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Testing a climate erosive forcing model in the Po River Basin

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ABSTRACT: Changes in the spatial and temporal features of precipitation patterns may have important effects on the magnitude and timing of erosive rainfalls, which will in turn result in changes in soil degradation response. This study presents a secular timescale environmental hazard assessment to account for the impacts of climate erosive forcing on an agricultural landscape identified as potentially vulnerable, mainly to erosional soil degradation processes. An empirical probabilistic model for temporal characterisation of this impact, termed CHIEF (Climate Hazard Index Erosive Forcing), was developed to evaluate the annual balance between climate driving and climate resisting forces in the Po River Basin (northern Italy) during the period 1775 to 2003. In the CHIEF approach, an ecological system adapted to the natural hydro-climatic regime was assumed; fluctuations in this regime, especially those exceeding thresholds of rainfall energy intensity, may trigger erosional soil degradation processes. In this way, the time sensitivity of the CHIEF model reflects the magnitude of annual input nested within patterns of long-term environmental change occurring within a specific temporal window, in order to capture different modes of climatic variability and their hydro-geomorphological implications.

KEY WORDS: Rainfall · Climate erosive forcing · Net erosion · Climate change · Po River Basin · Northern Italy

1. INTRODUCTION

Precipitation, temperature, relative humidity, wind, solar radiation and evapotranspiration can be seen as the primary driving variables not only for Earth's water cycle, but also for eco-hydrological disturbances often resulting from spatial and temporal coincident extreme events (Hayden & Hayden 2003) and human actions, especially during periods of strong weather and climatic variability. A direct consequence of the above-described causal chain is that repeated damaging hydrological events all over the world (e.g. downpours, overland flooding and erosional land degradation) can be viewed as a signal of climatic change (Bell et al. 2004), and can imply environmental and economic impacts higher than the more often feared global warming (Thornes & Alcántara-Ayala 1998, Allen & Ingram 2002).

The awareness of climate as a driving variable for hydro-geomorphological processes can complement the interpretations of scientists from many different disciplines (ecologists, engineers, geomorphologists, historians and so on), enhancing the degree of interdisciplinarity and the usefulness of their work (Zwiers & von Storch 2004). For example, an understanding of how landscape components react to climate forcing and land-use change has specific implications for modelling the temporal evolution of a hydro-geomorphological hazard (Higgitt 2001). In some parts of the world the historical knowledge of human activity covers several millennia, and the archives of the last 2 to 3 centuries provide quite accurate data on mesoscale changes, without, however, documentation of the scale or location of geomorphological processes (Brunsden 2001). These data can be the basis for an improved understanding of multisecular relation-

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ships between weather elements (e.g. weather types, climatic indices) and temporally coincident multisecular trends in erosional processes (Wilby et al. 1997). In these previous studies, climate erosive forcing was an important input for the estimation of: (1) potential changes in erosional soil degradation caused by the power of rainfall (termed erosivity); and (2) patterns of environmental change occurring on timescales with different sensitivity.

Some of the above-mentioned research also demonstrated that landscape sensitivity to disturbing forces involves largely non-linear effects (Schulze 2000); for example, according to the data, erosion decreases during low rainfall scenarios and increases during wet scenarios, with a relationship that exhibits a non-linear positive feedback in which erosion rates during wet years increase in comparison with that during dry years (Favis-Mortlock & Boardman 1995). Many scientists are aware of this non-linearity and have developed process model techniques for soil erosion modelling at different temporal scales, such as daily or monthly. Although these sophisticated approaches are an important and useful step for soil erosion assessment, they need several climatic and environmental inputs which are often unavailable, incomplete or insufficient in length, or only summarised into monthly archives; this makes simulations of soil erosion hazard difficult over a timescale of centuries.

Weather generators (e.g. Johnson et al. 1996) coupled with simulation models are used in an attempt to overcome the lack of high-resolution time series (after Goosse et al. 2005), but can present a lot of drawbacks (Toy et al. 2002), e.g. a powerful computer and extensive run-time. Data that are either not available or cannot be obtained without significant expense represent another constraint. Fewer problems are evident in recent approaches developed in order to improve the Revised Universal Soil Loss Equation (USLE-RUSLE; Wischmeier & Smith 1978, Renard et al. 1997), in particular: (1) the use of temporal simulation facilities of RUSLE within a geo-referenced framework (Renschler et al. 1999); (2) the adoption of fuzzy logic based modelling (Tran et al. 2001); (3) the employment of artificial neural networks (Licznar & Nearing 2003); and (4) the use of non-parametric analysis of the USLE data set (Sonnoveld & Nearing 2003).

The present study describes a simple algorithm termed CHIEF (Climate Hazard Index Erosive Forcing), which is useful for the generation of a measurement of the annual balance between climate driving and climate resisting forces (after Collison & Griffiths 2004) over a secular timescale, used in turn to detect the impact of climate on hydro-geomorphologic processes.

The methodology was applied to a test site located in the upland and midland Po River Basin (northern Italy) — an area that during recent decades has experienced several extreme precipitation events that have led to severe damage and fatalities, and that had not been previously addressed specifically by a historical study of rain-erosivity hazard. This study was based on the Milan-Brera Astronomical Observatory homogenised monthly series of precipitation data recorded from 1764 to 2003. The importance of this series is evident; beginning in 1764, it documents the period from the end of the Little Ice Age (LIA) to the present climatic phase.

The CHIEF model was calibrated and validated by means of sediment data collected from 2 turbidity sampling stations. The choice of turbidity stations representative of a substantial part of the basin is important, because it allows an appreciation of the contribution of mesoscale phenomena to soil erosion. The sediment transport of the Po river is also affected by local scale phenomena such as: (1) several types of landsliding, extreme phenomena sometimes important in the upper basins of the Po river and its tributaries; (2) re-mobilisation of sediments; and (3) the trapping of sediments by the large number of natural and artificial lakes or dams present along the course of the Po river and its tributaries.

Forest fire events are also a factor that increase soil loss (Ritsema & Dekker 2003). In the specific case of the Po valley, forest fire does not represent a key factor for soil erosion because the mountain forestry areas receive a good level of precipitation in summer, which means a very low risk of fire outbreak. On the contrary, the season with a higher risk of forest fire is winter, a season with low rainfall and very low erosivity (most precipitation is represented by snow).

2. ENVIRONMENTAL SETTING, RESEARCH DESIGN AND HISTORICAL DATA

The impact of climatic variability on economic activities (agriculture, transport, civil works etc.) tends to be quite pronounced in some European environments. In this general context, the Italian area shows a particular susceptibility to land degradation and erosive processes (Kosmas et al. 1997). This is because the area is subject to long dry periods followed by heavy bursts of erosive rains falling on steep slopes with fragile soils (Van Rompaey et al. 2003), resulting in many erosion-prone areas.

The subject of this study is the Po basin, for which the climate shows characteristics of transition between the sub-continental climate of central Europe (Cfb) and the Mediterranean (Csa) (see Koeppen's classification in Strahler & Strahler 2000). The yearly and seasonal distribution of precipitation over the area (Fig. 1a) is the result of synoptic circulation that advects air masses of different origin (Arctic, Polar maritime, Polar continental and Subtropical). This primary dynamical effect (Holton 2004) is strongly modulated by macrorelief (Alps, Apennines) that produces a series of effects at different scales, from macro to micro (Barry 1992). Other important effects are the advection of humidity from the Mediterranean (High Adriatic, Gulf of Genoa) and the high stability of air masses in the Po basin (Fea 1988), which allows a strong storage of humidity that represents the main energy supply for thunderstorms which are triggered by outbreaks of Atlantic polar maritime air in the middle troposphere (in the Po basin, the thunderstorm season usually extends from the end of March to mid November). The fragility of the Alpine relief is the result of a strong rain-erosivity triggered by intense precipitation from May to October (Fig. 1b,c). For example, during the period 1981 to 2005, it is possible to list strong erosive events that affected the Apennines (Oltrepò Pavese in October 1983 and Piedmont in November 1994) and Alps (province of Sondrio in July 1987, Piedmont in November 1994, province of Varese in September 1995, provinces of Brescia and Bergamo in November 1996, Piedmont and Valle d'Aosta in October 2000).

The Apennine relief is the southern limit of the Po basin and divides the basin from the gulf of Genoa. In this area, the principal erosion-prone zones are located in an intermediate belt between the mountainous portion of the region and the foothills, and are due to the unfavourable combination of: (1) high rain-erosivity capacity; (2) high erodibility characteristics of soils; and (3) channel networks that are rapidly saturated by limited inflows of water.

Milan is located in the central part of the plain almost equidistant between the Apennines and Alps (Fig. 2b); the precipitation regime of Milan (Fig. 1a) shows the co-existence of the endo-Alpine signal (precipitation minimum in winter [Feb.]) and the Mediterranean signal (precipitation minimum in summer [Jul]). These elements justify the belief that this very long time series can contain information about the behaviour of erosive processes in the Apennines and Alps.

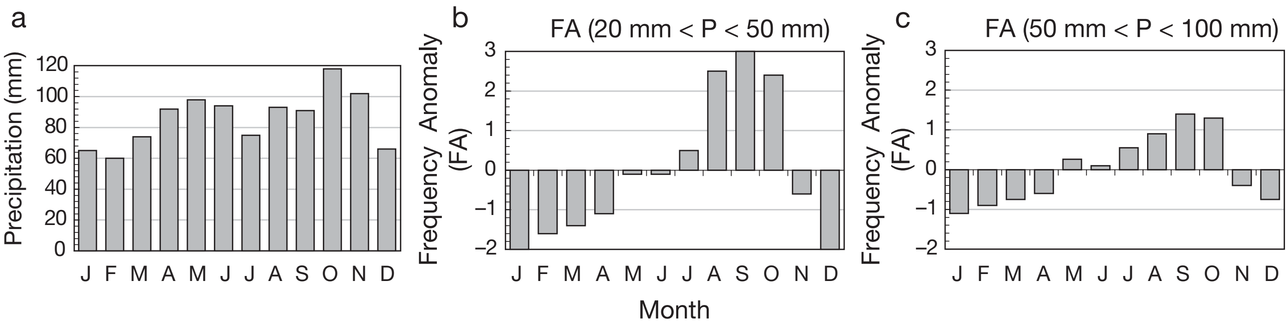

Fig. 1. (a) Monthly precipitation regime for Milan-Brera station (45.27° N, 9.11° E; reference period: 1951 to 2000). (b,c) Precipitation (P) frequency anomaly (FA) representing the deviation, calculated for the mean year, between the monthly number of events in the specified range (20–50 or 50–100 mm) and the mean monthly number of events in the same range

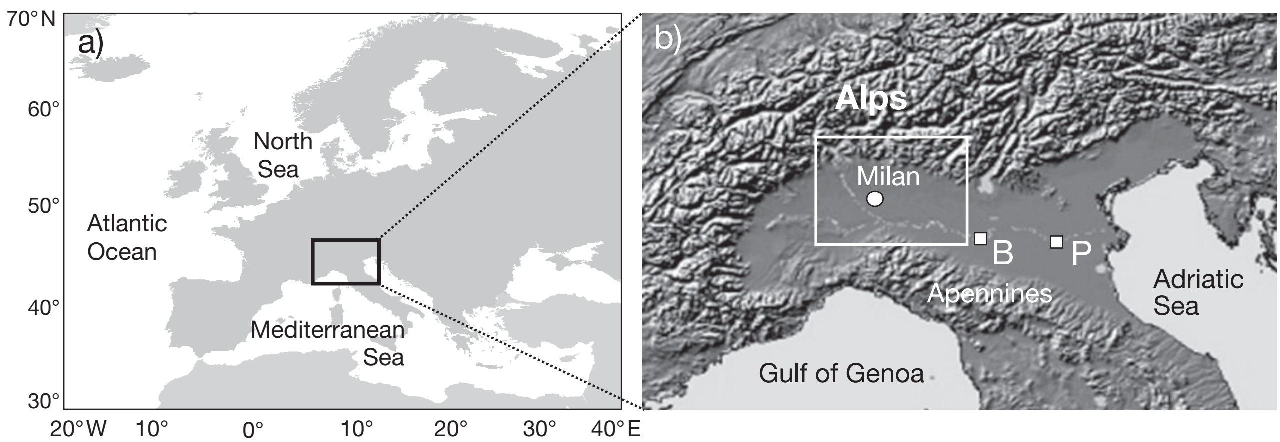

Fig. 2. (a) Location of northern Italy relative to Europe and (b) up- and midland Po River Basin (box), Milan district, and Boretto (B) and Pontelagoscuro (P) turbidometric stations

Many erosive processes of the Po valley are the result of raindrop impact and surface peak runoff, rather than of the volume of runoff; for this reason, rain-erosivity is more useful than runoff amount for the estimation of water erosion. Specifically, for time series reconstruction (Climate Hazard Index Erosive Forcing (CHIEF), variable over time), 2 conceptual components were adopted: (1) an erosive forcing factor, which is function of precipitation; (2) an erosive-resistance factor, which is function of climate variability.

Considering these 2 components, a central assumption is that a climate-erosivity model giving adequate results for selected years of the 20th century will also give acceptable results when run with changed erosivity and changed climate. In this way, the CHIEF model's time sensitivity attempts to reflect the magnitude of annual input nested within patterns of long-term environmental change occurring within a specific temporal window. A case study was carried out for the upland and midland Po River Basin, adopting the Milan-Brera Astronomical Observatory historical data series back to 1764. The regular registration of meteorological observation was started by the Padre Luigi La Grange, who joined the Milan-Brera Astronomical Observatory in December 1762 on the invitation of Padre Federico Pallavicini.

The precipitation series of Milan-Brera is well known and studied: the monthly totals were published by Buffoni & Chlistovsky (1992), who presented an analysis of daily values for the 1835 to 1990 period; recently the monthly totals were presented by Chlistovsky et al. (1999) for the 1764 to 1997 period. Updates to 2003 were released by L. Buffoni (pers. comm.). Over the last 10 yr, all the data and metadata available in the registers and contemporary publications from the beginning to the present day were recovered, corrected, validated and homogenised on the basis of historical documentation. In turn, rain-erosivity input for the CHIEF model was predicted from monthly precipitation (see Section 3.1). Sediment data were assessed using the records of 2 turbidity sampling stations belonging to the former Servizio Idrografico e Mareografico Nazionale: Boretto Station (Cati 1981) for the calibration period 1956 to 1973 ('B' in Fig. 2b), and Pontelagoscuro Station (De Marchi & Bondini 1931) for the validation period 1915 to 1929 ('P' in Fig. 2b). Finally, additional historical flood and vegetation data from the area surrounding Milan was derived from Crosio & Ferrarotti (1996), SICI-CNR (2005; available at http://sici.irpi.cnr.it/storici.htm), and L. Bonardi (pers. comm.) for floods; and from Siemoni (1872), Vecchio (1974), Camuffo & Enzi (1996), Cantù (2000) and Romanò & Dal Santo (2004), for vegetation.

3. CLIMATE EROSIVE FORCING MODEL DESIGN

3.1. General description

Net erosion of a basin is a measure of average sediment yield, over given time and space units, produced by all erosional sources (including overland flow, ephemeral gully and stream channel areas); and it is affected by climate, vegetation cover, land use and soil erodibility (Toy et al. 2002). Climate forcing can influence different characteristics of ecosystems, including the capability to absorb stresses caused by various forms of disturbance (after Mendoza et al. 2002). A specific topic linking hydro-geomorphology to other physical and earth sciences is the analysis of equilibrium, which focuses on the relationship between input forces and overall system response (Magilligan 1992). Erosive events in northern Italy are frequently observed with precipitation that falls from spring to autumn (Fig. 3). Spring and summer precipitation is often characterized by high intensity, owing to the prevalence of thunderstorms. These erosive events occur in places where vegetation is quite sparse, and where the complicated drainage schemes adapted in the 18th and 19th centuries to guarantee the correct drainage of excess waters in hilly areas have been simplified by irrational field tillage (e.g. failure to practice such measures as ploughing along the contours on sloping lands, proper crop rotation and, in particular, the growing of cover crops). Much damage also originates in fallows, grazing lands or uncultivated waste lands that are generally neglected. As a result, sediment erosion and transport is high and rapid. On the other hand, autumn precipitation is triggered by synoptic disturbances coming from the Atlantic area, fed by moisture flukes from the hot surface of the Mediterranean Sea and maintained by different mesoscale processes (Pinto et al. 2001). However, by the end of summer, locations normally receiving abundant precipitation have evolved dense vegetation, which can absorb, in part, the impact of falling rain at the beginning of autumn. In this way, rainfall is used by nature as both a climate driving and climate resisting factor. Firstly, the erosive influence of rainfall increases proportional to its amount and intensity; secondly, and opposing this influence, the protective effect of vegetation also increases with the precipitation amount. In this respect, the balance between climate driving and climate resisting forces can be expressed according to the following non-linear equation:

$$\mathrm{CHIEF}_t = \frac{\alpha \times R_t}{400 + \mathrm{Med}_w\left(\sum_{i=5}^{11} p_i\right) - 2 \times \mathrm{SD}_w\left(\sum_{i=2}^{11} p_i\right)} \quad (1)$$

CHIEF is the Climate Hazard Index Erosive Forcing for year t (CHIEF ≤ 1 for equilibrium and >1 for nonequilibrium conditions). R_t is the rain-erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}) that provides the forces applied to soil that cause water erosion and that can be subject to large time fluctuation; the detachment and transport capacity were modelled by rainfall energy, because soil erodibility and slope can be assumed to be temporally constant. The coefficient α is assumed equal to 0.48, imposing a 'tolerable erosion rate' of T = 2 Mg ha^{-1} yr^{-1} as adopted by Morgan (1995) for renewable soils. The term placed in the denominator is the resisting force represented by ground cover erosive-resistant climatic functions, where Med_w and SD_w are the median and standard deviation of precipitation expected on a moving time window (w = 11 yr) preceding the year t, respectively. The variable p_i is precipitation (mm) for the ith month (i = 1 for January, … i = 12 for December). Precipitation affects vegetative growth and decomposition of plant materials left by vegetation (Toy et al. 2002), which in turn reduces soil susceptibility to erosion. In this way, for northern Italy, the median (Med) accumulated precipitation from May to November is considered to be responsible for vegetation growth; in contrast, the interannual variability of rainfall induces important fluctuation into the average frequency and persistence of water stress for vegetation (Ridolfi et al. 2000), and consequently affects the ecosystem biomass stability (Mitchell & Csillag 2001). Therefore, the Med and SD values were preferred to arithmetic mean because they better represent the vegetation-protection bioclimatic function over time.

Since only homogenised monthly rain data were available in the reconstruction period, R_t was calculated according to USLE-RUSLE procedures devised by Diodato (2004a)

$$R_t = 1600 \times \left[\left(0.0245 \times \sum_{i=5}^{10}(p_i \times k_i) \times \sum_{i=1}^{12}\frac{(p_i)^2}{P_t} + 360\right) - 1510\right] + 1510 \qquad (2)$$

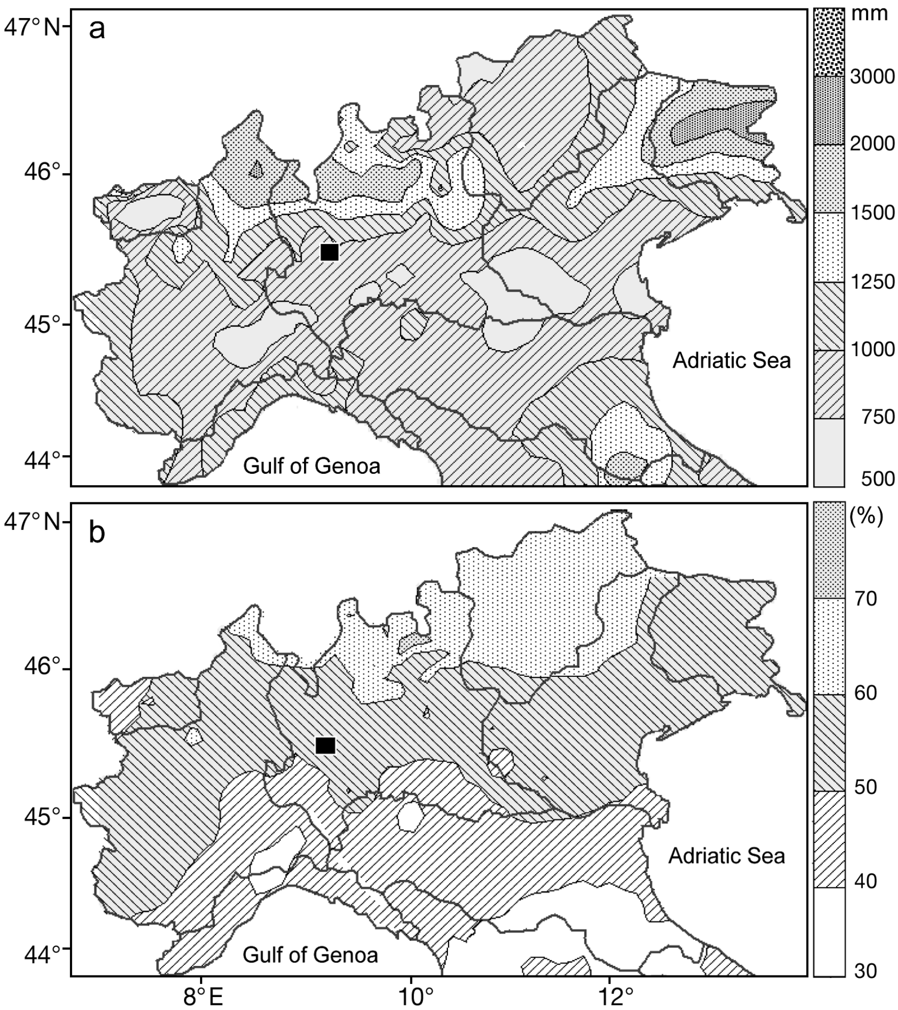

Fig. 3. Mean yearly precipitation in (a) mm and (b) % of yearly precipitation falling from April to September. Displays based on data from 448 stations for the reference period 1951 to 1980. ■: Milan district

P is the annual precipitation (mm): the first sum term (Σ) represents the most erosive rainfalls (thunderstorms and torrential rains) occurring during summer and autumn (i = 5 for June, … i = 10 for October), with 6 multiplicative constants (k_i = 0.7, 0.8, 1.0, 1.0, 0.8 and 0.2), and the second sum term (Σ) is the Food and Agriculture Organisation (FAO) Index (Arnoldus 1977). Different rainfall variables and parameters in Eq. (2) were estimated by Diodato (2004a), who obtained a Pearson correlation coefficient value of r = 0.94.

3.2. Evaluating the model for calibration and validation periods

In order to obtain a useful model, the: (1) calibration of a congruous data set; and (2) validation of an independent data set; followed by (3) an exhaustive description of predictive power and limitations of the model, are needed. These activities are fundamental steps required to obtain a more realistic representation of selected phenomena (Toy et al. 2002).

A preliminary task is the definition of a realistic threshold in order to identify hazardous years. A year can be classified as hazardous if the CHIEF index value is above the threshold represented by the 'tolerable erosion rate' (T), defined as the maximum permissible rate of erosion at which natural soil fertility can be maintained for at least 20 to 25 yr. In order to relate expected CHIEF values against the Boretto Station data during the calibration period (1956 to 1973), contingency diagrams were used (after Wilks 1995). Fig. 4a is an example of a contingency diagram with the assumption of $T = 2$ Mg ha^{-1} yr^{-1}, where the regression predictors in Eq. (1) were selected to simultaneously maximise the Pearson correlation coefficient and the hit rate (HR) (values of 0.77 and 83% were obtained, respectively). HR is the percentage of correct estimates equal to the ratio between the total of hit events in grey cells and the sample total in grey and white cells. Thus, we can conclude that climate erosive forcing in the tth year is hazardous if CHIEF > 1, because the corresponding net erosion is probably >2 Mg ha^{-1} yr^{-1}; conversely, for CHIEF ≤ 1, the climate erosive forcing hazard is negligible. In this context, we can deduce that climate erosive forcing reaches the critical threshold value of 1 when R_t is close to the erosive-resistant climatic function multiplied per α (0.48).

The erosive-resistant climatic function modulates the CHIEF index in different climatic periods. In fact, if after a long period of dry weather there is a transition to a wetter climate with greater rain-erosivity or flood magnitudes, the landscape may produce a high sediment discharge. Conversely, if a period of high rain-erosivity follows a wet period, the hill slopes may be more protected by the vegetation grown during the wet period, or may have been starved of sediments by the previous waterflows. However, a realistic representation of these contrasting phenomena is difficult, given the strong non-linear interdependence among climate, vegetation cover, sediment response, and feed-back phenomena. The speed of evolution of the above-mentioned phenomena is important too: as suggested by Wasson (1996), when the precipitation regime changes gradually, vegetation cover and land use may adjust to the changing moisture regime, and changes in response may be limited; on the contrary, when the discontinuity is abrupt, the shortage of time for adjustment may result in marked changes in erosion and material transport.

The second task is the validation of the CHIEF model. Data from the Pontelagoscuro Station for the validation period (1915 to 1929) were tested against predictions and scored by tallying results into a contingency diagram (Fig. 4b), obtaining a HR equal to 67%.

Another independent performance test was carried out correlating CHIEF predictions with flood frequency data series, both smoothed on a 31 yr running mean using the following digital filter (Polyak 1996):

$$\overline{V_t} = \frac{\left[V_{t-r} + V_{t+r} + (1-\gamma)\sum_{j=-(r-1)}^{r-1} V_{t+j}\right]}{1+\gamma+k(1-\gamma)} \quad (3)$$

where V is the current variable (CHIEF predictions or floods peaks), $r = [(k^{-2}) - 1]$, k is the selected window (31 yr), and γ is the series auto-correlation coefficient for lag = 1 yr. Results are shown in Fig. 5, where the linear regressions are superimposed for the 1775 to 1880 vegetated period (spatial coverage of 42%, Pearson correlation coefficient r = 0.45) and the 1881 to 2003 low-vegetated period (spatial coverage of 30%, Pearson correlation coefficient r = 0.89). The relationships show that the flood peaks closely follow the climate

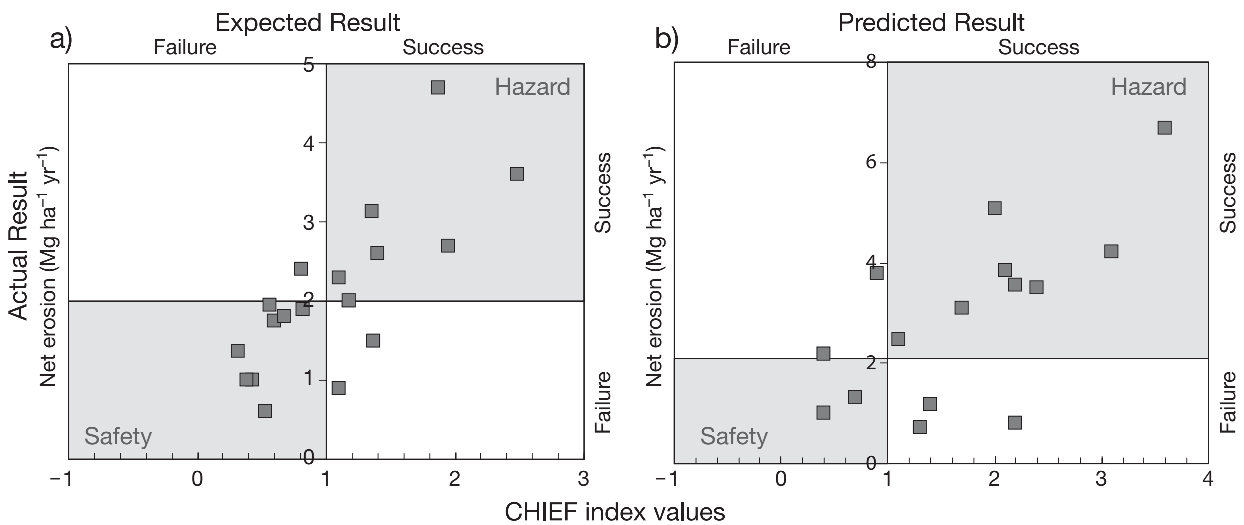

Fig. 4. Contingency diagrams of actual net erosion and expected CHIEF (Climate Hazard Index Erosive Forcing) index values for the (a) calibration and (b) validation samples. Horizontal and vertical lines crossing the 2-Net Erosion and 1-CHIEF threshold values, respectively, separate the safety-hazard cells of success (grey areas) from those of failure (white areas)

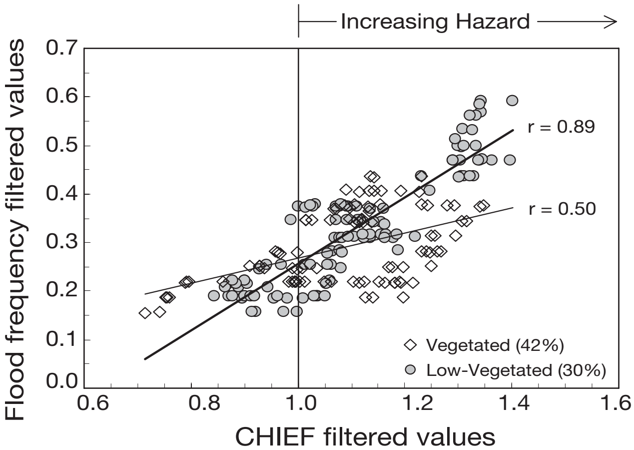

Fig. 5. Filtered values of CHIEF predictions and flood peaks, with linear regressions superimposed on the 1775–1880 vegetated period (◇, fine line) and 1881– 2003 low-vegetated period (●, bold line)

erosive signal, especially for CHIEF > 1, indicating a very good performance. In fact, when close to the CHIEF threshold value, climate erosive forcing and floods magnitude have a similar effect in a vegetated and little-vegetated river basin. However, higher CHIEF predictions (1.1 to 1.4) indicate far higher flood peaks in a de-vegetated basin.

4. CLIMATE EROSIVE FORCING DATA RECONSTRUCTION

The chronological series of the CHIEF index is presented in Fig. 6, where the horizontal grey line represents the threshold hazard. The most erosive periods are grouped into particularly rainy years or months (1810–1814, 1833–1846, 1878–1882, 1896–1905, 1934–1940, 1951, 1959, and 1976–1981) according to the climatic variability of storms over interannual to century scales, which punctuate the sequence of 'normal' years with some that were geomorphologically disastrous. It is also evident that the highest erosive peak occurred in 1976. An important question is whether such single events have become more common or whether there has been a shift in the extreme pattern of more erosive events. Analysis of daily and hourly rainfall would support the view that extreme rainfall became less frequent in northern Italy between 1920 and 1998 (Brunetti et al. 2001), and on the southern peninsular of Italy between 1950 and 2002 (Diodato 2004b). However, a significant increase in the number of daily events belonging to the highest intensity class interval was observed only in northern Italy between 1880 and 2002 (Brunetti et al. 2004). An increase in the power of storm events was recorded in other parts of the world too (e.g. Angel & Hollinger 2005, Riebau & Fox 2005). According to precipitation simulations worldwide that indicate positive changes in extreme events in a future warmed climate, albeit in a non-uniform manner (Meehl et al. 2005), these results are stronger than the corresponding changes in mean precipitation (Hegerl et al. 2004).

Although erosion processes and floods are driven by the hydrologic cycles, they are strongly influenced by historical events and social variables that drive the behaviour of farmers and, more generally, the policies of land management adopted in order to mitigate soil erosion. This is particularly true for the Po Valley, where a strong influence of human activities (manifested as rapid deprivation of the original vegetation) is detectable by at least the Bronze Age (1300 BC); during the Roman Age, at least 60% of the area was deforested and converted to farming. Furthermore, the reference period for this study (from the 18th to the 20th centuries) was characterised by many works carried out on the Po River and its tributaries, which reinforced and raised embankments and reduced the risk of flood inundation (Marchetti 2002).

From a historical perspective, the beginning of the reference period (1790 to 1814) was dominated by the Napoleonic wars; northern Italy, occupied by French armies, was re-organised in the Kingdom of Italy (1805 to 1814). During this period, land degradation was ac-

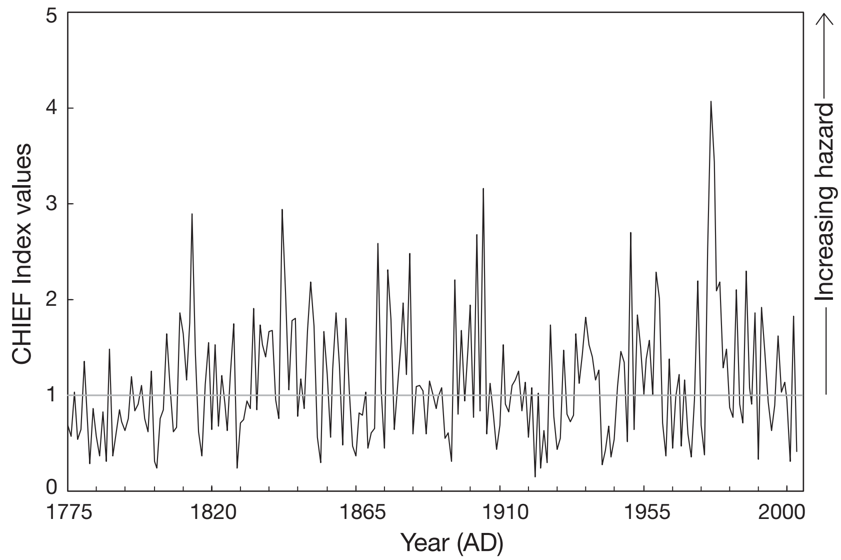

Fig. 6. Chronological series of the CHIEF index (1775–2003) at Milan-Brera Astronomical Observatory

celerated by many causes, listed in the writings of important agronomic writers such as Filippo Re and Carlo Perotti, and by the chief of the Department of Statistics of the Kingdom, the illuminist philosopher Melchiorre Gioia (Vecchio 1974). These causes included: (1) damage directly resulting from war campaigns; (2) instability of government and consequent increase in the misuse of forest areas (e.g. extended cuttings, grazing of goats) owing to insufficient control over the territory; (3) increase in the area exploited for agriculture, further aggravated by the increase in population during the 18th century; (4) sale of vast forest areas previously owned by the church; these forests where immediately cut down by the new owners owing to their low confidence in the stability of the new political regime and their need to re-appropriate money.

During the following phase (1815 to 1859: restoration after the Congress of Vienna), Lombardy and Piedmont were characterized by an important increase in the percentage of territory exploited for agriculture, with: (1) reclamation of new marginal moor lands with problems of acidity and excess of organic matter (Cattaneo 1857); and (2) construction of artificial canals (e.g. Naviglio di Pavia Canal in 1819, various canals in the Vercelli province from 1837 to 1847).

From 1860 the Po Valley was ruled by the new Italian Kingdom, and from 1860 to 1918 the increase in agricultural land area effected during the preceding period was an important factor in the acceleration of erosion processes. This acceleration began in 1870 (the year of the conquest of Rome, which symbolised the achievement of the unity of the new nation). Artificial canals became more common in this period following the construction of Cavour Canal (after 1866) and Villoresi Canal (1881 to 1891).

The period after the First World War was distinguished by a strong increase in the exploitation of marginal lands (e.g. mountainous areas of Apennines) in order to increase the area available for the production of winter cereals (this policy of the fascist regime was named 'battaglia del grano', battle for wealth). This initiated a new increase in erosion rates until 1945. After the Second World War the exponential increase in industrial activities triggered a strong urbanisation of the rural population, with erosion processes relating to land abandonment particularly important in mountainous areas. Land abandonment was only partially followed by reforestation. Furthermore, the need for sand and gravel for the construction of new buildings encouraged the use of in-channel extraction (now illegal but very intense in the 1960s and 70s), a significant causative factor of erosion along rivers. In-channel extraction can produce: (1) significant changes in the shape of meanders, with a reduction in the total length of the river course; (2) significant changes in the shape of channels with modifications of the value and spatial variability of water depth; (3) an increase in the velocity of water; and (4) enhancement of bank erosion. The above-mentioned phenomena have significant effects on erosion, transport and deposition of solid materials (Marchetti 2002).

Historical data presented by Siemoni (1872), Vecchio (1974) and Cantù (2000) on the area of Lombardy (total surface area of region: 2 385 855 ha), vegetated by forests and heaths during the reference period, are presented in Table 1. Forests and heaths can be considered a form of land cover that minimises erosion. In the last part of the 18th century, forest occupied important areas of the Alps and the high plain; in contrast, the majority of the acid soils that dominate the high plain were colonised by natural vegetation dominated by dwarf shrubs such as heathers (*Calluna vulgaris*, *Erica carnea*). A strong reduction in these areas of natural vegetation was observed during the 19th century corresponding to the expansion of agriculture, and a reversal of this trend, with a progressive increase of naturally vegetated areas was observed during 20th century.

Adopting a climatic perspective, it is possible to subdivide the reference period into the sub-periods listed in Table 2, where the main climatic phases are represented. These historical and climatic periods can be

Table 1. Extent (ha) of forests and heaths in Lombardy (total area 2 385 855 ha) from 1796 to 1997 (Siemoni 1872, Vecchio 1974, Cantù 2000)

Year	Forest	Heath and other uncultivated areas	Total	% of total regional surface
1796	576 000	610 642	1 186 642	50
1850	409 000	424 642	833 642	35
1911	386 080	169 656	555 736	23
1936	378 960	168 300	547 260	23
1951	446 439	106 354	552 793	23
1960	464 599	70 071	534 670	22
1970	486 079	66 308	552 387	23
1980	472 549	226 598	699 147	29
1990	493 849	221 016	714 865	30
1997	513 537	221 412	734 949	31

Table 2. Main climatic phases for reference period

Period	Temperature	Precipitation
1764–1821	Gradual decrease	Gradual increase
1822–1880	Gradual increase	Almost stationary
1880–1912	Decrease	Decrease
1912–1920	Increase	Increase
1920–1941	Increase	Decrease until 1930, increase thereafter
1941–1976	Decrease	Almost stationary
1976 onwards	Strong increase	Almost stationary

useful in order to split the time series of the CHIEF index into stationary components with 'fast' and 'slow' variability, in order to identify possible links with environmental changes. The digital time filter presented in Eq. (3) was used for this purpose. The final results are presented in Fig. 7, where 4 main features can be detected. (1) During the period 1790 to 1850, the negative effects (increase in the territory exploited for agriculture and the progression of climatic hazard) are counterbalanced by resilience of the environment and by human activities of mitigation. The result is that the increase in flood events is delayed, and becomes evident only in the last part of the period. (2) During the period 1851 to 1880, the increase in the occurrence of floods is a possible consequence of the instability of the ecosystem owing to the effects of previous changes in land use. In particular, the milder climate (end of the LIA) that characterised the second half of the 19th century was accompanied by a high number of floods in the Po River Valley, with extreme events recorded in 1859, 1860, 1862, 1863 and 1864 (L. Bonardi pers. comm.). (3) During the period 1881 to 1925, the decrease in climatic hazard (with values under the critical threshold from 1910) is in phase with the progressive decrease in flood occurrence with extreme flood events observed in 1889, 1890 and 1892 (L. Bonardi pers. comm.). This can be explained by the little variation in land exploitation which aided the process of restoration of the ecosystem. (4) From 1926 until today, the increase in agricultural mechanisation and area of marginal lands exploited for agriculture exacerbates the consequences of the progression of climatic hazard, giving an increase in flood occurrence. This general picture is maintained after 1960, when land abandonment become the dominant phenomenon in mountain territory

With these multiple time lines, it can be argued that in the Mediterranean region the climate erosivity fluctuations are forced by zonal circulation (after Hurrell 1995, Slonosky et al. 2000), the variability of which can be used as a measure of climatic system equilibrium for middle latitudes (Lockwood 2001). On the climatological scale, this variability exhibits jumps represented by phase changes in the NAO index (Werner et al. 2000). In particular, during the 20th century, 3 main abrupt jumps (1912, 1941 and 1976) were observed, which defined 4 main climatic phases (Karl et al. 2000): (1) 1880 to 1912: weak winter westerlies over Europe; decrease in global mean temperatures; (2) 1912 to 1941: strong winter westerlies over Europe, increase in global mean temperatures; (3) 1941 to 1976: weak winter westerlies over Europe; decrease in global mean temperatures; (4) 1976: strong winter westerlies over Europe, increase in global mean temperatures.

The existence of a relationship between these abrupt global climatic changes and the behaviour of the

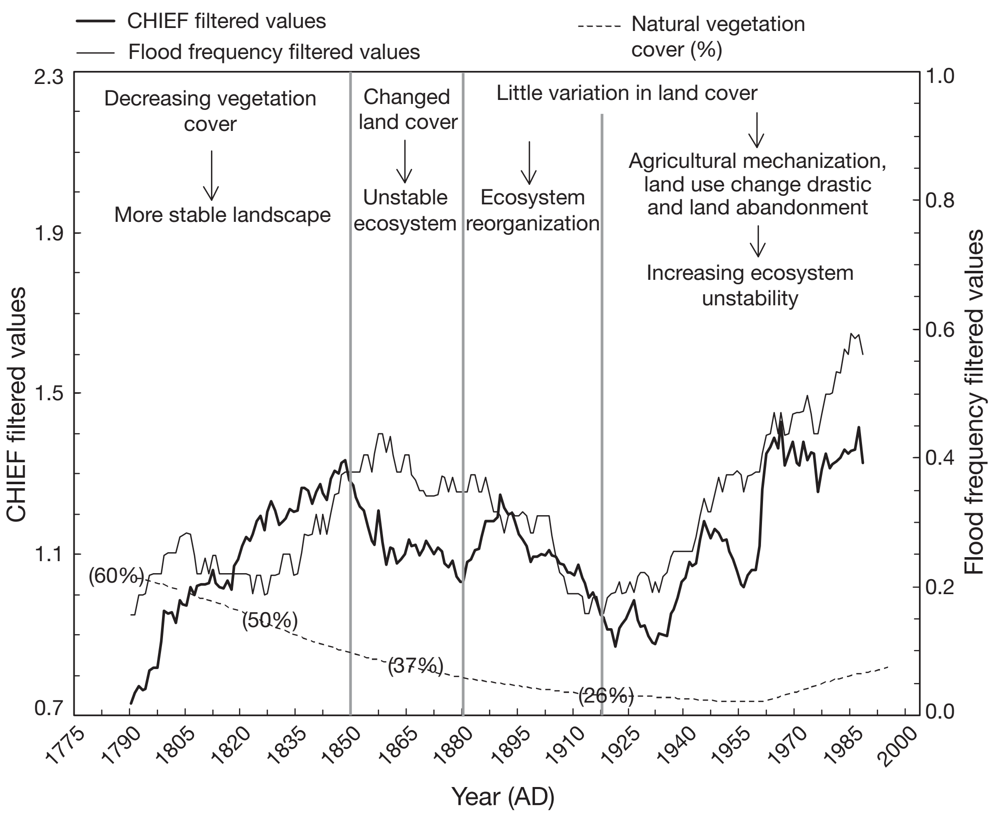

Fig. 7. A 31 yr running digital filter of the CHIEF index, flood series and variation in vegetation cover (wood + heath + grass) from 1790 to 1989, with superimposed discontinuities (vertical grey lines) associated with the main environclimatic changes that took place in the upland Po River Basin surrounding the Milan district

CHIEF index can be hypothesised; in particular, the CHIEF index (Fig. 7) shows the main changes of phase (in 1922, 1945, 1960 and 1960). (1) The global climatic change of 1912 is followed by a change in the behaviour of the CHIEF index, with a transition from low to high values; (2) The global climatic change of 1941 is followed by a temporary decrease in the CHIEF index from 1945; (3) A new abrupt change in the CHIEF index is observed in 1960, with a strong increase.

This relationship between the CHIEF index and global climate must be considered with caution, owing to the large number of non-climatic factors influencing the index. Nevertheless, it is reasonable to assume that the strong influence of global climatic shifts on regional precipitation and temperature can result in a change in erosive forcing.

5. CONCLUSIONS

In this study we implemented, calibrated and validated an empirical dynamical model in order to characterize the behaviour of erosive climatic hazard in the Po Valley. The results obtained show that the model is able to describe some hydrological features of the upland and midland Po Basin. Some evaluations were presented in order to point out the possible relationships existing between historical and social events during the period 1775 to 2003. The link with the variability of climate during the period was also discussed.

The results suggest that the response of the Po River Basin to climate erosive change is highly influenced by local land-cover conditions; this means that the historical land-use changes in the study area have a strong impact on the typology and strength of hydrological events. Future improvements on this study could focus on new time series of erosion, useful for the calibration and validation of the model for other territories inside and outside the Po River Basin.

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