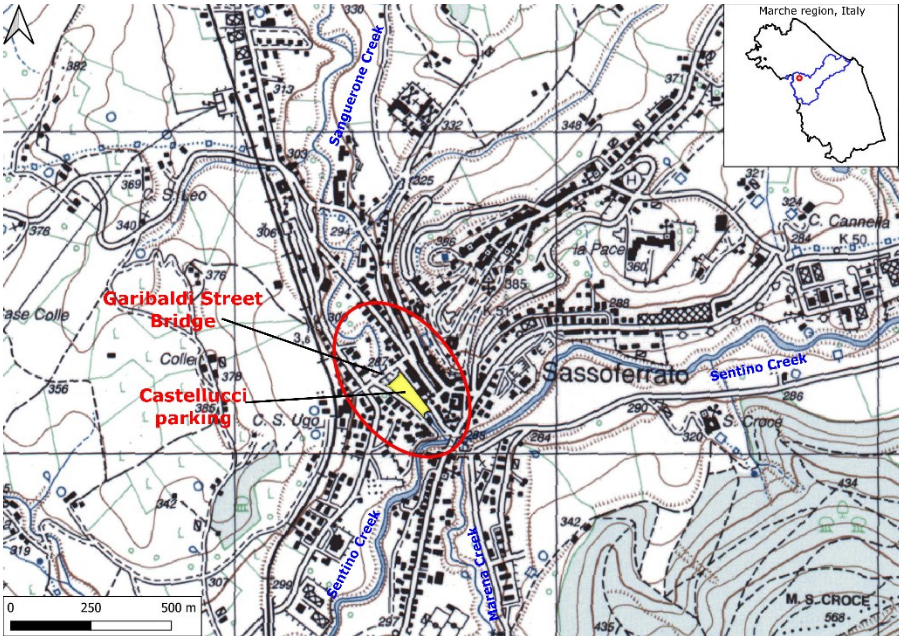

Figure 27: Topographic map of the Military Geographical Institute- IGM of Sassoferrato (AN) with the buried stretch of Sanguerone Creek below the Castellucci parking highlighted in yellow. In the extent rectangle, the Marche region (black border), the hydrographic basin of the Esino River in blue and the town of Sassoferrato in red. Cartographic layers from Regione Marche, n.d.

The mountain stretch of Sanguerone Streams is characterised by a progressively urbanised floodplain over time, with the presence of structures and infrastructure (Fig. 28) close to the riverbed. In many cases, the watercourse was so obliterated by vegetation and sediment that the Roman bridge was no longer visible, often unknown to the most recent generations (Fig. 26b).

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Figure 28: The railway upstream of Monterosso Stazione, completely damaged by the flood (images from https://www.ilfattoquotidiano.it/2022/09/16/alluvione-nelle-marche-il-drone-sorvola-la-ferrovia-a-monterosso-stazione-binari-sommersi-e-massicciata-erosa/6806043/ (accessed on 12.11.2024).

Starting from the bridge on Garibaldi Street, the entire riverbed of Sanguerone Stream was tunnelled with a three-segmented concrete box structure of about 200 meters in length, which reduces the original section of the ancient bridge built by the Italian Army General Staff (fig. 29). The watercourse returns to the open space only one hundred meters before its confluence into the Sentino Creek. The buried section was then covered with backfill material, above which the Castellucci parking was realised. The channelisation intervention, observed from upstream, shows how the original wide arches of Garibaldi Street Bridge were reduced to a box-like structure that greatly reduced the hydraulic section, making it undoubtedly undersized for the flow rates recorded during the September 15th, 2022, hydraulic event.

Figure 29: The Garibaldi Street Bridge saw from upstream with the evident, extreme reduction of the original flow section with a box-like structure (the markers on the wall on the left mark the hydrometric levels reached).

The flood eradicated and dragged trees and sediment along its course, which, once they met the narrowing imposed by the channelisation, obstructed the section, creating a lake in its upstream portion (markers on the wall in the left mark the hydrometric levels reached). Overpressures developed inside the buried section, the roof of which fortunately held up without being damaged. These overpressures, however, were released as they exited the channelized section, creating extensive erosions to structures located adjacent to it (fig. 30).

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Figure 30: The area exiting the tombed section of Sanguerone Stream under the Castellucci parking a) before, b) during and c) after the event.

In Monterosso Stazione and Sassoferrato, it is evident how inadequate man-made structures, together with neglect of maintenance along the river network, contributed to amplifying the destructive effects of the flood.

2.3.3.3 Restoration works and mitigation of hydraulic risk

The surveys focused on producing a map for each locality with indicated the encountered critical issues and the suggested interventions for the reduction of hydraulic risk. Seeing the impossibility of giving back to the river its floodplain, the main interventions for Monterosso Stazione identified a widespread need for:

- restructuring of the bridge,
- removal of dead or eradicated vegetation present in the riverbed and stacked near bridges,
- restoration of the original fluvial section by removal of over-flooded sediment, capable of narrowing the flow section,
- reinforcement of the embankments and installation of gabions on the eroding banks.

The most suitable solution would be the complete removal of the current roof on which the car park is located. Seen the impossibility of giving back to the river its floodplain, the main interventions for Sassoferrato are:

- it would also be advisable to build a new box structure for the Garibaldi Street Bridge, with a single span and with a considerably wider span than the previous one. Seeing the impossibility of doing this, an inspection of the box structure to assess its vulnerability has been suggested,
- removal of dead or eradicated vegetation present in the riverbed and stacked near bridges,
- restoration of the original fluvial section by removal of over-flooded sediment, capable of narrowing the flow section,
- reinforcement of the embankments and installation of gabions on the eroding banks,
- given the impossibility of relocating the affected buildings and structures, it is suggested to verify their stability.

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2.3.4 Case study 4 (foothill context): the western suburbs of Senigallia (AN)

One of the most damaged areas is located around the confluence between the Nevola and Misa Rivers, where the entire floodplain was flooded and where, unfortunately, almost all the fatalities were recorded. The catchment area of the Misa River covers a surface of 384 km^2, ranging from a minimum height close to sea level to a maximum height of 750 m. asl in the Apennine zone (Corti et al., 2024). The floodplain is consistently and abundantly more than one kilometre wide in the downstream portion near the abovementioned confluence. The territory is extensively urbanised, with large portions of the hamlets of Pianello and Casine (municipality of Ostra), Brugnetto (Trecastelli and Senigallia) and Bettolelle (Senigallia) falling within the flood plain and that was, therefore, completely inundated (fig. 31a).

The storm discharged most of the rain in the Apennine portion of the Marche region. Rainfall levels decrease from west to east, from upstream to downstream. The towns of Ostra and Senigallia, although they represent some of the most damaged locations, recorded a negligible rainfall of about 15-20 mm/m^2 for the 15th of September 2022 (Tab. 1 and 3). This, undoubtedly, contributed not to alarming the citizens too much. In many cases, unfortunately, they were caught by surprise by the flood wave as they were moving their cars out of their underground garages after they had heard on the news and social media about the flooding in the upstream areas.

2.3.4.1 Geomorphological setting

The area is close to the Adriatic coastline and, from a topographic point of view, is almost exclusively flat, as it is the floodable area of the Nevola and Misa Rivers. During the time many anthropic modifications to the hydrographic network have been made to manage the watercourse and allocate as much land as possible for agricultural, industrial, or urban development purposes.

The comparison between the flooded areas and the cartography of hydraulic risk of PAI (31b) confirms the reliability of the urban planning instrument, with the boundaries following those of the effectively flooded area (except for a small area in the hamlet of Cannella).

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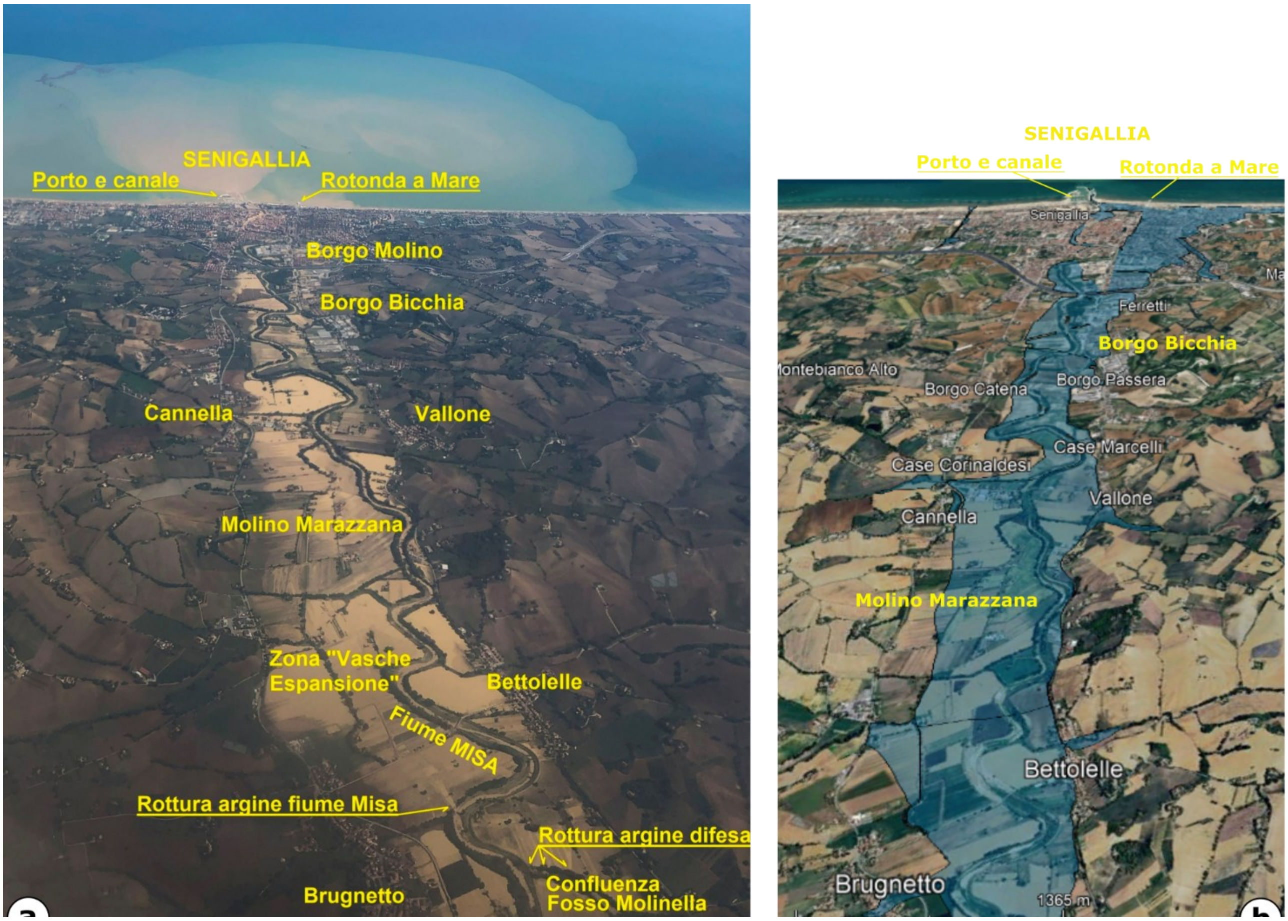

Figure 31: a) The flooded plain of the Misa River seen from an aircraft flying from Ancona to the United Kingdom on 16th September 2022 at 11.08 a.m. Italian time, with the well-recognisable flooded area, the main localities in yellow and the plume of sediments seaward. Image from https://www.senigallianotizie.it/1327562338/dalla-foto-ad-alta-definizione-si-individuano-punti-di-fuoriuscita-e-rottura-argini-del-misa (accessed on 12.11.2024); b) The map of forecast flood areas according to the PAI of Marche Region (updated to 2016) superimposed in @Google Earth, with the flooded area in light blue and the main localities for comparison with fig. 31 a).

2.3.4.2 Geomorphological setting

The case study of Senigallia represents a very didactic example of studying anthropogenic modifications of the territory. Looking at the comparison between the ancient cartography of the Geographical Institute "De Agostini Novara" of 1889 and the aerial image of 2023 (Fig. 32), it appears evident how the Misa River, at that time, had two channels, both flowing into the Adriatic Sea. Within them, the ancient castle of the town was built, defended with imposing walls to protect against sieges and floods.

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Figure 32: The comparison between the Misa River highlighted in blue near Senigallia. An ancient map of 1889 (Santoni G., & Morici R., 2021) on the left and a @Google Maps image of 2023 on the right, with the preexisting "Penna channel" dashed in yellow, subsequently occluded.

In the past, floods came very frequently in Senigallia. For this reason, over the years, the farmers built the embankments along the Misa River to protect field crops and livestock. At the same time, the municipal administrations built the "cavo Penna", an artificial channel which flowed below the actual IV November Street and reached the sea, where today there is the famous roundabout. Penna channel (fig. 33) was a sort of drainage ditch to protect the town from floods. Around 1920, after completing all the earthen embankments in the countryside and building the masonry embankments in the city, they decided to bar and fill the channel and urbanise the area above it abundantly.

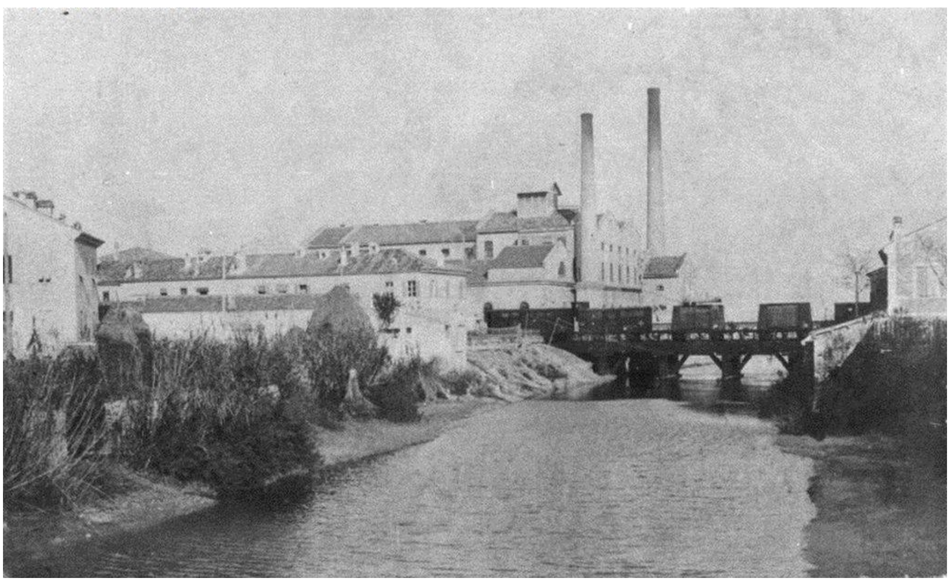

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Figure 33: The ancient Penna channel in a picture of the early 1900s with the sugar refinery, actual hotel Palace, at about 200 metres from the coastline. Image from https://archive.org/details/canale-della-penna-senigallia (accessed on 12.16.2024).

In 1889, the boundaries of Senigallia were represented by the historical medieval walls, whereas nowadays, the town's surface is about ten times greater. The intense, subsequent land consumption in the last century acted in sealing the soil and, together with a disproportionate population growth, contributed to an increase in the hydraulic risk of the area.

The spatiotemporal analysis conducted through the comparison of historical cartographies highlighted a widespread discrepancy between actual and ancient maps (Fig. 34). The Gregorian cadastre of 1835 shows the area at the confluence between the Nevola and Misa rivers, coming from the West and South, and shows significant modifications made to the hydrographic network during that time.

Figure 34: The ancient map of the Gregorian cadastre (Archivio di Stato di Roma, n.d.) with the superimposed actual watercourses of the Nevola and Misa rivers (light blue lines). The modifications of the hydrographic network are well recognisable.

Nowadays, this final portion of the Misa River appears completely channelled between artificial earthen embankments. On-field surveys and mapping also regarded these structures and identified their main criticalities.

Lidar images acquired through drone and on-field surveys highlighted the presence of large amounts of sediment (river point bars composed of cross-bedded sands) distributed and deposited along the riverbed, especially in the inner portions of the river bends (Fig. 35). River point bars develop where stream flow is locally reduced because of friction and reduced water depth. During a flood, this material may represent an obstacle to the runoff by reducing the hydraulic section or partially obstructing bridge arches.

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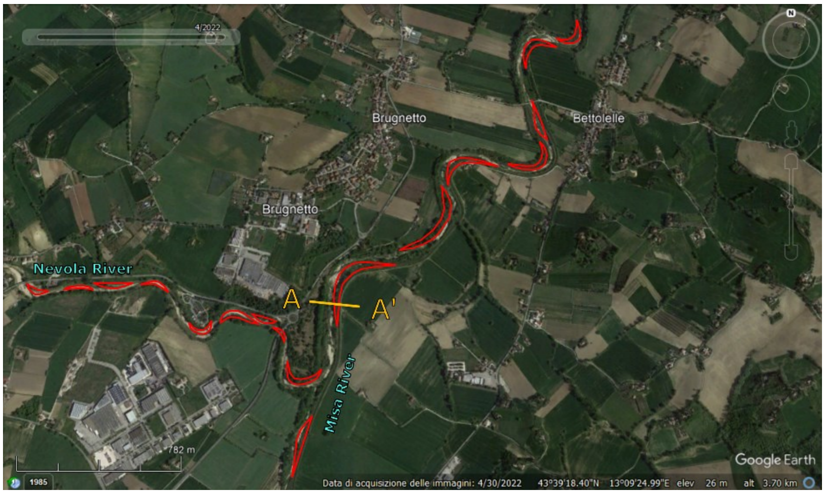

Figure 35: The presence of river point bars (contoured in red) along the Misa River around Bettolelle (Senigallia, AN) with the location of a hypothetical hydraulic section (A-A') in orange superimposed to @Google Earth. In the centre of the image is well recognisable an anthropogenic abandoned meander (oxbow).

Embankments of the Misa River were built with sand, silt and clay derived from the river itself. Before the flood event of September 2022, they were grassed and wooded, with a widespread presence of trees in the riverbed.

The main criticalities of the hydraulic section of the valley portion of the Misa River can be detected by observing the lidar acquisition. The topographic profile (Fig. 36) highlighted the asymmetry of the two embankments, with differences in height and thickness. In addition to this, the hydraulic section appears partially occluded from the river point bar on the hydraulic right.

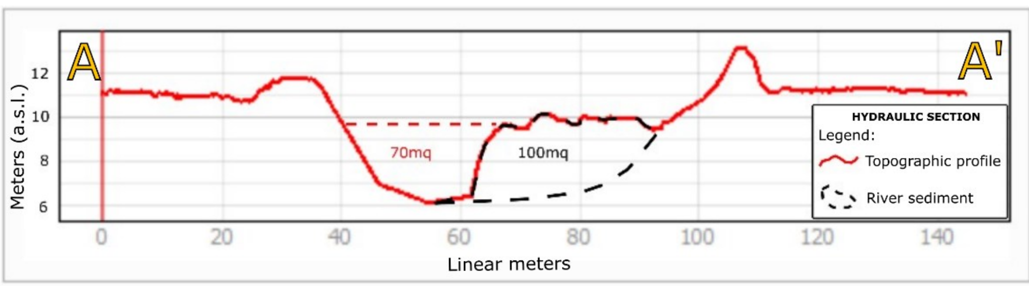

Figure 36: The topographic profile of a representative stretch of the Misa River in Bettolelle (Senigallia) acquired through lidar survey.

Furthermore, the on-field geomorphological-hydraulic survey identified the presence of widespread burrows of fossorial animals (Fig. 37), sometimes passing from one side to the other. During a flood, this can represent an important situation of weakness of the embankment and can therefore cause its erosion, piping and collapse. In addition to the embankment overflowing, this was one of the causes of the flooding of the Senigallia and Ostra area.

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Figure 37: The burrow of fossorial animals along the right embankment of Misa River in the hamlet of Borgo Catena (Senigallia), with A4 block notes for scale.

Within the historic centre of Senigallia, the Misa River is channelled through masonry embankments (Fig. 38a). The greatest criticalities are due to the large urbanization of this area, the ancient Penna channel that was eliminated and the presence of three bridges (Portone Bridge, Garibaldi Bridge and 2 June Bridge) that resulted undersized during the flood of 15 September 2022 that they were obstructed to the point of being obstructed by vegetation and causing the Misa to overflow from their sides (Fig. 38b, c). The Garibaldi Bridge was damaged, and it has been demolished. It will be rebuilt with a wider height.

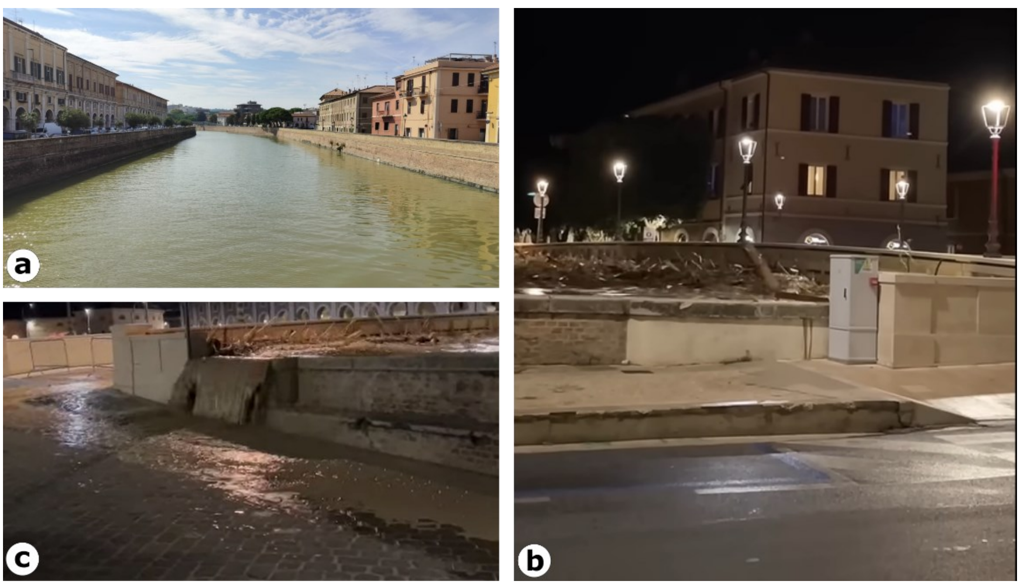

Figure 38: Three situations close to the 2 June bridge: a) the masonry embankments of Misa River in Senigallia seen from the 2 June bridge after heavy rain; b) the 2 June bridge with the intrados occluded by vegetation carried by the river a few moments (11:30 p.m. of 15 September 2022, Italian time) before the flood (youtube page of Storm Chasers Marche); c) the precise moment (00:05

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a.m. of 16 September 2022, Italian time) of the beginning of the Misa flood in the centre of Senigallia (youtube page of Vivere Senigallia). Note the methodology of prohibiting access to the bridge and the non-perforated edge protection of the bridge.

2.3.4.3 Restoration works and mitigation of hydraulic risk

The foothill environment showed a fluvial setting and dynamics that were totally different from the mountain ones. Watercourses present a lower slope and a wider riverbed (although today it is bordered by man-made embankments).

In the impossibility of giving the river all its space back to allow its dynamics, our research group suggested to the Marche regional administrators a series of interventions, variously distributed throughout the watercourse. Given the critical issues listed above, as also specified in Article 6, paragraph 1, letter b) of the Italian normative "Norme Tecniche di Attuazione del Piano di stralcio di bacino per l'assetto idrogeologico" it is necessary, especially in correspondence of meanders, to implement a management strategy aimed at safeguarding the natural hydraulic dynamics, with particular reference to flooding and morphological evolution of the riverbeds and to encourage the maintenance or restoration of the natural features of the hydrographic network.

To avoid the accumulation of vegetation eradicated from the riverbed in the narrowings, it was proposed to act along the hydrographic network by removing dead vegetation present along the river that could create a potential obstacle to runoff (fig. 39a). Action was also taken by removing the material deposited in the river bars to widen the hydraulic section (fig. 39b).

Another of the most important actions is the embankment restoration and reinforcement. The burrows of fossorial fauna (fig. 37) must be filled in, the embankments consolidated and reinforced, and the height of the hydrographic left and right embankments levelled.

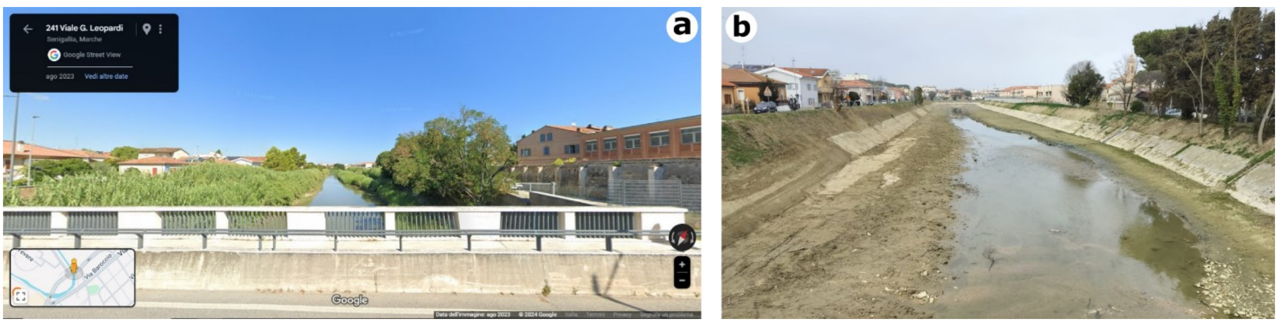

Figure 39: Two images of the same stretch of Misa River caught from Portone Bridge along Leopardi Street: a) in August 2023 (Google Earth image); b) in February 2024, after the works of the hydraulic section widening with the removal of sediments and vegetation.

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Figure 40: The works for the removal of river point bar sediments along the Misa River in Senigallia were executed in 2023. Image from https://www.adriaeco.eu/2023/10/13/alluvione-2022-sopralluogo-a-senigallia-per-la-verifica-dello-stato-dei-lavori-sul-misa/ (accessed on 12.16.2024).

The results of the hydrologic-hydraulic modelling showed that the city of Senigallia presents important criticalities represented by the bridges in the historical centre. During a flood, they can be obstructed by sediments and vegetation, permitting the water to flood laterally. The maximum flood discharge calculated from the document "Assetto di progetto media e bassa valle del fiume Misa" in the hydraulic section of the Misa River mouth has been calculated with Giandotti's method and a return time of 200 years in 607.24 m^3/s. This plan was adopted by the "Autorità di Bacino" of the Marche Region by resolution no. 67 of 25.3.2016 and it "represents the tool for defining the lines of intervention aimed at mitigating hydraulic risk at basin and sub-basin scale, structural interventions aimed at reducing the hazard and consequently the risk, to safeguard and secure human settlements from future and hypothetical flood events".

3 Materials and Methods

This event caused a widespread geomorphological evolution which brought deep scars on the land after the storm: the triggering of landslide phenomena, the migration of river point bars, valleys filled with sediments, bank erosions, broken structures and flood deposits distributed over large areas.

This event highlighted how the hydraulic response of the territory was mainly conditioned by the combination of different factors but first, by the wide and thoughtless anthropization represented by the presence of structures and infrastructures, which contributed to amplifying the damage following the floods.

The meteorological event caused widespread variations in the river regime, with a modification of the solid transport mainly consisting of fine-grained material, predominantly sands (50%) and silty clays (50%), with coarse-grained sediments only in the mountain environment close to the carbonate ridges of the Apennines.

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The study evidenced that the hydraulic behaviour and response strictly depend on the environmental setting, with different dynamics and critical issues: in the mountain territory, as well as having observed a high number of landslides, the higher slope of the watercourse and the narrower riverbed can trigger many erosive phenomena along the rivers. In the foothill contexts, rivers are channelled in earthen embankments and, in the event of their overtopping or collapse, they can flood the entire wide floodplain, also for about a kilometre after the confluence between the Nevola and Misa Rivers.

Excellent results were obtained by implementing the on-field surveys with the new tools and technologies available (GIS software, drones, satellites) that provided a more extensive overview, improving the level of knowledge on the territory and the detail and quality of the final work. Among other things, this work led to the creation of a GIS database containing all useful spatial information for territorial management.

Thanks to hydrological-hydraulic modelling, it is now possible to know detailed flow rates and hydrometric levels in each section of the investigated catchment areas (aimed at dimensioning the reconstruction of bridges and other risk reduction interventions).

The final aim of this study was the production of analysis and synthesis cartographies. The first one permitted condensing all the observations and led to the production of a series of critical issues maps (fig. 18), reporting all geomorphological-hydraulic variations and the structural damages observed. The latter represents the most important product of our research group because it led to the drafting of a series of maps of proposed interventions in each section of the watercourses affected by the event (fig. 19). This resulted in a series of about thirty technical and economic feasibility projects to the regional administration in which interventions were proposed to restore the functionality of structures and infrastructures, plan for future reconstruction in the affected areas, mitigate the future hydraulic risk and trigger the reconstruction phase.

It appears clear that these cannot represent an immediate and definitive solution to the problem, which would require relocations with large economic resources and the predisposition of retention basins distributed along the watercourse. However, it can represent a starting point towards future hydraulic risk mitigation in vulnerated areas.

4 Discussion and conclusions

The analysis of the rainfall distribution shows that most of the rain fell in the inland mountainous area and almost nothing in the foothills of the Apennines and the coast (a cumulative rainfall of 15.6 mm/m2, recorded in Senigallia, is equivalent to saying that it rained almost nothing). Therefore, in the latter areas, as there has been no heavy rainfall, people have underestimated the event and continued stationing near waterways or occupying ground floors or underground rooms. These unfortunate circumstances, together with a not-yet-present early warning system to signal the sudden migration of the flood from upstream to downstream, can be identified among the major responsible of the increase in risk. For this reason, it is at least necessary to undertake initiatives to communicate to citizens (public engagement) how hydraulic risk is managed and what correct behaviour they must adopt during an emergency.

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In addition, some of the most significant hydrometers were washed away by the flood (tab. 2), not allowing them to be monitored and recorded in real-time during the flooding event. This presupposes the need to re-arrange a meteo-pluvio-hydrometric network and also provide for its upgrading, especially in these catchment areas that are frequently subject to this type of event.

Station	**River basin**	**Data interruption (Italian time)**	**Causes**
Pontedazzo	Burano	From 7:57 pm to 11:15 pm	GPRS cell transmission problems
Pergola	Cesano	From 8:20 pm	Sensor plate damaged by a falling branch
Serra de' Conti	Misa	From 8:26 pm	The sensor cable on the bridge sheared by the flood
Pianello di Ostra	Misa	From 8:32 pm	The flood deflected the station pole against the road parapet
Corinaldo	Nevola	From 8:55 pm	The flood washed away the station
Passo Ripe	Nevola	From 9:25 pm to 10:42 pm	Interference caused by river flooding
S. Vittore	Sentino	From 10:31 pm	The flood took away the station

Table 4: hydrometers washed away by the flood (Civil Protection of the Marche region, 2022).

In addition to highlighting an extremely large amount of rainfall, results showed a widespread presence of criticalities along the watercourses, such as:

- an extremely anthropized territory and sealed soil,
- the frequent behaviours aimed at making changes to the hydrographic networks (fig. 24, 32, 34),
- the progressive abandonment of mountain and agricultural land that has affected the territory with a lack of slope and river network management practices,
- long-standing neglect of maintenance of riverbeds, banks and embankments,
- the presence of under-dimensioned structures crossing the watercourses,
- absence of retention basins along the watercourses,
- hydrometric instrumentation detached by the flood (Civil Protection of the Marche region, 2022),
- the lack of an early-warning system that could provide immediate communication to prevent hazardous situations,
- poor knowledge of the correct behaviour to undertake during an emergency on the part of citizens.

Only by trying to improve each of these aspects can the problem of hydraulic risk be solved. Meanwhile, the only solution is to relocate structures and infrastructures falling in flood areas.

Some authors believe that from in situ surveys, historical research and morphological and cartographic studies it is possible to deduce that the consequences recorded in the historical centre of Cantiano are not only attributable to the exceptional nature

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of the rainfall event but also to the response of the hydraulic network, especially in the plain area where anthropic pressure almost definitively cancels out any natural character and functional specificity (Morelli et al., 2023).

The proposed interventions will certainly help in mitigating the effects of a new flood, but the results of the hydrological-hydraulic modelling showed that hydraulic restorations along watercourses would not be sufficient to prevent future flooding. They can be an excellent solution to solve local problems, by reinforcing embankments, protecting banks and securing structures and infrastructure, but they can't be decisive in containing floods. Therefore, in addition to what was proposed, it is necessary to create areas for the natural expansion of watercourses, allowing them to dissipate their energy in urbanised areas and restore their naturalness.

It is obvious that to do this, in many cases, it will be necessary to intervene through expropriations, which may sometimes include the loss of crops or the inability to use the real estate above the affected land parcels.

The research object of this work certainly highlighted the exceptional nature of the event in terms of intensity and, therefore, the need to consider climate change and integrate it into hydraulic studies and flood risk management maps. These studies may be considered very useful at the basin scale and PAI maps of flood areas could be updated, both derived from direct post-event observation and numerical modelling.

Future research may focus on extending this type of multidisciplinary approach to other catchment areas (not considered in this paper) with similar settings and characteristics under the geological, geomorphological, hydraulic, hydrologic and urbanistic points of view, by extending them not only to vulnerated watercourses but also looking to reduce the risk in watercourses in which the same criticalities are found.

Analysing the areas affected by the recent (September 2024) flooding events in Tuscany and Emilia-Romagna Regions in Italy, we noticed that some of the river basins affected are the same ones that were affected last September (i.e. Lamone, Reno, etc.). A similar situation was observed in Senigallia (AN) during the surveys carried out for this study. After the September 2022 floods in the Marche region, there were several instances of hydrometric thresholds being exceeded in the following months. At least one instance in December 2022 and one in May 2023 are remembered.

This was immediately linked to a statement made in March 2023 by farmers in the Mulino Marazzana area of Senigallia during the on-field surveys. Several months after the main event, residents reported a groundwater level of 1.5 metres below ground level, compared to the usual constant level of 4.5 metres recorded in "peacetime". Our consideration may seem obvious, but the fact that the piezometric level of the sub-riverbed aquifer has risen may promote new flooding (the capacity to store excess water underground would be greatly inhibited by the availability of space in the unsaturated zone). Although we are aware that, during storms, most of the water runs off the surface (runoff) without penetrating too deeply, we believe it is appropriate to mention this consideration.

Author Contributions

Conceptualisation: F.B., P.F.; Methodology: F.B., P.F.; Writing: F.B.- original draft preparation: F.B.; Writing - review and editing: P.F., M.B., M.M.; Funding acquisition: P.F.; Supervision: P.F., M.B., M.M. Material preparation and data collection were performed by F.B., M.B. and M.M. performed drone surveys and hydrologic-hydraulic modelling. All authors read and approved the final manuscript.

Financial support

There is an agreement (STI532001- Accordo Regione Marche "Studi bacino fiume Misa-Nevola"- Farabollini) between the Geology Division of the University of Camerino and the Commissarial structure of the Marche Region for the drafting of technical-economic feasibility projects for risk mitigation in vulnerable areas. Author P.F. has received research support from the Marche Region.

Competing Interests

Authors are required to disclose financial or non-financial interests that are directly or indirectly related to the work submitted for publication. Interests within the last 3 years of beginning the work (conducting the research and preparing the work for submission) should be reported. Interests outside the 3-year time frame must be disclosed if they could reasonably be perceived as influencing the submitted work.

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