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ANALYSIS AND MODELLING OF THE SEPTEMBER 2022 FLOODING EVENT IN THE MISA BASIN

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EXTENDED ABSTRACT

Le catastrofi naturali rappresentano un problema critico per la società umana in termini di perdite umane ed economiche, aggravato dal cambiamento climatico. L'Italia, attraversata dalle catene montuose delle Alpi e degli Appennini, è uno dei Paesi europei più esposti alla cosiddetta pericolosità idro-geomorfologica, ovvero quella relativa a frane e alluvioni, come evidenziato dai numerosi episodi dannosi registrati ogni anno. Tra i più recenti, quello avvenuto presso la città di Senigallia e nei bacini idrografici dei fiumi Misa, Cesano e Metauro (Regione Marche) nel settembre 2022 riveste particolare interesse scientifico.

Nella notte tra il 15 e il 16 settembre, una quantità di precipitazioni senza precedenti ha causato piene eccezionali, con conseguenti esondazioni nella piana alluvionale, provocando 13 vittime, 50 feriti, 150 evacuati e danni stimati per 2 miliardi di euro. Il picco di precipitazioni massimo, pari a 400 mm/giorno, è stato registrato presso l'abitato di Cantiano (PU) e supera le curve di possibilità pluviometrica valutate in passato per l'area. Allo stesso tempo, un'erosione diffusa su tutti questi bacini, specialmente lungo le sponde dei torrenti, insieme alle numerose frane pluvio-indotte nel territorio montuoso hanno contribuito a generare ingenti volumi di sedimenti, alberi divelti e detriti. Questo materiale, trasportato a valle dal reticolo idrografico, è risultato determinante nella provocazione dei danni. Questo evento eccezionale è risultato essere legato allo sviluppo di una tempesta tropicale (temporale autorigenerante di tipo *V-shaped*) nel mare Adriatico, un fenomeno raro a queste latitudini e perciò interpretato come direttamente causato dal cambiamento climatico.

Questo lavoro intende sottolineare la rilevanza della modellazione idrologica nella gestione del rischio a scala di bacino, considerando scenari estremi già verificatisi, in un'ottica di prevenzione in vista delle variazioni attese nel regime delle precipitazioni dovute al cambiamento climatico. Il presente studio propone un'analisi dell'evento eccezionale del 2022 e delle sue implicazioni dal punto di vista idrologico per il bacino idrografico del fiume Misa, ovvero quello dove sono stati registrati i maggiori danni. Considerato che questa stessa area era stata già più volte colpita in passato da esondazioni, il caso del 2022 è stato confrontato con il precedente del 2014, al fine di valutare i picchi di portata, i processi di erosione e di trasporto dei sedimenti per diversi scenari. Si è scelto quindi di analizzare come termine di paragone anche l'anno 2017, per l'assenza di eventi critici. Le analisi sono state condotte a partire dai dati disponibili e sono state supportate dalla modellazione idrologica a scala di bacino, tramite i modelli fisicamente basati SWAT e SMART-SED. SWAT, strumento open-source ampiamente impiegato in letteratura, fornisce risultati sui processi attivi nel canale, mentre SMART-SED, sviluppato recentemente dal Politecnico di Milano, offre risultati sull'intero bacino idrografico. Date le dimensioni estese del bacino in oggetto di studio (~ 380 km^2), si è scelto di utilizzare SWAT per le simulazioni annuali e SMART SED per le analisi di dettaglio sull'evento del 2022. L'integrazione di queste due scale di analisi, unite ai sopralluoghi sul campo, ha permesso una migliore comprensione dell'evoluzione dei processi superficiali durante gli eventi.

Si è osservato che la principale differenza tra le precipitazioni nei tre anni analizzati sia la loro distribuzione nel corso dell'anno. Nel 2022 infatti risultano essere concentrate principalmente nel mese di settembre, mentre nel 2017 e nel 2014 sono più uniformi. Anche dal punto di vista spaziale e della durata, i due eventi risultano essere diversi: nel caso dell'alluvione del 2014, ha piovuto in maniera uniforme sull'intero bacino per un giorno, mentre nel 2022 l'evento è durato solamente dodici ore ed è stato circoscritto alla zona montuosa. Queste diverse caratteristiche degli eventi alluvionali hanno una ripercussione sui processi erosivi, che è stata confermata dalla modellazione numerica. Infatti, anche se non è stata possibile una valutazione quantitativa accurata del trasporto solido del fiume Misa a causa della mancanza di dati sui volumi di sedimenti accumulati nel tempo, le simulazioni hanno dato un'idea qualitativa degli effetti dei diversi scenari di pioggia sull'erosione nel bacino. Sebbene le precipitazioni totali dell'anno 2014 siano maggiori, la concentrazione del 20% circa delle piogge annuali in sei ore avvenuta nel 2022 ha portato ad avere un volume simulato di sedimenti finale più alto. In particolare, questo evento avrebbe prodotto il 40% dei sedimenti annuali. Questo suggerisce che gli eventi di precipitazione intensa e concentrata comportano un rischio maggiore di erosione e trasporto solido rispetto a eventi più distribuiti, come evidenziato anche dalla letteratura sui cambiamenti climatici.

L'utilizzo di modelli fisicamente basati a scala di bacino consente quindi di valutare il rischio in funzione di diversi scenari, con un possibile supporto per la gestione del territorio e delle emergenze in Italia, soprattutto alla luce degli scenari futuri legati al cambiamento climatico.

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ABSTRACT

Natural hazard is recognized to be a threat to human society that is becoming more critical under the perspective of climate change. Italy is one of the most exposed European countries to hydro-geomorphological hazard, as proven by the annual casualties and economic losses. Among the most recent events, the one happened in the Misa river catchment in 2022 is of particular interest for the great amount of rainfall poured in just one night, which led to extensive erosion. The mountainous part of the catchment was hit by several landslides, and the resulting sediments and debris, transported downstream by rivers, increased the amount of damages. This event was interpreted as directly caused by climate change, as it was linked to a tropical storm not common at this latitude. This work proposes an analysis of this exceptional event from a hydrological point of view. The 2022 event was compared with other relevant events from the past, in order to evaluate the peak discharge, the sediment erosion and transport processes in the area for different scenarios. The analysis included the modelling at catchment scale with two physically-based models: SWAT, which provides results on channel processes, and SMART-SED, working at the catchment scale. The two scales of analysis, together with field surveys, gave a better understanding of the evolution of the shallow processes during the events. Finally, this work intends to highlight the relevance of hydrological modelling for the management of hazard in different scenarios at catchment scale.

***Keywords**: Misa river, geohazard, sediment transport, climate change, hydrological modelling.*

INTRODUCTION

As reported by national and global natural disaster databases, numerous damaging events linked to flood and landslides occur in Italy every year, certifying the fact that the country is one of the most exposed in Europe to hydro-geomorphological hazards (Salvati *et alii*, 2010; Jaedicke *et alii*, 2014). Considering that the main triggering factor of these phenomena is rainfall and that the rainfall regime is changing under climate change (Kundzewicz *et alii*, 2014; Li & Fang, 2016), the study of these natural processes is becoming more and more relevant (Corti *et alii*, 2022; Fusco *et alii*, 2022; Panzeri *et alii*, 2022). Among the most recent catastrophic events, the one that occurred in the Marche Region (Central Italy) in September 2022 is of particular scientific interest. During the night between the 15th and 16th of September, an exceptional amount of precipitation generated widespread floods and landslides in the river basins of Misa, Burano, Cesano, and Metauro. The rainfall event, which was classified as a "V-shaped" thunderstorm (Castorina *et alii*, 2023; Donnini *et alii*, 2023), hit an area of ~ 5,000 km^2, including the mountainous, hilly and coastal areas of the region. The peak of rainfall intensity of 419 mm in 9 hours was measured in the Cantiano Municipality, in the Burano basin. The rainfall records do not show any significant events in the 30 days before the 15th of September, suggesting dry soil conditions before the thunderstorm (Santangelo *et alii*, 2023). As a consequence, 13 fatalities, 50 injuries and 150 evacuations were registered, and remarkable damages to properties and infrastructure, estimated at around 2 billion euros, were recorded in the entire area (Polaris, 2023). In addition, the mountainous parts of these basins experienced numerous landslides induced by rain (Donnini *et alii*, 2023; Santangelo *et alii*, 2023), while intense erosion characterized the entire area, particularly along riverbanks. The high volumes of sediments, uprooted trees and debris, transported downstream by the hydrographic network, contributed to the extensive damages.

This study proposes an analysis of this exceptional event and its hydrological consequences for the Misa river basin, where the most significant impacts were recorded. As this area had previously been affected by floods, the 2022 event was compared with the previous one, which occurred in 2014. Additionally, a year without exceptional events, 2017, was also inspected to assess peak flows, erosion processes, and sediment transport in the area for various scenarios.

CASE STUDY: THE MISA 2022 FLOOD

The study area is located in the Marche Region (Italy, Fig. 1), where a V-shaped thunderstorm in September 2022 resulted in several floods and damages associated with sediment transport in the basins of the Misa, Esino, Cesano, and Metauro rivers (Donnini *et alii*, 2023). The rainfall event mainly affected two river basins: the Burano basin, where the highest rainfall intensity was recorded in Cantiano, and the Misa basin (Fig. 1). From a geological point of view, the two basins have different characteristics. The Burano basin is mainly characterized by permeable calcareous rocks (especially Scaglia Rossa, Scaglia Bianca, Maiolica and Corniola formations) that allowed the water to infiltrate the rocky formations during the event. Diversely, the Misa basin is mostly characterized by the less permeable arenaceous and clayey rocks of the Argille Azzurre formation (Fig. 2). Due to this, although the precipitations were more severe in the Burano basin, the most extensive floodings occurred in the Misa basin. For this reason, the Misa basin was selected to be studied in this research. The Misa river originates from the southwestern slopes of the mountains in the area of the municipality of Genga (AN) and flows for about 50 km before reaching the Adriatic Sea in the city of Senigallia (AN). The catchment area covers an area 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. Before the 2022 event, the Misa basin had been already affected by similar catastrophic floodings. The most recent one was the 2014 flooding, where three people died and damages of 180 million were recorded. Other similar

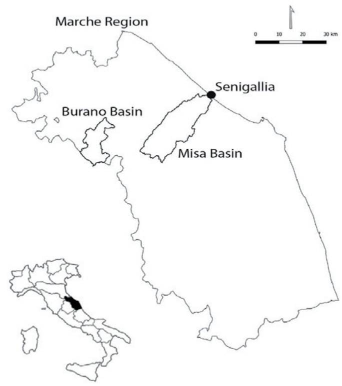

Fig. 1 - Location of the Burano and Misa basin in the Marche Region (Italy)

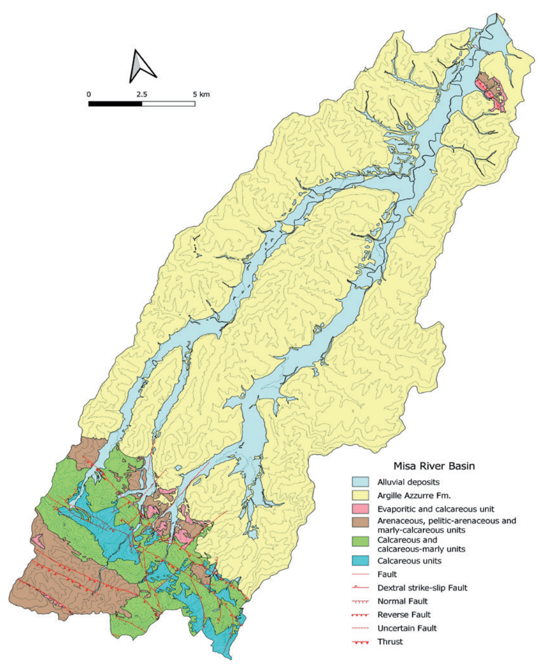

Fig. 2 - Geological setting of the Misa basin

events testifying to the hazardousness and vulnerability of the area were documented in August 1976, October and September 1955, October and September 1949, November 1940 and May 1939. Between the 15th and 16th of September 2022, the Marche Region experienced an exceptionally intense rainfall event. In just a few hours, over 400 millimetres of rain poured down in the upper parts of these watersheds, causing widespread geo-hydrological instabilities such as shallow landslides, debris flows and extensive erosion (Polaris, 2022; Donnini *et alii*, 2023; Polaris, 2023). This extreme event was triggered by two atmospheric components: the volume of water vapour flux, which is essential to generate precipitation, and an atmospheric force capable of initiating cloud formation. Fig. 3.a illustrates the water vapour flow (IWV, Integrated Water Vapour) that Central Italy experienced on Thursday, the 15th. The long band runs from the western Mediterranean to the Caspian Sea and the red colour is an indication of an extreme condition (IWV 600-700 kg/m/s), leading to an exceptional transport of vapour for the formation of rainfall, as confirmed for other extreme events (Abbate *et alii*, 2020; Abbate *et alii*, 2021; Abbate *et alii*, 2022).

The flow was oriented from southwest to northeast and showed an acceleration near the region affected by the flood event on the afternoon of Thursday 15th September. This abrupt increase in the flux speed has activated the lifting of hot and humid air in the lower troposphere, determining its condensation into clouds and rain. The satellite image in Fig. 3.b shows the development of a "V-shape" type convective regenerating thunderstorm (McCann, 1983) on the eastern flank of the Apennines, between the Marche and Umbria regions (Protezione Civile, 2022).

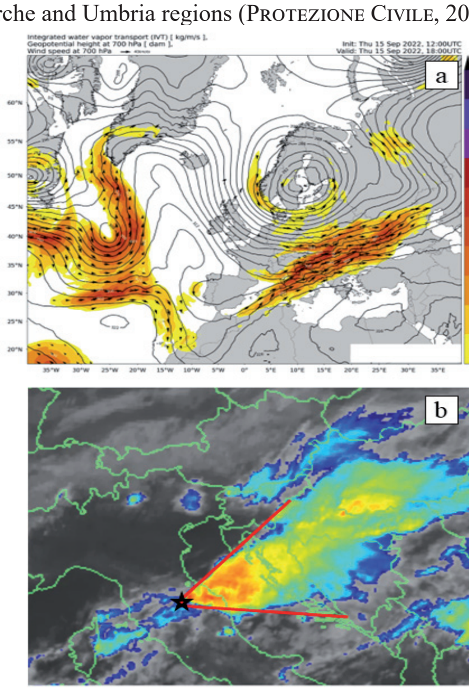

Fig. 3 - a) Integrated Water Vapour (IWV) recorded on 15th September 2022 across Europe (credits: Papavasileiou, 2022; data sources: NCEP Global Forecast System, GFS, North American Mesoscale Forecast System, NAM, Global Ensemble Forecast System, GEFS – v12, European Centre ECMWF); b) Infrared satellite image of the V-shaped thunderstorm occurred over Marche Region (modified after Protezione Civile, 2022)

On the vertex of the "V"-shaped supercell, located near the Cantiano station (highlighted by a red star in Fig. 3.b and shown in the map in Fig. 4), the most intense and violent precipitations were recorded: 384 mm of rain poured in less than six hours. Here, the quasi-stationary storms persisted for more than 4-5 hours at very high intensities (Idrologia Polito, 2022; Polaris, 2022).

Duration	1 h	3 h	6 h	12 h	24 h
Maximum registered height (mm)	101	257	384	419	419
Average intensity in the time interval (mm/h)	101	85.5	64.0	34.9	17.5

Tab. 1 - Precipitation data observed at Cantiano (PU) station on the 15-16th of September 2022 (source: Idrologia Polito, 2022)

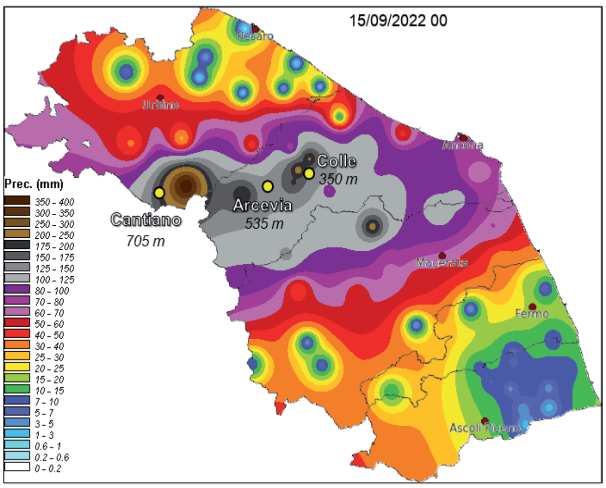

Fig. 4 - Total rainfalls recorded over the Marche Region on the 15th September 2022. The highest intensities were in the mountainous area of the Misa and Burano basins. Rain gauges locations are shown with their altitude in meters above sea level (from Tognetti, 2022)

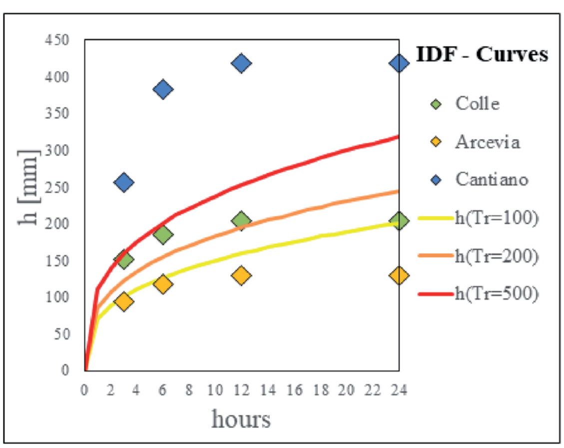

Fig. 5 - IDF (Intensity-Duration-Frequency) Curves calculated for the Marche area compared to Colle, Arcevia and Cantiano station rainfall values during the event. As can be appreciated, the Cantiano station showed extreme rainfall amounts with respect to the others (modified after Mattavelli, 2023)

The magnitude of this event significantly surpassed the literature Intensity-Duration-Frequency curves (Fig. 5), categorizing it as an "outlier event," likely triggered by the ongoing climate change across the Mediterranean climate "hot spot".

The rainfall event lasted approximately twelve hours. The maximum values measured at different time intervals confirm the persistence of strong intensities for an extended period, as indicated in Table 1. Rainfall stations near the study area recorded average values exceeding 100 mm, with peaks registered in the municipality of Cantiano (PU) reaching 419 mm in a single day (Idrologia Polito, 2022), as in Fig. 4.

MATERIAL AND METHODS

The analyses were conducted considering rainfall and hydrometric available data, and they were supported by hydrological modelling, employing two physically based models at the catchment scale: SWAT and SMART-SED. The SWAT (Soil and Water Assessment Tool) model was developed by the USDA (Douglas-Mankin *et alii*, 2010; Neitsch *et alii*, 2011) and it is currently widely used in literature. It analyses spatially distributed data on topography, soils, land cover, land management, and weather to predict water, sediment, nutrients, pesticide, and bacteria yields. Results are provided at the subbasin scale (runoff and erosion processes, soil water movement, evapotranspiration, crop growth and yield, soil nutrient and carbon cycling, pesticide and bacteria degradation and transport) and at the channel scale (flows, settles and entrains sediment, and degrades nutrients, pesticides, and bacteria during transport) on a daily interval for every sub-watershed outlet (Douglas-Mankin *et alii*, 2010). On the other hand, SMART-SED (Sustainable MAnagement of sediment transpoRT in responSE to climate change conDitions), developed by Politecnico di Milano (Brambilla *et alii*, 2020; Gatti *et alii*, 2023), yields catchment-wide outcomes of hydrological processes on an adaptive time step. In particular, the main advantages of this new tool are the automatic identification of the drainage network, the statistical downscaling of the soil input maps (Gatti *et alii*, 2020), the few and commonly open input data required and the automatic handling of a wide range of transients. This model proved its reliability after its application case studies with different geological settings (Corti *et alii*, 2023). Given the wide extension of the study area (approximately 384 km^2), the simulations were organised as follows. First, SMART-SED was implied for a detailed analysis of the 2022 event, covering the period from September 13th to 17th, to assess the model's ability to predict the flooding development based on topographic and rainfall data. Next, annual simulations for the years 2014, 2017 and 2022 were conducted using the SWAT model. This decision was made due to the higher temporal resolution of SMART-SED, which provides outputs at desired time intervals, compared to SWAT, which provides only daily, monthly and yearly results. The entire years of 2022, 2017, and 2014 were considered in order to investigate whether different rainfall distributions could have influenced sediment erosion and damage to riverbanks and infrastructures during the critical events. As mentioned, 2014 was marked by a flooding event, while 2017 was selected as an example of a year without flooding. These two scales of analysis, combined with field surveys, improved the understanding of surface process evolution during the events.

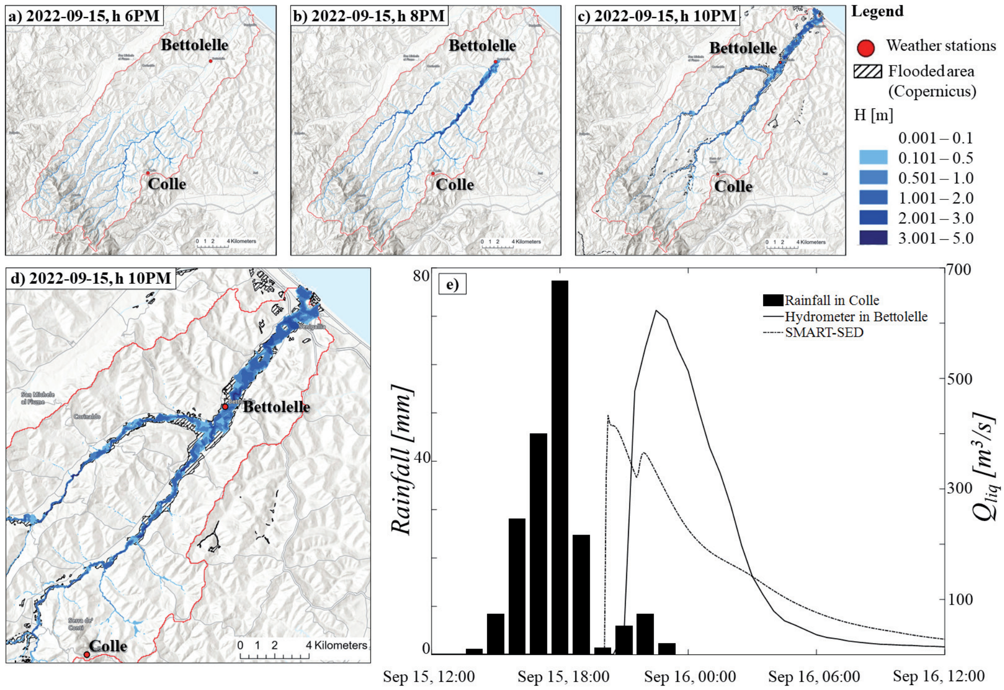

Fig. 6 - SMART-SED simulation of the September 2022 event results. Panels (a), (b) and (c) show the spreading of the simulated flood wave over time in the Misa catchment. Also, flooded areas identified by Copernicus EMS mapping service (Copernicus Emergency Management Service) are reported in panel (c) and (d) for comparison. Panel (d) provides a zoom of the flooded areas. Finally, panel (e) shows rainfall recorded at Colle weather station, the measured discharge in Bettolelle (solid line) and the simulated discharge (dotted line) in Bettolelle by SMART-SED.

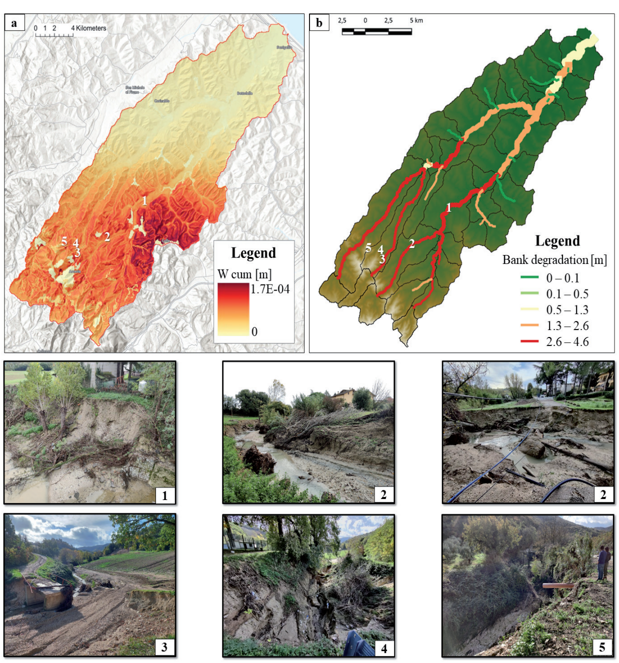

Fig. 7 - Simulated erosion compared to field evidences. (a) SMART-SED cumulative erosion post-event in meters per pixel, corresponding to a total eroded sediment volume of 1.7 x 104 m³ in the catchment; (b) SWAT bank degradation. The numbers are referred to field survey locations visible on maps. The height of the trees (~ 2 m) provides scale

RESULTS AND DISCUSSION

This section proposes an analysis of rainfall that influenced the Misa river discharge and the sediment volumes generated for the three analysed years and for the September 2022 event. As for the SMART-SED simulation results, illustrated in Fig. 6 and Fig. 7.a, a satisfactory evaluation of the water discharge was achieved. The Nash-Sutcliffe Efficiency index (Nse, Nash & Sutcliffe, 1970) was computed to quantify the quality of the discharge prediction. This index is calculated as one minus the ratio of the error variance of the modelled time-series divided by the variance of the observed time-series, and the closer it is to one, the better the prediction. An NSE index value of 0.53 was obtained for this simulation, indicating a satisfactory level of discharge prediction. As presented in panels a, b and c of Fig. 6, the flood wave originated from the mountains in the southwest of the basin, where the most intense rainfall was recorded. A comparison between simulated and mapped flooding by Copernicus is proposed in panels c and d, showing an excellent overlap (65%). The graph in Fig. 6.e displays the time lag between the rainfall peak recorded in Colle and the discharge peak measured by the hydrometer downstream, near the Bettolelle bridge. The simulated discharge closely reflects this time lag, which is related to the concentration time (Kirpich, 1940; Viparelli, 1961), estimated around 8 hours for the whole catchment area and around 4 hours for the distance between Colle and Bettolelle.

The simulated erosion after the event was notably higher in the mountainous area and near Colle (Fig. 7), as indicated by both SMART-SED and SWAT simulations. However, due to the absence of data on sediment volumes over time in the Misa river, the calibration of the model's empirical parameters was not feasible. Field surveys corroborated these findings, highlighting significant erosion along the riverbanks (Fig. 7).

As depicted in panels a, b and c in Fig. 8, rainfall distribution varied spatially and temporally in the years 2014, 2017 and 2022. Cumulative total rainfall amounts were similar across the four weather stations considered in 2014 and 2017. On the contrary, 2022 exhibited a 30% difference between the lowest and the highest recorded rainfall per station (Bettolelle and Colle stations locations shown in Fig. 6). Additionally, if the red dashed line is taken as a reference threshold for a generally intense rainfall event, it becomes evident that rainfall was evenly distributed over time in 2014 and 2017, whereas it was concentrated during the September event in 2022 (Fig. 8). Moreover, the rainfall peaks in 2014 are lower, with 7 events exceeding 30 mm/day and a maximum of 100 mm/day recorded by a weather station during the main event. In contrast, the peaks in 2022 peaks were higher, with 7 events in the mountainous area and 3 events in the coastal area exceeding 40 mm/day and a maximum of 200 mm/day recorded by a station during the main event. Additionally, the main event in 2014 lasted two days, while in 2022, it lasted less than twelve hours.

Therefore, although the total rainfall amount in 2014 was higher than in 2022, the intensity of the event and, in particular, the concentration of the 20% of annual rainfall in less than twelve hours may have contributed to the greater extent of damages incurred (180 million euros vs. 2 billion euros).

This assumption can be confirmed by the hydrological simulations of generated sediments, visible in panels d, e, and f of Fig. 8. Even though the physically-based models could not be calibrated as mentioned, and a precise quantitative evaluation of the sediment transport was not possible, simulations provided a qualitative framework of the effects of different rainfall scenarios on erosion in the basin. First of all, as a consequence of rainfall distribution, 2022 was the year with the highest simulated sediment volume. Specifically, the event of September 2022 would have produced 40% of the annual sediment load in this scenario. As for the rainfall analyses, distributions of sediment amounts and final values are similar for 2014 and 2017. Thus, intense and concentrated precipitation events pose a greater risk of erosion and sediment transport compared to more distributed events, as highlighted in the literature on climate change (*e.g.* Li & Fang, 2016). These observations suggest that the 2014 event, while critical, was not as exceptional as the one in 2022, particularly when compared to a year without flooding. The 2022 flooding can be directly linked to climate change, evidenced by the tropicalisation of rainfall patterns and the type of thunderstorm, classified as V-shaped.

CONCLUSIONS

In summary, this paper analysed the extreme flooding event that occurred in September 2022 in the Marche Region, which is of particular scientific interest for its direct link to climate change. A tropical V-shaped thunderstorm originating in the Adriatic Sea hit the region during the night between the 15th and the 16th. Although the highest rainfall intensity was measured in the Burano basin, the highest discharges and damages were recorded in the Misa basin, as a consequence of the local geological setting. To understand the influence of different rainfall distributions on erosional processes and damage to riverbanks and infrastructures, this study simulated the 2022 event along with three annual scenarios (2014, 2017, 2022) using physically-based erosion models. It was observed that, even if the total rainfall amount in 2014 exceeded that of 2022, its distribution throughout the year led to a lower amount of generated sediments and a less disruptive critical event in May. Conversely, rainfalls in 2022 were concentrated at the end of the year, following a dry spring and summer, and the extreme event lasted only twelve hours but with twice the amount of precipitation compared to the 2014 flooding. This is reflected in the sediment production, which was simulated to be 40% of the total annual sediment load for this single event, resulting in significantly more damages in 2022 compared to 2014. The concentration of rainfall in 2022 is typical of tropical climates, where rainy seasons alternate with periods of warm and stable weather. This trend is expected to increase in future. The comparison with field data demonstrated the reliability of the models in simulating real events. SMART-SED, recently developed by Politecnico di Milano, provided precise maps and plots of the flood wave, while SWAT allowed for considerations over a long time scale on a wide catchment (~380 km^2). These characteristics are fundamental for future applications in land management and the development of new emergency plans, particularly considering future climate change scenarios.

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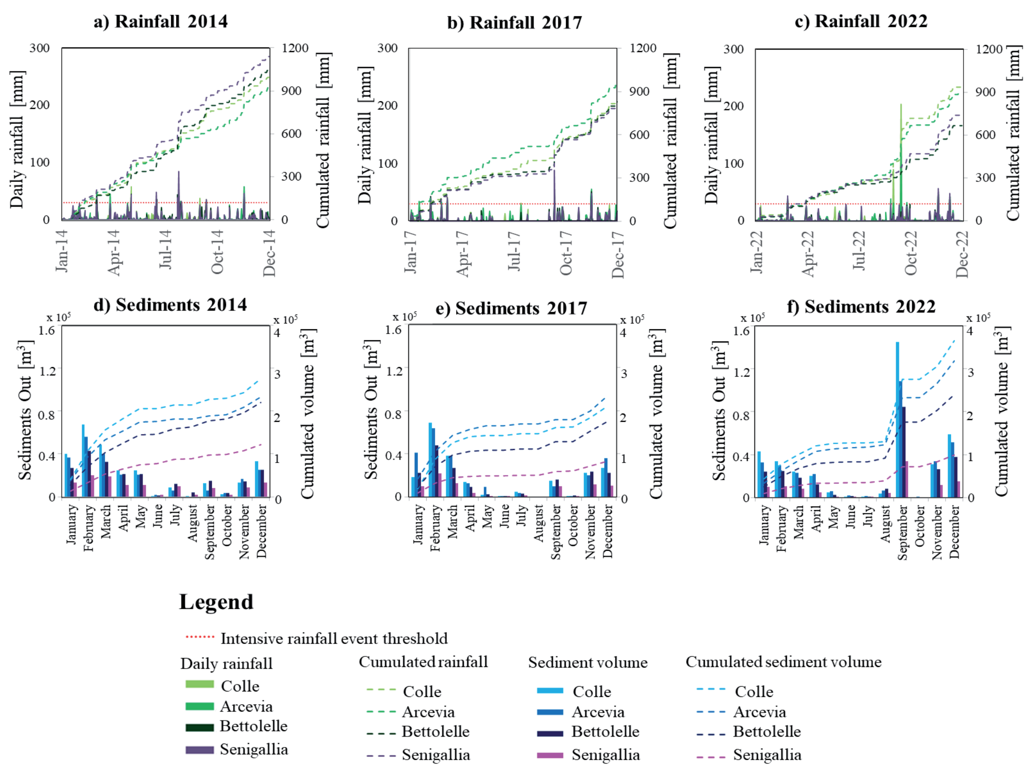

Fig. 8 - Daily and cumulated rainfalls in panels (a), (b) and (c) for the three analysed years. The red dashed line represents an indicative threshold for a general intense rainfall event. In panels (d), (e), (f), monthly and cumulated sediment volumes resulting from the SWAT simulations at the outlet of the subbasins for the same scenarios are shown. "Sediments Out" is the name of the SWAT output that describes the volume of sediments leaving the channel (Swat Soil & Water Assessment Tool). Final amounts of sediments are unfortunately not accurate due to the lack of data required for model calibration

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