A millennium-long climate history of erosive storms across the Tiber River Basin, Italy, from 725 to 2019 CE

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Rainfall erosivity drives damaging hydrological events with significant environmental and socio-economic impacts. This study presents the world’s hitherto longest time-series of annual rainfall erosivity (725–2019 CE), one from the Tiber River Basin (TRB), a fluvial valley in central Italy in which the city of Rome is located. A historical perspective of erosive floods in the TRB is provided employing a rainfall erosivity model based on documentary data, calibrated against a sample (1923–1964) of actual measurement data. Estimates show a notable rainfall erosivity, and increasing variability, during the Little Ice Age (here, ~ 1250–1849), especially after c. 1495. During the sixteenth century, erosive forcing peaked at > 3500 MJ mm h⁻¹ yr⁻¹ in 1590, with values > 2500 MJ mm h⁻¹ yr⁻¹ in 1519 and 1566. Rainfall erosivity continued into the Current Warm Period (since ~ 1850), reaching a maximum of ~ 3000 MJ mm h⁻¹ yr⁻¹ in the 1940s. More recently, erosive forcing has attenuated, though remains critically high (e.g., 2087 and 2008 MJ mm h⁻¹ yr⁻¹ in 1992 and 2005, respectively). Comparison of the results with sediment production (1934–1973) confirms the model’s ability to predict geomorphological effects in the TRB, and reflects the role of North Atlantic circulation dynamics in central Italian river basins.

Alterations of the hydrological cycle are likely to aggravate both storm-erosivity, and other extreme rainfall-related hazards, in regions that are already particularly vulnerable to soil erosion, such as the Mediterranean countries¹. Storms drive rainfall erosivity, overland flow (or runoff) and, in turn, erosional soil degradation, which have become one of the most prevalent major environmental issues, resulting in economic losses around the globe²–⁵. Understanding the dynamics of these damaging hydrological events, and their impacts on the landscape poses huge challenges, especially in Mediterranean environments⁶, where local-scale effects between storms and orography contrasts are evident⁷. An example of this is the river Tiber, in central Italy, at time of Roman civilization, as the naturalist Pliny the Elder (23/24 BCE–79 CE) recalls in his words (Italian translation by Castiglione, 1599, p. 50)⁸:

Nasce il Tevere […] nell’Appennino in una montagna detta boggi la Faltona, sul Casentino, corre più di 150 miglia, riceve da quarantadue fiumi, e torrenti. Onde non è maraviglia, se quando piove dirottamente nelle montagne, da tante bade ne venghì a Roma inodazione.

The Tiber has its source in the Apennines in a mountain called boggi la Faltona, on the Casentino, runs more than 150 miles, receives from forty-two rivers and streams. So it is no wonder that when it rains heavily in the mountains from so many streams it floods Rome.

Thus, the flooding of the river Tiber was a phenomenon that the inhabitants of Rome were used to, and had to cope with, since ancient times. In particular, the flooding of the city of Rome, due to deluges (that is, floods caused by a huge amount of rainfall in a short time) and erosive storms, has been a recurring phenomenon since the times of ancient Rome, as recalled by historians Titus Livy (64/59 BCE–12/17 CE), Gaius Cornelius Tacitus

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(c. 56–c. 120 CE) and other writers of the Imperial Era (from 27 BCE to the fall of the Western Roman Empire in 476 CE). According to the legend about the foundation of the city of Rome, it was the river Tiber, perhaps in flood in the eighth century BCE, that dragged the basket of the legendary twin brothers Romulus and Remus, whose story tells the events that led to the founding of the city of Rome (traditionally indicated as 21 April 753 BCE) and the Roman Kingdom by Romulus (753–716 BCE). Already the Roman poet of the Augustan Era Publio Virgilio Marone (70–19 BCE), in the *Aeneid* (book 5), wrote that although the river Tiber is usually placid and peaceful in its course, making it dangerous with its floods (Carcani, 1875, p. 27):

> Sternit agros, sternit sata laeta boumque labores, Praecipitesque trahit silvas.

> It lowers the fields, destroys crops and toil, and drags the forests precipitously.

Since then, during almost every decade—with greater or lesser impetus—the waters of the Tiber have emerged from its bed, flooding large areas of the city and the surrounding countryside. For instance, the Benedictine monk Paul the Deacon (c. 720s–796/799 CE), in his *Istoria Langobardorum*, recalled the flood of 555 CE (Frosini 1977, p. 143):

> A causa delle continue piogge il Tevere a Roma gonfiò talmente che le sue acque lambirono le mura e allagarono parecchi quartieri.

> Due to continuous rainfall, the Tiber in Rome swelled so much that its waters lapped the walls and flooded several districts.

However, the river was not only a danger with its floods and consequent destruction of farms, houses and bridges, and mills (Fig. 1a), but at the same time an inexhaustible source of drinking water, and energy to power its historical mills (Fig. 1b).

Linking environmental and hydrological variability to human history remains constrained by the scarcity of high-resolution climatic data in medieval and earlier times. Proxy-based considerations of cyclone variability are restricted to evidence of long-term changes at sparse spatial scales, limiting our understanding of the forcing imprint, and the relevance of the processes involved in cyclone intensification for historical climate periods. Ljungqvist et al. furthermore identified knowledge gaps and biases in the existing scholarship on the past climate–human history nexus, including geographical biases, and a disproportionate focus on extremely cold periods, restricting our capability to produce plausible future scenarios. In particular, fluctuations in climate and its extremes across different time-scales can produce changes in the occurrence and intensity of storms and, in turn, in the rainfall erosivity, i.e., the power of rainfall as defined by the R-factor of the Universal Soil Loss Equation (USLE) and its revised forms. Rainfall erosivity is a major factor for understanding the dynamics of surface processes such as erosional soil degradation as well as other landscape disturbances such as floods and landslides. It also offers the opportunity to capture the fingerprint of climate change, not the least in the Mediterranean region, which is a climate change “hotspot” and a particular sensitive region in terms of hydro-climatic variability. An improved knowledge of the temporal variability in erosive rainfall is important because its changes indicate varying magnitudes of hydrological events that damage Mediterranean landscapes. This is of great importance for the development of conservation and environmental management plans in a changing climate. The Mediterranean region is marked by a composition of gradual and abrupt changes of rainfall patterns, including variable patterns of erosive storms. Deep in the warm sea, Mediterranean cyclones form mainly
around a few centres, with a dominant area in the Gulf of Genoa, where slowly moving low pressure can move large amounts of precipitation. Damaging hydrological events, and thus rainfall erosivity, occur here mainly due to: (1) intense and highly convective rain showers (often less than one hour in duration), with rainfall amounts generally below 100 mm that are susceptible of flash-floods, and (2) mesoscale convective rainfall causing stationary rainfall for several hours or days resulting in large rainfall and more than 200 mm in just a few hours.

Already in historical times, these hydrological extremes were documented in diaries. For instance, in the third book of his work “On the Tiber”, Andrea Bacci (a sixteenth-century Italian philosopher, physician and writer) describes a flash-flood in Rome in the year 1557 (cited from Brioschi, 1876, pp. 23–24):

In quel dì che fu il 14 Settembre 1557, essendo tempo quasi sereno si vide in un subito ingrossare il Tevere, e da ivi a poco non senza meraviglia che pareva quasi ritornare indietro rincalzato dal mare, cominciò prima ad uscire dalle chiaviche, ed appresso dal pieno del fiume a traboccare, e scorrere sì furiosamente per tutte le strade, che in pochissime ore fece la più parte di Roma navigabile.

On that day, September 14, 1557, when the weather was almost clear, the Tiber was seen to swell at once, and from there on, not without wonder, as it seemed almost to have been pushed back by the sea, it began first to flow out of the culverts, and then from the middle of the river to overflow, and flow so furiously through all the streets, that in a few hours it made most of Rome navigable.

Longer and large rainfalls in the year 1415 were, instead, described in the Diarium Romanum Gentilis Delphini and Cod. Mss. Vatican. (Carcani, 1875, p. 39):

Il giorno di giovedì ultimo del mese di Ottobre dell’anno 1415 [...] fu una terribile procella di venti, lampi, tuoni e pioggia: «ita quod apparebat quod totus Mundus deberet finire». Nè cessò mai di piovere, giorno e notte, fino al 25 Novembre.

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From these historical records, we understand that the Italian lands (Fig. 2a) have been exposed to floods and, in turn, to aggressive rainfall. This is shown by the fact that the annual maximum daily rainfall is also today likely to reach critical values in central Italy (Fig. 2b). In particular, the Tiber River Basin (TRB), the focus area of this study (Fig. 2c), is even more exposed than other Italian areas, where high erosivity produces considerable soil erosion and floods. On average (period 2003–2012), rainfall erosivity over the TRB varies from about 1000 to 3000 MJ mm⁻² h⁻¹ yr⁻¹ (Fig. 2d, black squared). Recently published studies on the relationship between hydrological extremes and climate change, including rainfall erosivity, indicate a new focus of...
environmental science about the history of extreme hydroclimatic events. Indeed, there are studies regarding the relationship between erosive forcing and climate in the central Mediterranean region\textsuperscript{38–44}, indicating renewed attention to environment–climate interactions in historical and ecological research in support of reconstruction of extreme rainfall events (including rainfall erosivity) and planning decisions, especially in agriculture. However, the Italian landscape, and that of the TRB in particular, has been shaped by stormy and erosive events (with related floods) that have influenced human life in the basin and its main city, Rome, since the Middle Ages and before. High-resolution and well-dated records are needed to understand the long-term hydroclimatic variability in this region over such a long period. In particular, rainfall records with a sub-hourly temporal resolution are required to obtain actual rainfall erosivity values compatible with the (R)USLE methodology\textsuperscript{23}. This makes historical studies challenging, as such detailed observations are not available before the modern instrumental period (digital measurements began systematically in the 1980s\textsuperscript{45}).

One way to reduce the gap in rainfall detail is offered by modelling approaches, which use indirect inputs from storms and floods as extracted from historical documentary data. In this way, modelling rainfall erosivity requires exploring mechanisms inherited from past hydrological extremes like storms and floods\textsuperscript{46}, using parsimonious models to overcome the limitations imposed by detailed models, which required detailed data and cannot be applied to historical periods\textsuperscript{46}. In particular, low-resolution historical documentary records of extreme weather events can be adopted to help predict rainfall erosivity when satisfactory instrumental data are not available\textsuperscript{37}. However, the floods of the Roman period, and earlier times, are almost all dated on an annual time-scale. It was not until c. 725 CE that monthly data became available on a more continuous basis. These data allowed us to estimate not only the intensity of flood events, but also their seasonality, and then erosivity, which cannot be predicted from annually-dated events alone. Thus, our analysis extends no further back in time than 725 CE. It is only from this period that storms and floods are sufficiently documented in historical documentary records and effects preserved in the built environment that can help reconstruct past climate. Documents such as personal manuscripts and official records, as well as printed materials, artworks and, more recently, electronic data, pose particular problems of homogenisation\textsuperscript{50}. It is well established, for instance, that small, localised storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have established a reasonable standard for the events recorded (MSSI: Monthly Storm-Severity Index) to transform subjective information into an objective vector of erosive storms can be frequent, but tend to be underestimated, especially when occurring in remote locations. To overcome some of these uncertainties in our database, we have establish...
the logarithmic relationship between the cumulative number of events (CEN) and the MSSI values in the range 1 ≤ MSSI ≤ 4, as follows:

\[
\log_{10}(CEN_{ij}) = a + b \cdot MSSI_{ij} \quad \text{with } i = 1, \ldots, 4 \text{ and } j = 1, \ldots, 3
\]

where \(i\) and \(j\) indicate severity class and sub-period, respectively. In total, 285 events were extracted in the range 1 ≤ MSSI ≤ 4, which are represented in qualitative terms as stormy, very stormy, great stormy, and extraordinary stormy. The negative slopes in the three sub-periods, and in the entire dataset, reflect a downward trend in frequency as storms become more severe. With coefficients of determination \(R^2 = 0.98\), it can be assumed that the storms in the 725–2019 CE period are scale-invariant.

**Rainfall erosivity model assessment.** Using our simplified, non-linear multivariate additive model (REM_{5PR}), we estimated annual values of mean areal rainfall erosivity over the TRB (REM_{5PR}) taking into account (via MSSI inputs) the interrelationship between spatial patterns of hydroclimate and storm erosivity, consistent with a sample (1923–1964) of detailed (R)USLE-based data obtained for the study area—Eq. (2)—after removing the 1965 outlier of 2875 MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\) (~ 2% of the dataset of 43 years), not considered for model calibration (not shown in Fig. 4a). We obtained an annual mean erosivity value of 1357 MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\) (± 537 MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\) standard deviation) over the study period, which is close to the mean of actual data of 1360 MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\) (± 568 MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\) standard deviation). The actual values varied

\[
\begin{align*}
\text{sample mean:} & = 1336.6 \text{ MJ mm h}^{-1} h^{-1} yr^{-1} \\
\text{sample standard deviation:} & = 570.8 \text{ MJ mm h}^{-1} h^{-1} yr^{-1}
\end{align*}
\]

The modelled annual rainfall erosivity (orange curve) and suspended sediment yield (grey histogram) at the mouth of the river Tiber in the 1934–1973 period.

**Figure 4.** Rainfall erosivity model calibration and indirect validation for the Tiber River Basin. (a) Scatter-plot (dotted black regression line and red line of identity) of actual versus modelled—Eq. (5)—rainfall erosivity (MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\)) for the 1923–1964 period, with the inner bounds showing 90% confidence limits (power pink coloured area), and the outer bounds showing 95% prediction limits for new observations (light pink); the MAE in the box in a) is also in MJ mm h\(^{-1}\) h\(^{-1}\) yr\(^{-1}\); (b) Q-Q plot (theoretical versus sample quantile values); (c) Percentiles of actual (blue curve) and modelled (orange curve) rainfall erosivity; (d) Co-evolution of modelled annual rainfall erosivity (orange curve) and suspended sediment yield (grey histogram) at the mouth of the river Tiber in the 1934–1973 period.
the calibration dataset), they are not likely to change the structural characteristics of the erosivity model and its ability to interpret geomorphic processes in the basin.

**Historical reconstruction of rainfall erosivity.** Figure 5 shows the erosive forcing and other features that have occurred over the historical course on the landscape of the Tiber River Basin. In particular, Fig. 5d shows the evolution of the areal-mean annual erosivity values (blue circles) during the 725–2019 CE period, as obtained by Eq. (5). The long-term areal-mean value of estimated erosivity data is 1005 (± 335 standard deviation) MJ mm h^{-2} h^{-1}. To detect possible trends and oscillations in the discrete values, and to compare contem-
poratory and historical patterns, the time-series of annual rainfall erosivity was smoothed with the filtered 11-year Gaussian function (Fig. 5d, bold blue line). The pattern of quantiles, with 50-year return period, was also shown (Fig. 5c, red curve). From the smoothed trend it can be seen that from the LIA onwards, erosivity is characterized by two major oscillations, within which there is a marked inter-annual variability.

This contrasts with the MCA, during which the estimated erosivity fluctuates more erratically. Before the year 1000, the MCA is characterized by relatively moderate erosivity (on average 941 MJ mm h⁻¹ h⁻¹ yr⁻¹), rarely (in 12 years) exceeding 1200 MJ mm h⁻² h⁻¹ yr⁻¹, in a period when Italy and the Tiber River Basin experienced intense deforestation and colonisation activity, favoured by religious orders, especially the Benedictines. After the year 1000, the mouth of the river Tiber shows intermittent activity (no longer suitable for navigation since 1118), attesting to frequently reduced river flows.

Longman found a similar distribution for the Eastern Mediterranean region, where erosivity reflects less rainy conditions during the MCA, with relatively low hydroclimatic variability. With the onset of the LIA, however, erosivity became more vivid, with notable values often exceeding 1400 MJ mm h⁻² h⁻¹ yr⁻¹ (in 11 years between 1250 and 1400). Stormy events had also affected other regions at that time, with disastrous consequences in much of Western Europe.

Entering the hydrologically most active central part of the LIA, change-points in the erosivity time-series were detected well before the Maunder Minimum of reduced solar activity (c. 1645–1715 CE): in 1474 with the Buishand statistic, and in 1495 and 1497 with the Standard Normal Homogeneity Test-double shift. These change-points mark a transition towards a more extreme rainfall erosivity in a period (late fifteenth century) characterised by afforestation, with the reforestation of grasslands, or sometimes the joint expansion of grasslands (meadows and pastures) and forests. In particular, the flood of the river Tiber in the year 1495 (red arrow in Fig. 5d) has been handed down to us by direct testimonies of its disruptive force, and among them the most interesting is that of the Venetian oratories (ambassadors) who wrote:

Dopo due giorni e mezzo di quel turbine di pioggia il 4 dicembre il cielo torno sereno. Tosto il Tevere cominciò a gonfiare con straordinaria celerità allagando tutta la città bassa [...] Le acque toccavano la sella dei nostri cavalli. Ad un’ora di notte la piena giunse anche alla nostra via.

After two and a half days of this whirlwind of rain, the sky cleared up again on 4 December. Soon the Tiber began to swell with extraordinary speed, flooding the entire lower city [...] The waters touched the saddle of our horses. At one hour of the night the flood reached even our street.

As the fifteenth century progressed, floods became increasingly frequent. In the two centuries between 1400 and 1600 CE, floodplain forest returned to the valley and mesic forest expanded on the slopes. The change-point in the year 1495 (2570 MJ mm h⁻² h⁻¹ yr⁻¹) marks a crossroad after which nothing will resemble the previous centuries, with erosivity becoming more aggressive and changeable, with erosive storms tending to oscillate more, as the smoothed values also show. Thus, the sixteenth century was undoubtedly the most hydrologically damaging for the TRB, with five of the most disastrous floods that Rome has ever known, in the years 1530, 1557, 1589 and 1600 CE, floodplain forest returned to the valley and mesic forest expanded on the slopes.

However, the most ruinous of all was that of December 1598, and from its description we can see that it affected an immense area of the city of Rome (D’Onofrio, 1980, p. 160):

Da che si conosce che i diluvii antichi sono stati maggiori di questo [1598] che avanzò però quello del 1557 e quello del 1530 più alti di quanti ne erano segnati ne marmi che si trovano incastri con muri di case e Chiese e altri luoghi per Roma, chio ho potuto ritrovare.

It is known that the ancient floods were larger than this one [1598], but the one of 1557 and the one of 1530 were higher than those marked in the marbles that are set in the walls of houses and churches and other places in Rome, which I could find.

To conclude, the sixteenth century was a period of concentrated storms with different spatio-temporal scales: we have in fact a mean erosivity of 1087 (± 494 standard deviation) MJ mm h⁻² h⁻¹ yr⁻¹, while the extreme values are 3531 (in 1590), 2593 (in 1519), and 2570 (in 1566) MJ mm h⁻² h⁻¹ yr⁻¹, corresponding to return periods of > 100 anni for the first value and about 50 years for the second and third. Count Onofrio Castelli (1580–c. 1658) claims that indiscriminate deforestation was the cause of the great floods of the Tiber that occurred at that time (Brioschi, 1876, p. 28).
The progressive and increasing deforestation, which caused timber prices to rise so high […] The appearance of the hills and mountains also changed from wild to cultivated […] In heavy rain, the accumulated water is not impeded by the trees.

In fact, forest cover in the basin area fell from 69% in 1800 to 62% in 1900 (based on the HYDE3.2 historical land-use database, https://www.pbl.nl/en/image/links/hyde). Today we can imagine how damaging these storms were for the farmers due to the erosive action of the rains by looking at the annals of Italian agriculture, which illustrate the different processes—those that perhaps best preserve the material traces of the age-old work of the farmers due to the erosive action of the rains. Today we can imagine how damaging these storms were for the farmers due to the erosive action of the rains by looking at the annals of Italian agriculture (estimated value of 1468 mm·hm⁻²·h⁻¹·yr⁻¹ in 1702, 1742, 1750, 1783, 1784 and 1789). A resumption of storm-erosivity activity took place in the nineteenth century (on average 985 mm·hm⁻²·h⁻¹·yr⁻¹, with the estimated peak of 2570 MJ·mm·h⁻¹·yr⁻¹ in 1805 and 1870), when deforestation increased again in the upper Tiber River Basin (Brighenti, 1860, p. 9).

Il progressivo, e crescente disboscamento per cui salirono tanto in alto i prezzi del legname […] Anche l’aspetto delle colline e dei monti mutato di selvoso in coltivato […] Nelle pioggie dirotte le acque accumulate non trovano impedimento dagli alberi.

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By the end of the nineteenth century, Sacheri (1901) recalls the famous flooding of the Tiber River in December 1870: an extraordinary and imposing flood that inundated the city of Rome and the surrounding countryside, and on the 28th and 29th reached 17.22 m above the zero level of the Ripetta hydrometer (in a river wharf located along the upper-most part of the urban course of the Tiber River), a height that contemporaries could hardly remember as being comparable with the greatest floods that had occurred several centuries earlier.

During the twentieth century (1248 MJ·mm·h⁻²·h⁻¹·yr⁻¹ on average ± 456 MJ·mm·h⁻²·h⁻¹·yr⁻¹ standard deviation), erosive forcing resumed, exceeding 2000 MJ·mm·h⁻²·h⁻¹·yr⁻¹ in 1928 (2380), 1929 (2570), 1935 (2141), 1937 (2964), 1976 (2013), 1982 (2231), 1992 (2087) and 2005 (2008), and remaining critically high thereafter (e.g. 1928 MJ·mm·h⁻²·h⁻¹·yr⁻¹ in 2010). These values are similar to those of the sixteenth century, but with longer return periods (about 100 years for the first two extremes: 2964 and 2570 MJ·mm·h⁻²·h⁻¹·yr⁻¹ in 1937 and 1929). These annual rates are remarkable, considering that they are smoothed over the basin area, which means that even much larger erosive events may have occurred locally in the basin. From 1980 onwards, however, an overall decrease in both annual rainfall erosivity and its extremes is observed. According to Sharma, basin-wide erosivity would decrease due to the smaller storm extent at this scale: with fewer major storms there is less major flooding and less erosivity, especially extreme erosivity. This is consistent with the projected decrease in mean winter storm precipitation and dynamic weakening of cyclones over the Mediterranean region.

However, the attribution of extreme erosive events associated with floods and heavy rains to climate change signals remains uncertain, not the least due to the high spatial variability and long-term unpredictability of
increase on average from medieval times to the recent warming period (from 941 to 1159 MJ mm\(^{-2}\) h\(^{-1}\) yr\(^{-1}\)), periods of maximum erosivity values) and the \(\sim 22\)-year solar cycle and Atlantic teleconnection patterns in the absorption of solar energy in the atmosphere and ocean\(^90\). In Europe, the strength of solar activity apparently northwestern Italy over the 1701–2019 CE period. These studies provide evidence that regional patterns of pre-processes in northern Italy.

influence on river flood discharges, and suggested that the Sun could be one of the precursors of hydrological oceanic and atmospheric patterns over the North Atlantic region\(^91,92\). We refer here to circulation patterns, which modulates the connection between the frequency of regional precipitation oscillation peaks and the persistence of the North Atlantic, and modulating the strength and latitudinal location of westerly flows\(^96,97\).

of cyclone frequency in spring often offset by positive trends in summer\(^81\).

MSSI: Medieval Climate Anomaly; LIA: Little Ice Age; CWP: Current Warm Period.

Table 1. Descriptive statistics for three climatic sub-periods of the modelled time-series of rainfall erosivity.

| Climatic sub-period | Mean (MJ mm\(^{-2}\) h\(^{-1}\) yr\(^{-1}\)) | Coefficient of variation (%) | Percentiles (MJ mm\(^{-2}\) h\(^{-1}\) yr\(^{-1}\)) |
|---------------------|---------------------------------|-----------------------------|---------------------|
| MCA (725–1249 CE)   | 941                             | 27                          | 1217 1271           |
| LIA (1250–1849 CE)  | 1017                            | 35                          | 1707 2345           |
| CWP (1850–2019 CE)  | 1159                            | 36                          | 2011 2325           |

 Influence of solar and teleconnection cycles. The wavelet power spectrum (Fig. 5a) reveals significant high-frequency periodicities in the erosivity time-series with a scattered \(~11\)-year cycle, together with a more regular \(~22\)-year period during the LIA as well as during the recent warming phase. Both periodicities are key features of solar activity variability, with the \(~22\)-year magnetic solar cycle composed of two \(~11\)-year sunspot cycles with opposite polarities\(^92,93\). While significant periodicities less than \(~11\) years occasionally occur without any relation with climatic periods, other low-frequency periodicities are also significant. The quasi-secular periodicity appearing during the late fifteenth century to the present reflects the periodicity of \(~100\)-year cycle of Gleissberg\(^84\), while the periodicity of \(>300\) years extending over the central part of the LIA (and beyond but outside the reliable region formed by the time axis and the bell-shaped contour) may reflect combinations of the \(~210\)-year Suess/de Vries cycle and the Gleissberg cycle\(^85,86\).

The Sun can affect the hydrological cycle through feedbacks at multiple scales, which can lead to complex geographical distributions of solar-related signals in hydroclimatic factors. Within a river basin, in particular, the integrated nature and inertia of sediment discharges can reveal pulses driven by the Sun that amplify precipitation signals, while the links between solar activity and precipitation can be weak\(^87,88\). Here, reconstructed floods (translated into rainfall erosivity data) can be considered as suitable proxies for the Tiber River discharges. Zanchettin et al.\(^89\) provided Sun-like periodicities related to sunspot magnetic activity as an indication of solar influence on river flood discharges, and suggested that the Sun could be one of the precursors of hydrological processes in northern Italy.

Diodato et al.\(^90\) also found statistical links between precipitation hazard metrics (erosivity density and return periods of maximum erosivity values) and the \(~22\)-year solar cycle and Atlantic teleconnection patterns in northwestern Italy over the 1701–2019 CE period. These studies provide evidence that regional patterns of precipitation or temperature changes can be modified by large-scale climate teleconnections induced by changes in the absorption of solar energy in the atmosphere and ocean\(^90\). In Europe, the strength of solar activity apparently modulates the connection between the frequency of regional precipitation oscillation peaks and the persistence of oceanic and atmospheric patterns over the North Atlantic region\(^72,82\). We refer here to circulation patterns, which are reflected by the Atlantic Multidecadal Variability (AMV) or its internally generated component, commonly referred to as the Atlantic Multidecadal Oscillation (AMO), i.e., the variability of the sea-surface temperature over a timescale of several decades\(^95\). As also reported for the Arno River Basin (1000–2019 CE) in central Italy\(^49\), we observe that higher rainfall erosivity values in the TRB tend to be associated with dominant warm phases of the AMV (reconstruction by Wang et al.\(^94\) from 800 to 2010 CE, not shown). Sea-surface temperature anomalies also induce atmospheric pressure gradients\(^95\), redistributing air masses between subtropical and subpolar latitudes of the North Atlantic, and modulating the strength and latitudinal location of westerly flows\(^96,97\).
The North Atlantic Oscillation (NAO), in particular, measures the fluctuations in the difference of air pressure at sea level between the Icelandic Low (at ~38°N) and the Azores High (at ~65°N). Major influences of the NAO on precipitation regimes in the central Mediterranean are documented and our analysis support a relationship between rainfall erosivity in the TRB and the proxy-based multi-annual NAO reconstruction (Fig. 5a) of Hernández et al. In particular, we observe that the intensification of erosive forcing after the end of the fifteenth century corresponds to the transition to substantially negative NAO values in the fifteenth century (~0.28 on average, ±0.09 standard error, Student- \( t_p ~ 0.00 \)), which follows a long phase (725–1475 CE) with no clear dominance of positive or negative NAO states (0.12 on average, ±0.10 standard error, Student- \( t = 0.21 \)).

However, the NAO index presents large inter-seasonal and interannual variability, particularly the winter NAO, which also has substantial decadal and longer time-scale variability. The negative phase of the NAO dominated the Atlantic circulation between the mid-1950s and the 1970s, followed by an abrupt transition to positive phases during the winter of 1979–1980 (with the atmosphere persisting in this mode during the winter of 1994–1995) and a sharp slowdown. Furthermore, the high spatio-temporal variability of rainfall regimes due to topography and the presence of sea masses make it difficult to establish the actual role played by the NAO on erosive precipitation in southern Europe, especially when wide areas are considered and long-term time-series (i.e. over a millennium) are not available. We thus highlight the need to understand in more detail the links between large-scale atmospheric and oceanic variability and rainfall erosivity, which depend on the geographical context (e.g. large regions or catchments) and the time scale (e.g. annual or decadal) over which the hydrological response is assessed. To this end, we advocate the use of a limited-area (basin-scale) model on time scales longer than a millennium because, as this study shows, it can be appropriate to assess changes in hydrological responses that are controlled by large-scale circulation patterns. The most intense and localized precipitation events are, however, subtle and difficult to detect when working with annual-scale time-series.

We envision that in the future will be able to conduct an in-depth analysis with reconstructed series that will enable to better highlight the most likely trend in a changing climate. With this in mind we conclude this article with a quotation from Brioschi (1876, p. 17):

*L’antica Roma che ebbe tanto a soffrire del Tevere, non ci ha nulla lasciato che potesse mettere un freno per sempre alle inondazioni, noi abbiamo da lei a prender alcun esempio la cui ricordanza ci metta nella via di più vaste ricerche*

Ancient Rome, which suffered so much from the Tiber, has left us nothing to stop the floods forever; we can take from it an example whose memory will put us on the road to a wider search.

**Methods**

**Study area and climate.** Formerly called Albula (after the Latin *albus* = white referring to the light colour of its blond waters), or Thybris (from the Etruscans) or Rumon (linked to the ancient Etruscan-Latin name of Rome), the Tiber is the main river of central and peninsular Italy. With 405 km of course, it is the third long-
est Italian river (after the Po, 652 km, and the Adige, 410 km). The source of the Tiber river is on the slopes of Mount Fumaiolo (1268 m a.s.l.), on the side turning towards Perugia (upper Tiber River Basin, Fig. 7), near Balze, a village of Vergyhereto (in the province of Forlì-Cesena). The Tiber River Basin is rich in tributaries and sub-tributaries, but the river receives most of its water from the left bank, where its main adductors are the Chiascio-Topino system, the Nera and the Aniene. The tributaries of the right bank are the Nestore with Caina and Fersinone, the Paglia (with the Chiani) and the Treja, between the provinces of Rome and Viterbo. The Tiber River also passes in the vicinity of Perugia, Marsciano, Deruta and Todi, while Tivoli and Subiaco are crossed by the Aniene tributary, at east (Fig. 7).

The river was used for many centuries as a means of communication: in Roman times merchant shipping could go directly to Rome, to the Emporium at the foot of the Aventine, while smaller vessels suitable for river navigation transported goods and agricultural products from Umbria, through a capillary navigation system that penetrated the region also through the tributaries, in particular Chiascio and Topino.

From a climatic point of view, the TRB can be divided into three sub-regions (Fig. 7): the flat sub-region, which includes the area surrounding the city of Rome and the rural areas northeast of the city (areas coloured in white tending towards yellow and green); the sub-region of the Apennine valley along the main branch of the Tiber, which also includes the surrounding mountainous territories, such as Todi and Perugia (areas coloured in green); and the third sub-region at east, mainly mountainous, which includes the provinces of Terni and Rieti (areas coloured in ochre brown). The climate of the first sub-region is temperate, with a hot summer and an annual rainfall of 800–1000 mm. The second and third sub-regions are the most interesting from a hydrological point of view, as they are the main source of deluges and floods, which play an important role in driving the most important erosive storms of the year. The climate is mainly continental, with moderately hot summers in the valley bottoms (roughly province of Rieti), and not very hot summers in the hills (roughly province of Perugia). The amount of annual rainfall is about 800 mm at Perugia, and over 1000 mm at Rieti. The rainfall is distributed over 80–100 days per year, with two peaks: the main peak in autumn and the second in late spring. Summer and autumn storms are common in all three sub-regions.

**RUSLE-compliant actual rainfall erosivity data.** To develop and calibrate a parsimonious model for rainfall erosivity estimation in the study-area, we used the areal-mean of actual rainfall erosivity (MJ mm h⁻¹ hr⁻¹ yr⁻¹) for the TRB \(R_{TRB}\), as calculated for each year of the 1923–1965 period, by adapting an equation originally developed by Diodato⁴¹:

\[
R_{TRB} = \Phi \cdot \sqrt{P_{TRB} \cdot d_{x_{TRB}} \cdot h_{x_{TRB}}}
\]

(2)

where \(\Phi\) is a scale parameter to convert the term under square root into the rainfall erosivity unit (MJ mm⁻¹ hr⁻¹ yr⁻¹), \(P_{TRB}\) is the areal-mean annual precipitation (mm yr⁻¹) as derived from GPCC (Global Precipitation Climatology Centre) 0.25° × 0.25° Full Data Monthly Product Version 2020⁴⁵ via Climate Explorer (http://climexp.knmi.nl), while \(d_{x_{TRB}}\) and \(h_{x_{TRB}}\) are the areal-mean maximum annual daily \((d_x, \text{mm} \text{d}^{-1})\) and hourly \((h_x, \text{mm} \text{h}^{-1})\) rainfall, respectively, estimated annually as:

\[
d_{x_{TRB}} = (\phi + MSSI_{\text{max}}) \cdot \sqrt{d_{x_{RO}}} + \Omega \cdot d_{x_{TRB}(NCEP)}
\]

(3)

\[
h_{x_{TRB}} = \psi \cdot \left[1 - 0.4 \cdot \cos \left(6.28 \cdot \frac{m - 1.5}{23 - m}\right)\right] \cdot d_{x_{TRB}}
\]

(4)

where \(MSSI\) is the Monthly Storm-Severity Index for which the maximum value is taken from the group of months \(Y (i=1, 2, 3, 4, 8, 9, 10, 11, 12)\) as in Eq. (5), \(m = 1, \ldots, 12\) is the month of year in which \(d_{x_{TRB}}\) takes place,
dxRO is the annual daily maximum rainfall (mm d−1) from the Roman College Observatory105 and dxTRB(NCEP) is the annual daily maximum rainfall (mm h−1) from the NCEP–Reanalysis data106 via Climate Explorer. The two equations include empirical parameters of position (ϕ) and scale (Φ, Ω, ψ).

The main issue was to obtain a homogeneous and continuous areal series of dx and the only way was to find a correlation between the years in which the basin was covered by a sufficient number of recording rain-gauges so as to have a homogeneous observed series of dx TRB, and a corresponding number of homogeneous and continuous predictors, dx RO, MSSIi(max) ∈ Y and dx TRB(NCEP) that could give us a sufficiently strong relationship to estimate rainfall erosivity over the dx basin area for the entire 1923–1965 period. The scatter-plot in Fig. 8 shows a sufficient proximity between the modelled dx TRB data, Eq. (3), and the observed dx TRB data available from the former SIMN (Servizio Idrografico e Mareografico Nazionale) and now present in the Annali Idrologici project (https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corsodacque-interne-e-marino-costiere-1/progetto-annali). In particular, we obtained annual areal values of dx TRB by averaging the data observed by weather stations in the basin in the years when data from at least 30 recording rain-gauges were available. In this way, we aimed to cover more than 70% of the basin area based on high-quality rainfall data.

The high-magnitude/low-recurrence erosivity value of 2875 MJ mm h−1 h−1 yr−1, occurred in 1965 was excluded from the dx actual series because it gives a strong indication of an anomalous value, likely due to the occurrence of a notable rainfall event in the basin, concentrated on September 3. Similar erosivity values obtained in other years tended to be closely associated with pronounced precipitation and non-zero MSSI values in different months, whereas in 1965 MSSI = 3 occurred in September while it was equal to zero in each of the other months. The rain that fell on September 3 proved to be erosive but did not produce sufficient force to develop a flood outside September (which in fact was not recorded in the chronicles of the time). Given the rarity of such situations, their representation is somewhat hampered by the low resolution of the model, Eq. (5), which does not attempt to capture the details of rainfall erosivity fluctuations.

REM—Rainfall erosivity model. For the historical estimation of annual rainfall erosivity (MJ mm h−1 h−1 yr−1), we performed a regression model, hereafter referred to as the Rainfall Erosivity Model for the Tiber River Basin (REM TRB), which uses the MSSI data and their variability as inputs. The non-linear derivation of rainfall erosivity from rainfall intensity was obtained with a parsimonious approach comparable to the scenario depicted by (R)USLE-based erosivity data33. The non-linear model of annual erosivity in the TRB takes the following form:

\[ REM_{TRB} = A \cdot \left( \alpha + \sum_{i \in X} MSSI_i \right)^k + B \cdot \left( \beta + SD_{ieY}(MSSI_i)^k \right) \cdot \left( \gamma + \sum_{i \in Z} MSSI_i \right) \] (5)
associated with convective processes that drive flash-floods\textsuperscript{30,108–110}. In late autumn and winter, on the other hand, static (Fig. 9, shaded blue box). The seasonal gap in rainfall characteristics is governed by convective processes, which are more frequent and dynamic in late summer (when rain showers dominate), or by a variable mixture of convective and advective precipitations, which are more frequent in autumn (when overland flows dominate, Fig. 9, light red shaded box). These processes are mostly captured in the REMTRB—Eq. (5)—by the storm-severity index (MSSI)\textsuperscript{111}. Convective events, or those of mixed convective-advective nature (whose high kinetic energy is a shape parameter; SD is standard deviation; \(X (i = 1, 2, 3, 4, 8, 9, 10, 11, 12)\) and \(Z (i = 1, 2, 3, 4, 12)\) are different groups of months (the symbol \(\in\) stands for “belongs to”).

The idea of the REM\textsubscript{t-22} model is summarised in Fig. 9. Erosive precipitation is dominated by complex climatic features, which depend on rainfall-runoff and flood generation mechanisms, and it is difficult to separate the climatic component from natural variability. According to Waldam\textsuperscript{107}, the non-linear relationships that are created in river basins depend on the processes that dominate given hydrological regimes. Monthly rainfall, for instance, is not sufficient to describe these non-linear processes (Fig. 9, blue curve). In the central Mediterranean, erosive storms are expected to occur mainly in autumn (Fig. 9, red-contoured bars), when storm episodes are closely associated with convective processes that drive flash-floods\textsuperscript{30,108–110}. In late autumn and winter, on the other hand, precipitation (of long duration and low intensity), generally caused by extensive frontal activity, transports large volumes of rainwater (through stratiform orographic precipitation) leading to large-scale hydrological processes such as flooding\textsuperscript{111}. Late spring and summer rains are likely to cause a different regime of hydrological extremes than August–October, when extreme flooding is more frequent, meaning that August–April is a key time window in the year to estimate the rainfall erosivity of fluvial basins.

The separation between convective and advective events is important because convective precipitation (which is short and intense) is more dynamic and variable than advective precipitation events, which tend to be more static (Fig. 9, shaded blue box). The seasonal gap in rainfall characteristics is governed by convective processes, which are more frequent and dynamic in late summer (when rain showers dominate), or by a variable mixture of convective and advective precipitations, which are more frequent in autumn (when overland flows dominate, Fig. 9, light red shaded box). These processes are mostly captured in the REM\textsubscript{t-22}—Eq. (5)—by the storm-severity index (MSSI). Convective events, or those of mixed convective-advective nature (whose high kinetic energy causes local showers and leads to splash-erosivity) are interpreted by the standard deviation (SD) term.

Trend assessment. The quantile approach was applied to identify step trends at any REM\textsubscript{t} with return period \(T = 50\) years. The T for the annual rainfall erosivity falling above the \(j\)th quantile was ranked using the lognormal distribution, according to Aronica and Ferro\textsuperscript{112}:

\[
Q(\text{REM}_{X_{i-w}})_{T} = \exp \left[ \mu \left( \text{REM}_{X_{i-w}} \right) + \frac{\sigma \left( \text{REM}_{X_{i-w}} \right)}{t} \right]
\]

where \(Q(\text{REM}_{X_{i-w}})_{T}\) is the \(j\)th rainfall erosivity density (REM\textsubscript{t}) quantile of the log-normal distribution with assigned return period; \(\mu \left( \text{REM}_{X_{i-w}} \right)\) and \(\sigma \left( \text{REM}_{X_{i-w}} \right)\) are the mean and the standard deviation of the variable \(\text{REM}_{X_{i-w}}\). The subscript \(i-w\) indicates the calculation of a generic variable at time \(t\) over a 22-year moving window \((w)\); \(\mu\) is the log-normal dimensionless coefficient of 2.05 for \(T = 50\) years\textsuperscript{44}. The 22-year moving window has proved effective in showing long-term trends, smoothing out secular variation and more volatile changes from one year to the next\textsuperscript{113}.

Model calibration and assessment. To evaluate the model statistically and graphically, analyses were carried out with STATGRAPHICS (http://www.duke.edu/~rnau/gw5in5.pdf), WESSA (https://www.wessa.net) and AgriMetSoft (https://agrimetsoft.com) online calculators. For the calibration of the parameters in Eq. (5), the first condition was to minimize the mean absolute error (optimal, 0 < MAE < \(\infty\), MJ mm \(^{-1}\) hm\(^{-2}\) h\(^{-1}\) yr\(^{-1}\)). The second condition was to maximise the coefficient of determination \((0 \leq R^2 \leq 1\), optimal\)), which is the variance explained by the model. As a third condition, we approximated the unit step of the regression of the actual versus modelled data \((b = 1\), optimal\).

Other performance indices were also calculated. The mean absolute percent error (MAPE) offers the advantage of being scale-independent and intuitive (e.g. the model is reasonable with MAPE < 30\% and very accurate with MAPE < 10\%). The Kling-Gupta index \((- \infty < \text{KGE} \leq 1\)) was used as a measure of efficiency, with KGE > −0.41 indicating that the model is a better predictor than the mean of observations\textsuperscript{114}. A second efficiency metric, the Nash–Sutcliffe index \((- \infty < \text{EF} \leq 1\), optimal\)) was also calculated to assess model performance uncertainty, as EF > 0.6 indicates narrow parameter uncertainty\textsuperscript{116}. To select the set of inputs important for the parsimonious modelling of the actual erosivity, we iteratively added predictors, one at a time until satisfactory solutions with small MAE and large \(R^2\) values were obtained. A third criterion was added for the final selection, i.e. \([b = 1] = \text{min}\). Each predictor was repositioned for > 50 iterations until convergence. The Durbin-Watson statistic was calculated to test whether the residuals were auto-correlated. ANOVA p-values were used to present the statistical significance of the regression between actual data and estimates. The wavelet power spectrum with Morlet basis function was presented as a time–frequency plot to identify potential nonstationary oscillations at different frequencies in the time-series, using the Paleontological Statistics Software Package for Education and Data Analysis (PAST\textsuperscript{125}).

Numerical and categorical inputs. In a first phase, research was carried out in the major archival and library centres in Italy. Then, the documentary sources were consulted by means of a web search (https://books.google.com), which generated ~ 100,000 bibliographical records. In this way, we collected a massive number of bibliographical sources but only ~ 300 records have met the criterion of including the keywords abundant rainfall, storm, downpour, diluvial, flood and alluvial (piogge abbondanti, tempesta, diluvio, nubifragio, piena, inondazione, alluvione), as well as some Latin locutions (e.g. magnae pluviae, aqua maxima, diluvium, excrescentia flaminum, inundatio) that were chosen for careful reading. Useful information was found, however, only in the
following documentary sources: Castiglione8, Bacci118, Bonini119, Chiesa and Gambarini12; Carcani2; Brioschi3; Gregorovius120; Betocchi121 and in others recent studies122–124. For the most recent Tiber River floods we refer to the Autorità di Bacino Distrettuale dell’Appennino Centrale (http://www.autoritadistrettocatino.it/notizie/l-opera-capo) and Perugia Meteo (http://www.perugiameteo.it/home/Che-tempo-ha-fatto/Eventi-meteo-di-rilievo-vol1-Epsi6-po-geo-intensi-collegati-alle-piante-del-fiume-Tevere-1976–2007.aspx). In this way, data series were extracted by converting the information included in the historical accounts into numerical values on an index scale (see Methodological criteria and Catalogue of Monthly Storm-Severity Index (MSSI) in Methods and Supplementary Information). The transformation process required a dynamic understanding of the historical information used in the analysis, with a thorough knowledge of regional and sub-regional climates, and familiarity with the relative strengths and weaknesses of each type of source. A procedure, called weather hindcasting125, was used to become familiar with well-documented anomalies in the instrumental period before analysing similar cases in the pre-instrumental epoch. Storms occurring during the early part of the summer season (May to July) were not considered in this study, as they generally only affect small or isolated areas of the TRB and are not representative for storm reconstruction. A scoring system126 was then established to classify the MSSI in the period of the year between August and April. The MSSI were graded as: 0-normal, or average storm or storm that went unnoticed, with no comment on its severity or its impacts on society and the economy: 1-stormy, or heavy rainfall with limited damage, with isolated flooding recorded; 2-very stormy, heavy rainfall with some flooding occurred; 3-great stormy, or extreme rainfall event, with severe and extensive flooding, agricultural works suspended and urban communications suspended; and 4-extraordinarily stormy, or sporadic, very extreme event, with a century-long recurrence rate (these extreme flood events affect several river basins at the same time, killing people and animals, and knocking down trees).

This kind of understanding is exemplified in the form of a table (Table S1), which incorporates monthly and annual values, and their sources for exemplary years. The study was based on a systematic and critical analysis of the data concerning the above-mentioned phenomena provided by the Italian documentary sources. For most of the information it was possible to carry out an event check considering more than one documentary source on the same event. It was also possible to contextualise storms with other types of historical events (e.g. social, agricultural, and religious). In this way, the reliability of information was assessed by going beyond quantitative data and explore other sources of information such as diaries, newspapers, chronicles and local stories.

Data availability
All data used in this study are freely available. Spatial patterns of mean annual erosivity over the European region (Fig. 2) are freely available from the ESDAC (European Soil Data Centre) dataset at https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity. The proxy-based NAO dataset (Fig. 5) is available at https://doi.pangaea.de/10.1594/PANGAEA.921916. Areal mean of annual precipitation for the Tiber River Basin datasets were retrieved from the Global Precipitation Climatology Centre (GPCC) through http://climexp.knmi.nl. The full set of raw data and the equations that support the findings of this study (erosivity model, time-series reconstruction, precipitation data and storm-severity index inputs), are available in the Supplementary Table S1.

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