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A GEOSTATISTIC APPROACH TO THE MAPPING OF RAINSTORM HAZARD IN THE SANNIO DISTRICT OF THE CAMPANIA APENNINES (SOUTHERN ITALY)

ABSTRACT: DIODATO N. & RUSSO F., *A geostatistic approach to the mapping of rainstorm hazard in the Sannio district of the Campania Apennines (Southern Italy).* (IT ISSN 0391-9838, 2003).

In this note we maintain that the frequent rainstorms in the Sannio district, Campania, Italy, are to all intents and purposes morphogenetic agents. From a documentary survey we have carried out it is evident that this kind of meteorological event greatly influences the lithological, forest and anthropic elements of the landscape, often producing non-reversible changes to the general physiographic order. Besides direct and documentary observations, the effects of rainstorm erosion on the landscape are also clearly cited in the specific literature.

We used a geostatistic approach to survey the spatial variability of rainstorm days occurring in the Sannio district (Province of Benevento) and in the surrounding area from 1981 to 1999. The data have enabled us to draw up a map aimed at identifying areas characterised by recurrent rainstorm events.

The techniques applied to elaborate the data are those typically used in geostatistic surveying. Firstly, we began with a structural survey with calculation of semivariance. A mathematical model was adapted, then a test of cross validation was applied to the obtained data. Finally, we used the punctual ordinary Kriging as a technique of linear interpolation of the data. All the data were elaborated using MS Windows-compatible software available on the Internet.

The result obtained is a map of distribution of the frequency of rainstorm days in the Sannio district and surrounding areas. As regards specifically erosive effects, we can deduce from the map that the areas characterised by the high recurrence of days with violent downpours are potentially those where hydrogeologic instability is or will be particularly marked, with subsequent negative socio-economic consequences and damage to the landscape. In this way, the phenomenon of violent rainstorm days constitutes a significant item in environmental risk.

KEY WORDS: Geostatistic, Rainstorm hazard, Hazard mapping, Soil erosion, Province of Benevento (Italy).

RIASSUNTO: DIODATO N. & RUSSO F., *Un approccio geostatistico per la mappatura della pericolosità da nubifragio nel Sannio beneventano (Appennino Campano, Italia meridionale).* (IT ISSN 0391-9838, 2003).

In questa nota si attribuisce al fenomeno dei nubifragi, che colpiscono con discreta frequenza il Sannio beneventano, il ruolo di agenti morfogenetici. Oltre che dalle osservazioni dirette e documentaristiche, l'effetto in termini di erosione dei nubifragi sul paesaggio è accertato ampiamente anche dalla letteratura specifica. Infatti, dall'analisi documentaristica effettuata si rileva che questo tipo di eventi meteorici impatta profondamente sugli elementi litologici, agro-forestali ed antropici che caratterizzano questo territorio, determinando spesso modifiche irreversibili al suo assetto fisiografico generale.

In questo articolo è stata esaminata con approccio geostatistico la serie dei nubifragi occorsi nel Sannio beneventano ed aree immediatamente limitrofe nel periodo 1981-1999; l'estrema variabilità spaziale dei dati ha consentito una opportuna mappatura finalizzata alla individuazione di aree caratterizzate da diversa ricorrenza del fenomeno.

Le tecniche usate per l'elaborazione dei dati sono quelle classiche dell'analisi geostatistica: si è proceduto per prima cosa all'analisi strutturale con calcolo della semivarianza; un modello matematico è stato adottato, poi, ai dati ottenuti sui quali è stato applicato un test di *cross validation*, infine si è usato il *Kriging* puntuale ordinario come tecnica di interpolazione lineare dei dati. Nel loro complesso i dati sono stati elaborati utilizzando procedure *friendly* per PC-Windows disponibili in rete.

Il risultato ottenuto è una carta della distribuzione e frequenza dei nubifragi nel Sannio beneventano ed aree limitrofe. Con riguardo ai soli effetti erosionali, da questa mappa si deduce che le aree caratterizzate da elevata ricorrenza dei nubifragi sono potenzialmente quelle dove più marcato è o sarà il dissesto idrogeologico, con ricadute anche sul piano socio-economico ed agro-forestale. In tal senso il fenomeno nubifragi si connota come elemento di pericolosità che può incidere anche in termini di rischio ambientale.

TERMINI CHIAVE: Geostatistica, Pericolosità da nubifragi, Cartografia della Pericolosità, Erosione del suolo, Provincia di Benevento.

INTRODUCTION

Among the phenomena that model the Apennine landscape in a catastrophic way are undoubtedly the rainstorms. This is due to their particular characteristics: hydro-meteorological events in the form of violent down-

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pours that occur in a landscape already heavily modelled by human activity and which determine various types of instability. The rainstorm, therefore, is not only a meteorological phenomenon, but a markedly more complex event. It includes various factors which work together, such as local geomorphology, vegetation cover, agricultural practices, man-made infrastructures present in the area, etc.

Among the effects produced by a rainstorm are the mobilisation of soil and the relative loss of functionality of the productive agricultural system. In this regard, the occurrence of a rainstorm in a particular geographical area means there is the real possibility of instability or degradation of environmental conditions typical of the area and therefore without doubt represents a hazard.

Due to its geo-environmental characteristics the Sannio district (Province of Benevento) has always regularly experienced the inauspicious effects of violent storms both in terms of damage to man-made structures and soil erosion (the area's fertile soils are an important productive resource for the region). As regards this last aspect it is important to consider that in the area, since the end of World War II, there has been a simplification in the structural pattern of the countryside, due both to the reduction in hedgerows and bushes and to the indiscriminate use of agricultural mechanization and chemical fertilisers and pesticides. This is the latest phase of a long period of historical transformation by man of the agricultural and forest landscape of the Sannio area (Diodato, 1999a). Even though the problem of environmental degradation has recently been put down to non-local factors, such as climatic variations (Ortolani & Pagliuca, 1994), soil losses variable from 20 to 40 t ha^{-1}, with exceptions beyond 100 t ha^{-1}, occurring due to erosion associated with storms, with a frequency of every 2 or 3 years, have been regularly estimated in Europe (Morgan, 1995). In Italy, extreme rainfall events able to transport large amounts of sediments in worked soils occur commonly (Chisci & *alii*, 1990; Bazzoffi & *alii*, 1997; Diodato, 1999b). It appears evident that violent rainstorms are an environmental hazard and inevitably represent risks in the areas affected by these phenomena.

This note attempts to extend the study, geostatistically, of the incidence of rainstorms in the Sannio area of the Campania Apennines. We illustrate our methodological approach to the problem of analysis and cartographic representation of data that testify to what is a rapid environmental evolution of the landscape.

THE STUDY AREA

The area of Sannio, which approximately coincides with the administrative boundaries of the Province of Benevento (fig. 1), is located, in southern Italy, in the internal part of the Campania Apennines. It is mainly hilly with wide valley bottoms, but with few mountainous zones. It is not open to the sea but has a Mediterranean climate with continental tendency, typical of the internal Apennine areas. Large rivers cross the region (Calore, Fortore, Sabato, Tammaro) with numerous tributaries, which cut through an essentially clayey landscape. It is due to these geographic characteristics that this region, due to the lithological complexity of outcropping sediments and its high seismicity, is characterised by hydrogeological instability. This is widespread and often extensive, and negatively influences, in terms of conservation and soil management, the local socio-economic situation. The local economy is composed of agricultural activities with development of seed nurseries and highly productive specialised crops (*eg.* fruit, vine and olives). Furthermore, deforestation and intensive human activity have made the area particularly fragile, prone to accelerated morphogenetic processes, which result in widespread and high impact erosive phenomena (Diodato, 1999b; De Paola & Diodato, 1999).

FIG. 1 - Location of the Sannio district of Benevento (grey area) in Southern Italy.

In the north-western sector of the study area («Fortorina» area), for example, woodland has gradually been replaced by herbaceous crops, leaving uncultivated those areas where soil and morphological conditions were not suitable for working (Leone & Sommer, 1996).

METHODOLOGY AND DATA ANALYSIS

In recent years we have observed that the greatest potential instability of the agro-ecosystems in the Sannio area occur during intensive rainfall events. This instability is shown by the triggering of erosive processes which worsen unstable local situations, often already critical, determined by human intervention and by the geomorphological characteristics of the area. The spring-summer periods are those in which these events systematically occur, with a duration varying from several minutes to a few hours. The rainstorms strike from time to time different localities with erosive effects being most evident in areas where there are torrents and in agricultural areas. They can result in the total removal of the soil layer (storm of 29 May 1999) or instability phenomena such as landslips and slides (storms of 8 and 29 July 1999). When there is a hailstorm (rainstorms of 14 May and 8 June 2000 and May 2001) the energy in play is even higher, to the point that the seasonal landscape is devastatingly modified. There is formation of erosion rills and channels that cut the slopes, flattening of crops, defoliation of trees, destruction of orchards and vines.

Although there are rarely rainstorms in winter, they have become more common in the area and with wider-ranging effects than in the past. In fact, after the rainstorm of 13 November 1997 a State of Natural Calamity was declared for the whole Province of Benevento and surrounding areas.

Spatial sampling and georeferencing system

All the administrative districts were examined. This coincides with most of the municipal districts of the Province of Benevento and neighbouring Provinces affected by the rainstorms in the period 1981-1999 (Archives of the Inspectorate of Agriculture of Benevento, STAPA - Cepica, Campania Region). The data relative to 80 sampled districts were georeferenced in plane co-ordinates according to the UTM 33N referencing system and, as can be expected, the distribution of sampled points, in agreement with Sharov (1996), is random (fig. 2).

Analysis of the data examined and their mapping were not simple, given the extreme spatial variability of the rainstorms. Production of the maps involves estimating values in points where data is not available. This means that it is necessary to study and characterise the most relevant variables, select them carefully and chose the most appropriate estimation procedure.

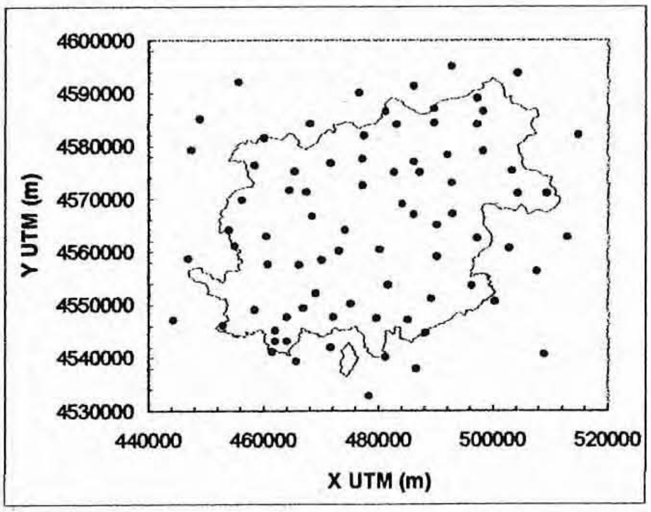

FIG. 2 - Representation of the area of data coverage with indication of samplings (points) and administrative boundaries of the Sannio district.

Geostatistical analysis

The total number of rainstorms (NU) occurring in the period 1981-1999 was elaborated with geostatistical techniques (Bruno & Raspa, 1994; Castrignanò & Stelluti, 2001) with the aim of estimating their spatial variability and of producing maps of interpolation. The procedure essentially consists of the following three phases:

a) *Structural analysis* with: (1) calculation of the experimental *semivariance* for the chosen variable; (2) adaptation of one of the mathematical models allowed by the *semivariance* values previously calculated;
b) Assessment of the reliability of the procedure by means of a *cross-validation* test;
c) Use of a technique of linear interpolation like «Kriging».

In analysis of spatial data, and particularly in climatic-environmental data, it often happens that the values observed in some zones of the area have a great variability compared to values in other areas. Therefore the hypothesis of homogeneity of the variance was assessed by testing the coefficient of correlation (with respect to the hypothesis of correlation zero with the *student* test) between the mean and the variance calculated within each of the 4x4 mobile windows, obtaining an insignificant relation between them of 95%. This allows us immediately to assume the basic geostatistical hypothesis of *intrinsic stationariness.*

Another concept of classic geostatistics is the assumption of spatial continuity, which says that it is plausible that samples closer together are more similar than more distant samples. Among the various statistical techniques that translate into formal terms and, therefore, to quantify the degree of «similarity» between the samples, there is the so-called *semivariance.*

The values of *semivariance* $\gamma(h)$ were calculated on the couples of values separated by all the possible distances h according to the expression:

$$\gamma(h)=\frac{1}{2n(h)}\sum_{i=1}^{n(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \qquad i=1,\ldots,n(h)$$

where $n(h)$ represents the number of couples of samples separated by the distance $\boldsymbol{h}$; $Z(x_i)$, the observed value of the storm variable (NU) in station x_i and $Z(x_i+h)$ the value of the same variable in the station separated by x_i of the distance vector $\boldsymbol{h}$.

The *semivariance* values in function of $\boldsymbol{h}$ (or semivariogram) can be useful to indicate the nature of the intrinsic spatial variability of the samples: if the variability is completely random, so the values of *semivariance* are approximately constant for any value of $\boldsymbol{h}$. On the other hand, if the hypothesis of spatial continuity is plausible, these values increase with increasing distance of separation ***h*** to the point of reaching an approximately constant value.

For a quantitative description of spatial variability and for interpolation it is necessary to adapt one of the authorised mathematical models to the semivariogram, chosen between the positive semi-definite functions which assure that the variances of each linear combination of functions is not negative. The adaptation of the function is based on a regression weighted according to the minimum squares criterium of optimisation. In our case we used the exponential model given by the function:

$$\gamma(h) = C_0 + C_1\left[1 - \exp\left(-\frac{h}{a}\right)\right]$$

where a, C_0 and C_1 are parameters of the model known, respectively, as «*Range*», «*Nugget*» and structural coefficient; the latter summed with the «*Nugget*» by the «*Sill*» (C_0+C_1). The physical interpretation of these parameters is that the *Range* represents the distance beyond which the variability of the samples is completely random; the *Nugget* is an estimate of the variance that in part can be attributed to heterogeneity at a scale smaller than the sampling interval and in part to measurement error; C_1 is a non-null parameter only if the variability is not random and the *Sill* is theoretically equal to the total sampling variance.

In order to verify the suitability of adaptation of the pre-selected model a procedure of *cross-validation* was carried out. This consists in a recursive process in which at each phase one observation at a time is eliminated and estimated using the remaining samples. The estimated value and the observed value are compared, and the difference constitutes the experimental error. The whole of their values can be analysed according to three statistics: 1) the arithmetic mean of the experimental error (AMEE), 2) the mean squared error (MSE), 3) the mean standardised squared error (MSSE). The values of AMEE should be close to 0 (absence of systematic error), like those of MSE, whereas those of MSSE should be close to unity. In formula the three statistics are given by:

$$AMEE = \frac{1}{N}\sum_{i=1}^{N}\left[Z(x_i) - Z^*(x_i)\right]$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left[Z(x_i) - Z^*(x_i)\right]^2$$

$$MSSE = \frac{1}{N}\sum_{i=1}^{N}\left\{\frac{\left[Z(x_i) - Z^*(x_i)\right]}{\sigma_K(x_i)}\right\}^2$$

where N is the number of points measured, $Z(x_i)$ is the value measured in point x_i, $Z^*(x_i)$ is the estimated value in the same point x_i, obtained using the remaining N - 1 values measured, and $\sigma_K(x_i)$ is the standard deviation of Kriging in point x_i.

The final phase of the geostatistical approach is the interpolation of the values of NU according to a prefixed grid, using ordinary point Kriging, which uses the semivariogram models and the measurements of NU to estimate values in points where there are no observations. The interpolated data, indicated with $Z(x_0)$, are obtained from the linear expression:

$$Z(x_0) = \sum_{i=1}^{N}\lambda_i Z(x_i)$$

in which N represents the number of points measured x_i used for interpolation in point x_0; $Z(x_i)$ the measured values of NU in points x_i; λ_i the weighting factors that depend on the semivariogram model adapted and on the relative positions of the observation points.

The Kriging uses the results from the previous structural analysis, relative to the characteristics of continuity of the measured variable, plus the information on the geometry of the surroundings used for the interpolation. In short, Kriging represents an improvement compared with traditional linear interpolators, because it takes spatial structure into account and considers the effective redundancy of data (spatial autocorrelation) so reducing the estimation error. In addition it gives, besides the estimated value, an important property, also its variance, which can be assumed, in the case of a Gaussian distribution, as an indication of its reliability.

Data elaboration

The classic statistical analysis and geostatistical analysis were carried out using MS Windows-compatible software, as Esri-Arcview, and other available on the Internet (http://137.204.60.110 of the Didactic Laboratory of the University of Bologna and www.usyd.edu.au/su/agric/acpa/vesper/vesper.html of ACPA - Australian Centre for Precision Agriculture).

The sampling distribution of the values of NU has a *skewness* coefficient (tab. 1) close to zero, so it can be assumed to be sufficiently symmetrical, but gives a shape parameter (*kurtosis*) which is quite far from normality. The statistical parameters calculated show, furthermore, the extreme spatial variability of NU. The non-normality of the sample (with a bimodal distribution, (fig. 3) therefore means that the Kriging variance is not appropriate as a measurement of error, even if the process of estimation for the production of the map is still valid (Zucca & *alii*, 1999).

TABLE 1 - Statistical values of NU on the original data

	ND	Mean	St Dev.	Var. Coeff.	Skewness	Kurtosis
NU	80	5.18	3.88	74.9%	0.34	1.92

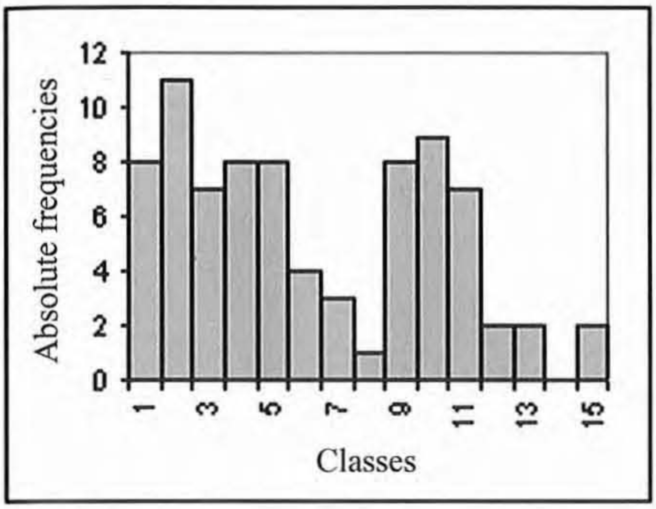

FIG. 3 - Frequency distribution of the rainstorms.

An isotropic semivariogram was calculated, considering only the modules of the distance between the observations. This because the limited number of observations, together with their irregular distribution, did not allow a reliable verification of possible anisotropies. In this regard it is worth remembering that several authors (Chua & Bras, 1980) believe that the meteorological structure of a rainstorm is not isotropic. However, as, in this particular case, the phenomena were aggregated over a long period (19 years), one expects less spatial variability with respect to the individual event. The hypothesis of isotropy therefore seems plausible, even though it cannot be expected that the sampling adopted is able to give a high level of precision on short-lasting phenomena (for example on an hourly or daily basis).

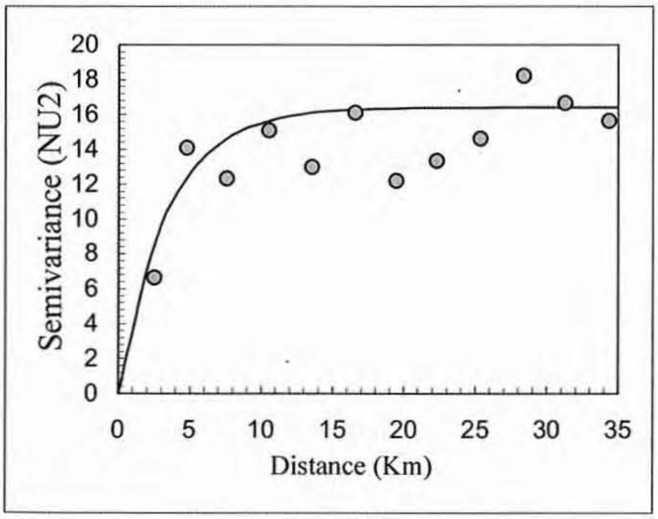

FIG. 4 - Experimental (points) and theoretical (curve) semivariogram relative to the variable NU.

A mathematical model was therefore adapted to the experimental semivariogram. The model's reliability was verified according to the Akaike criterium *(Akaike Information Criteria)* implemented in the VESPER (*Variogram Estimation and Spatial Prediction with Error*) software program developed by ACPA. The semivariogram of NU was calculated at intervals (*lag*) of 2.5 km, which assured the presence of a sufficient number of pairs of experimental points for each lag class. This calculation was extended to a maximum distance of 35 km, corresponding approximately to half the maximum size of the study area (fig. 4).

An exponential model was adapted to the experimental semivariogram. Its parameters are: *Nugget* = 0.0; *Range* = 3.6 Km e *Sill* = 15.6 (γ^2).

The semivariogram of figure 4 is well structured, which indicates a sufficient degree of continuity of the variable NU also at distances of a few kilometres. Furthermore, the value of *Range* is compatible with the range (< 6 km) of the area affected by phenomena which have a local origin and evolution, specifically those thermoconvective cells harbingers of the violent rainstorms object of this study. This agrees with the characteristics of the Kriging, which is essentially a local interpolator, as it is the samplings closest to the point of interest that have the greatest influence on estimation and variance.

The *cross-validation* was a good adaptation of the model of variogram chosen, because the AMEE (–0.07) and MSSE (1.06) errors were sufficiently close to 1 and 0, respectively.

The model of variogram previously described was therefore used in the following phase of interpolation with the ordinary Kriging, so allowing production of the map (fig. 5) of estimation of the number of rainstorms (NU).

DATA INTERPRETATION AND CONCLUSIONS

From the map of figure 5 we can identify the areas where storms are more common and without doubt these are areas that potentially experience storm-related erosion and/or damage. From a strictly geomorphological point of view it seems evident that particularly in these areas there is a higher potential predisposition to erosive processes and especially to those processes associated with rainfall impact and diffuse or concentrated rilling. Therefore, they are areas with an accelerated evolutive dynamics of the landscape, particularly in areas characterised by agricultural or forestry practices.

This interpretation of the data also indicates a clear state of hazard (*sensu* Russo & Valletta, 1993) for these areas which exists at specific seasonal time intervals, considering the particular meteorological phenomenon studied. In fact, given the origin of the data (Archives of the Inspectorate of Agriculture of Benevento, STAPA - Cepica, Campania Region) and our *a priori* analysis of the data we can see that the rainstorms studied have effectively had a significant local impact in terms of widespread soil ero-

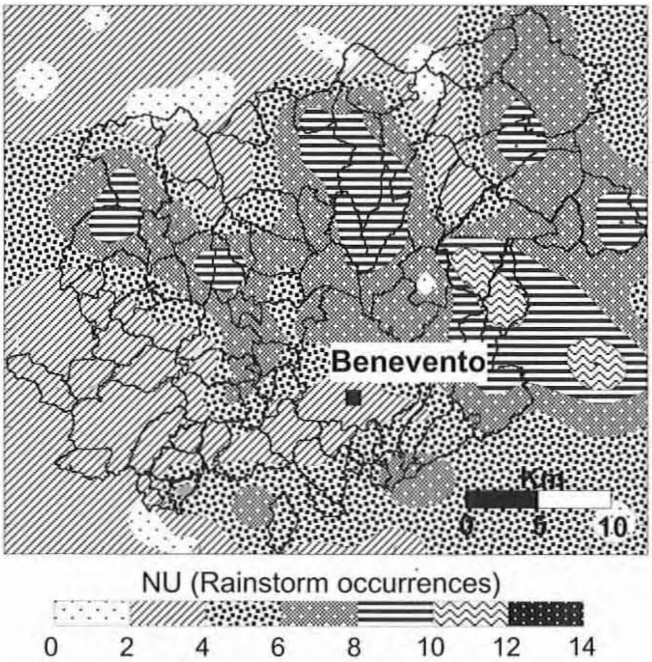

FIG. 5 - Map of the estimate of number of rainstorms (NU) occurring in the period 1981-1999 in the Sannio district and surrounding areas (the basic map shows only the municipal boundaries).

sion, together with damage of varying entities to man-made structures and infrastructures. In this regard, there is a clear situation of environmental risk (*sensu* Russo & Valletta, 1993) in the Sannio area, which is the district most frequently struck by this violent phenomenon.

Furthermore, from a preliminary comparison of the map of fig. 5 with other maps in the literature, considering the main geoenvironmental features of the study area (vegetation map, geological map, soil map, etc.), we can see that the areas most affected by violent rainstorms are also characterised by lithologies particularly prone to erosion (arenaceous-argillaceous-marly formations) or by agricultural practices that are precarious or unsuitable. However, this is something which still needs to be investigated, so as to relate the number and frequency of rainstorms, identified with this research, to geoenvironmental characteristics of the study area, thereby illustrating the possible consequences in terms of hazard and environmental risk.

Finally, still from examination of the map in fig. 5, it is possible to obtain, even if indirectly thanks to the geostatistical analysis, useful information on the occurrence of storms above all for those areas where there are no instrumental data or direct observations. It can happen that, during a rainstorm the most violent rain torrents might escape detection due to the sparse density of gauges, with respect to the variability of the phenomenon and its highly localised character. This mapping technique therefore enables us to extend considerations of hazard and environmental risk to areas uncovered by direct observations.

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