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Soil erosion caused by extreme rainfall events: mapping and quantification in agricultural plots from very detailed digital elevation models

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Abstract

This paper presents a method that can be used to quantify and map soil losses at field scale produced by extreme rainfall events. The amounts of sediment produced by overland flow and concentrated overland flow (inter-rill, rill and gully erosion) at the agricultural plot scale are evaluated from elevation differences computed from very high resolution digital elevation models (DEMs), from before and just after an extreme rainfall event. Geographical Information Systems (GIS) techniques are used to analyse the multi-temporal spatial data. The research case study presented makes reference to a mechanised vineyard plot located in the Alt Penedès–Anoia region (Catalonia, Spain). The rainfall event, which occurred in June 2000, registered 215 mm, 205 mm of which fell in 2 h 15 min. The average intensity of the downpour was 91.8 mm h^{-1}, with a maximum intensity in 30-min periods of up to 170 mm h^{-1}. The erosivity index R reached a value of 11,756 MJ ha^{-2} mm h^{-1}, 10 times greater than the annual value for this area. The volume of soil detached by the rainfall, as measured by the proposed method, was 828 ± 19 m^3. About 57% of those materials were deposited in other parts within the same plot. The balance was negative, with a total 352 ± 36 m^3 of soil loss from the plot, which represented a rate of 207 ± 21 Mg ha^{-1}. The paper analyses the characteristics of the rainfall event in relation to historical data and discusses the proposed method for soil erosion mapping at plot scales in relation to other measurement methods.

Keywords: Extreme rainfall event; Soil erosion; Plot scale; DEM; Catalonia

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1. Introduction

The Mediterranean environment is known globally for limited water and flooding, and for erosion phenomena caused by heavy downpours. The spatial and seasonal variability of rainfall follows a complex pattern, with wide and unpredictable rainfall fluctuations from year to year. The principal rainy season is September–November. Extreme rainfall events are not rare phenomena during these months, which usually are of high intensity (Llasat and Puigcerver, 1992, 1994; López-Bermúdez and Romero-Díaz, 1993; Ramos and Porta, 1994; Santos, 2000). Those frequent high intensity rainfalls, which occur after a very dry summer, and the high climatic fluctuation in short- and long-term (especially in rainfall quantity), have been pointed out as the main climatic characteristics affecting the vulnerability of the Mediterranean basin to erosion (Imeson, 1990; Poesen and Hooke, 1997). The other important rainfall period corresponds to spring, in which rainfalls are mainly of large duration and low intensity.

Regarding the occurrence of extreme rainfall events, different research works have recently stressed the importance of soil erosion in the Mediterranean basin under distinct land use/cover conditions (Poesen and Hooke, 1997). Other factors, such as abundance of unconsolidated parent materials (marls, limestones and sandstones) (Poesen and Hooke, 1997; Martínez-Casasnovas, 1998), rainfed crops that partially cover the soil (vineyards, almond and olive trees), abandonment of land and/or removing of soil conservation measures (Cerdà, 1994; Chisci, 1994; Porta et al., 1994; Pastor and Castro, 1995; Martínez-Casasnovas, 1998; Usón, 1998), also constitute favourable conditions for soil erosion by water and contribute to accelerated erosion processes.

The results of soil loss associated with extreme rainfall events show great temporal variability. Vineyards are the lands that incurred the highest soil losses: 47–70 Mg ha^{-1} year^{-1} in NW Italy (Tropeano, 1983), 35 Mg ha^{-1} year^{-1} in the Mid-Aisne region (France) (Wicherek, 1991), 22 Mg ha^{-1} year^{-1} in the Penedès–Anoia region (NE Spain) (Usón, 1998), 34 Mg ha^{-1} in an extreme rainfall event in SE France (Wainwright, 1996a,b), or 18–22 Mg ha^{-1} due to rill erosion measured at plot scale between September and November (Ramos and Porta, 1997). Due to difficulties in measuring soil loss at agricultural plot or field scales, it has been traditionally based on estimations from runoff plots measurements (Rubio et al., 1994; López-Bermúdez et al., 1998; Yu et al., 1998; Pickup and Marks, 2000). The results obtained, as in most of the above mentioned cases, overlook losses by ephemeral gully and/or gully erosion, computing losses by default. The last, according to research conducted by Poesen et al. (1996), Poesen and Hooke (1997) and Martínez-Casasnovas (1998), are far from negligible and may comprise 44–80% of the total soil lost.

Methods for measuring soil and parent material loss due to gullying (ephemeral as well as larger gullies) have been traditionally based on stakes and profiling (Zinck, 1997), on the application of photogrammetric techniques to map the volumetric changes in gullies (Thomas et al., 1986; Dymond and Hicks, 1986; Poesen et al., 1996), or on the comparison of cross-sections obtained from very detailed topographical surveys at different dates (Casalí et al., 1999). Most recently, the convergence and extension of photogrammetry, digital imaging technology and geographical information systems (GIS) have contributed to the use of multi-temporal digital elevation models (DEMs) to compute sediment production by gully erosion (DeRose et al., 1998; Martínez-Casasnovas, 1998; Betts and DeRose, 1999).

The objective of this paper is to quantify soil losses at the field scale produced by an extreme rainfall event. The amounts of sediments produced by overland flow and concentrated overland flow (inter-rill, rill and gully erosion) at the agricultural plot scale are evaluated from elevation differences computed from very high resolution DEM, from before and just after the extreme rainfall event. The event, which occurred in Catalonia (Fig. 1) in June 2000 and, among others, caused a loss of several human lives. The flooding of the drainage ways

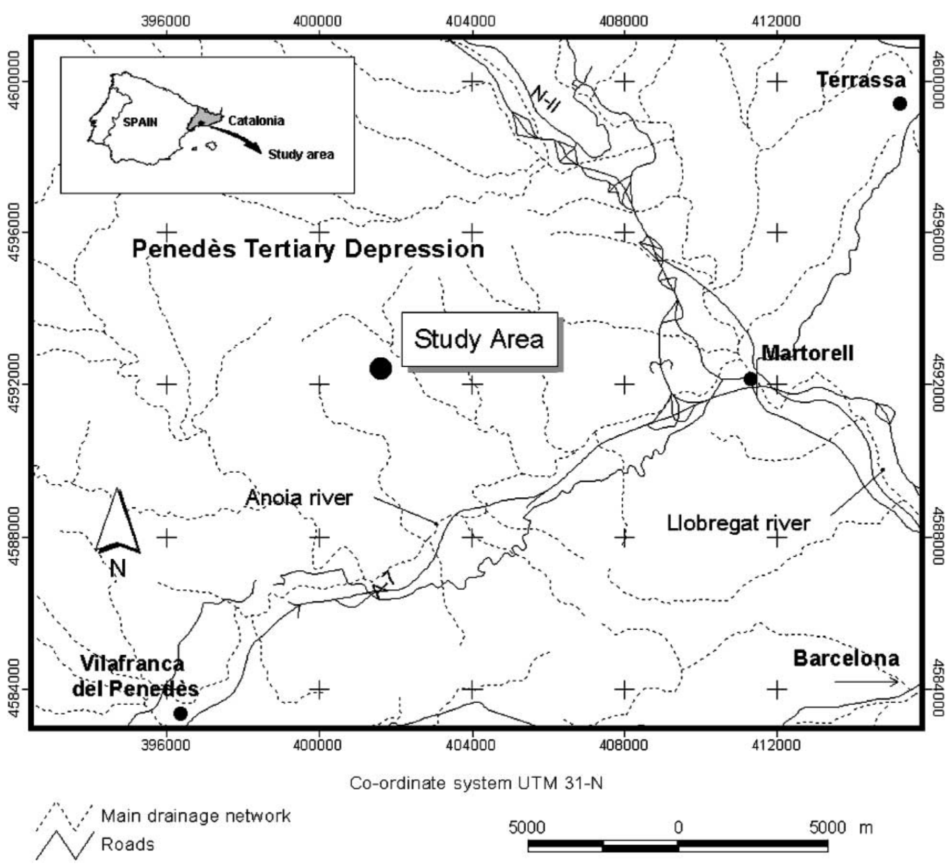

Fig. 1. Location of the study area.

produced very severe damage to road networks as well as in other infrastructures, and exceptional sediment movement.

The method proposed also allows evaluation and mapping of the contributing sediment and deposition zones within the plot. The effect of this storm was measured for a mechanised vineyard plot located in the Alt Penedès–Anoia region (Catalonia, Spain) (Fig. 1), and storm characteristics for the rainfall event were set in the context of historical data.

2. The study area

The Alt Penedès–Anoia region is located in Catalonia, about 30 km southwest of Barcelona, between the Sierra Prelitoral mountains and the Anoia and Llobregat rivers (41°28′N, 1°48′E). The land use is mainly for vineyards, which represents 80% of the cultivated area. This area is part of the Penedès Tertiary Depression, where calcilutites (marls) and occasional sandstones and conglomerates crop out as main lithological materials. Soils are highly calcareous. According to soil taxonomy (Soil Survey Staff, 1998), they are classified as *Xerorthents typics*, *Calcixerepts typics*, *Calcixerepts petrocalcics* and *Haploxerepts fluventics* (Martínez-Casasnovas, 1998). Most soil profiles have been truncated by hydric erosion and underlying horizons are now at the surface. Another important characteristic of the area is the dissection of the landscape by a dense and deep network of gullies. Inter-gully areas are usually undulating to rolling, with complex slopes. The gullies are characterised by vertical sidewalls and are between 11–60 m deep and 75–350 m in width (Martínez-Casasnovas, 1998).

The climate is Mediterranean, with mean annual temperatures of about 15 °C and an average annual rainfall of 600 mm, which is very irregularly distributed seasonally. The main erosive rainfalls are usually recorded during September to November, with high intensity in short periods of time (>100 mm h^{-1}), whereas the rainfalls recorded during spring are usually of long duration but low intensity. The rainfall erosivity factor R varies between 1049 and 1200 MJ mm ha^{-1} h^{-1} $year^{-1}$ (Ramos and Porta, 1994).

3. Materials and methods

3.1. Plot characteristics

The vineyard plot which is the subject of the present study has an area of 21,200 m^2 (175 m long × 125 m width). The average slope of the plot is 8.9% (Fig. 2). The planar form of the slope is mainly rectilinear, with few concavities. The plantation consists of trained vines, at 1.3 m spacing along rows and 3.1 m spacing between rows, which run along the contour. Every eight rows, there is a

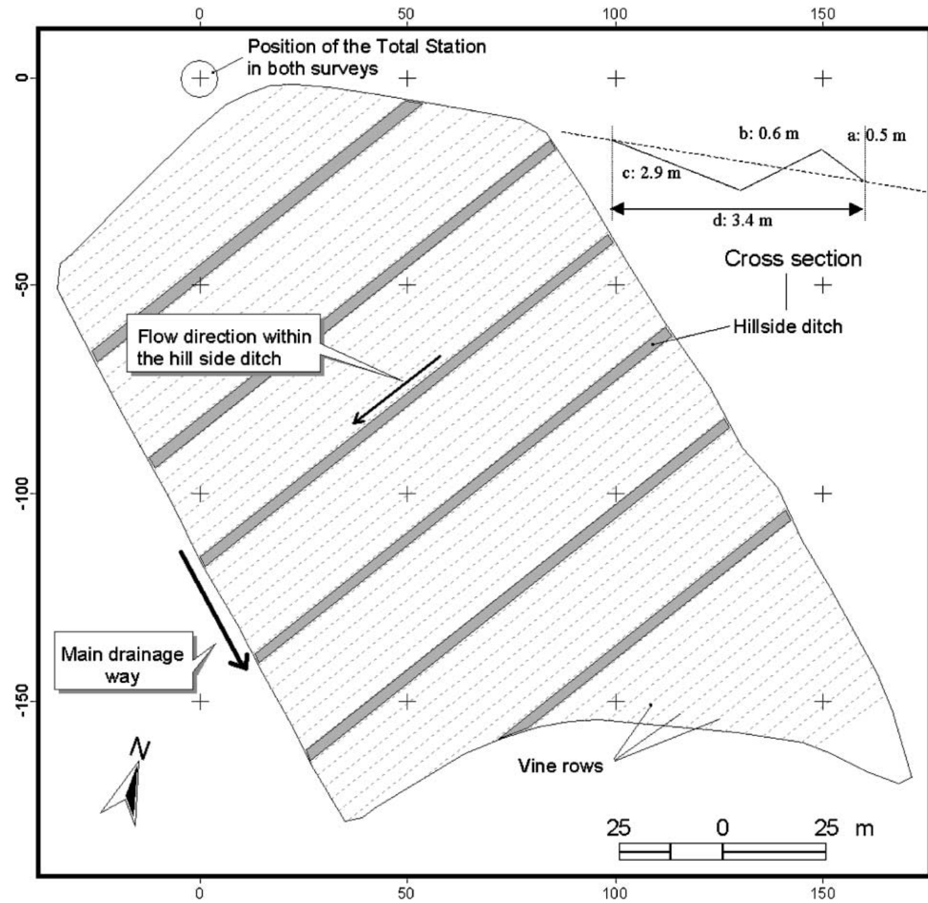

Fig. 2. Characteristics of the case study plot (relative co-ordinates are measured in meters with respect to the location of the total station).

hillside ditch or broadbase terrace (locally named "rasa"). Their function is to intercept surface runoff and convey it out of the field (Porta et al., 1994) (see detail in Fig. 2). Part of the sediment generated above these ditches is deposited in them. The terraces also provide access for farm machinery. Vineyards only partially cover the soil during the vegetation period, with a maximum crown cover of 50% for trained vines. At the time of the event analysed, coverage at the study plot was approximately 30%.

3.2. Analysis of the rainfall event

The analysed rainfall event occurred on 10 June 2000. Rainfall was recorded using a tipping bucket raingauge connected to a data logger, which recorded data every minute. This raingauge was situated on the same farm as the vineyard plot of the case study. From this information, the depth, duration and average and maximum intensity in a 30-min period were evaluated. The erosivity of this event was calculated by the R (KE$^*I30$) erosivity index proposed by Wischmeier and Smith (1978), where KE is the kinetic energy of the rainfall and $I30$ is the maximum intensity in a 30-min period. Kinetic energy was calculated from the intensity values, using the relationship obtained for this area (Ramos, 1999). Total rainfall was compared with historical series that belonged to the observatories of the Spanish Instituto Nacional de Meteorología (INM), located in the study area: Esparreguera, Gelida, Piera and Sant Sadurní d'Anoia.

A precipitation concentration index (PCI), similar to that proposed by Mannerts and Gabriels (2000), was calculated using 24-h rainfalls. This is an index that is used to analyse and compare the concentration of rainfall due to its emphasis on the relative distribution of rainfall irrespective of the total rainfall received. The PCI was defined by Eq. (1).

$$\mathrm{PCI} = 100\frac{\sum_{1}^{365}\left(P_{\mathrm{i}}^{2}\right)}{\left(\sum_{1}^{365}P_{\mathrm{i}}\right)^{2}} \tag{1}$$

where, P_{i} = daily precipitation (mm).

3.3. Soil loss mapping and quantification

The mapping and quantification of the sediments produced by the extreme rainfall event was based on the analysis (subtraction) of two high resolution DEMs (equivalent to a scale 1:200), one from before (17 March 2000) and one just after the heavy storm (20 June 2000, 10 days after the event, when it was possible to walk on the plot). Both DEMs were generated from independent very detailed topographic surveys. The purpose of the first survey was to generate a very detailed DEM to study the influence of topography on the spatial distribution of soil properties. The second survey was carried out specifically to map and quantify the effects of the extreme rainfall event studied.

Both topographic surveys were carried out by the same team using a TOPCON GTS-303® total station. This device measures distances by means of infrared light emission to a receptor prism. The precision of the distance measurement is 0.0105 m km^{-1} for a range of 2000 m. The number of points registered for each survey was 237 (17 March 2000) and 288 (20 June 2000). Those figures are above or within the range of the number of points recommended for very detailed topographic surveys in the case of undulating or complex relief (between 150 and 250 points for scale 1:200) (Ojeda, 1984). Both surveys were made without interference due to atmospheric conditions.

The representation of the topographic data acquired in the surveys and the construction of the contours (0.2 m elevation interval) for each date were made with the software TCP (Autodesk®). From the contours, and for each survey, the DEMs were generated by means of a random triangulation using all the points following the Delaunay method of triangulation. For that, ARC/INFO Version 7.1.2 (ESRI®) was used. This method ensures that any point on the surface is as close as possible to a node. Points along contours were considered as mass points and the boundary of the plot was used as a breakline. The resulting triangulated irregular networks (TINs) were used to compute both grids by means of spatial interpolation. The boundary was maintained as triangle edges in the resulting TINs. Contours were used as mass points. Cells were given the height value found at the intersection between the perpendicular at the center of each cell and the corresponding triangle in that spatial location. The spatial resolution given to the grids was 0.2 m. The software used for that purpose and for the analysis of the grids was Arcview 3.2 (ESRI®).

Two main types of errors occur in the elevation measurements from the total station: random errors and systematic errors. The random errors are generated by the imprecise determination of azimuths and distances due to the accuracy of the equipment used. This type of error is referred to as elevation uncertainty of the radiation. According to the characteristics of the equipment and the survey, the random error in the determination of elevation was, as a maximum, less than ± 0.018 m in each point. Those errors cancel out when the surface elevation is calculated from a large number of points. They were not considered to compute errors in volume calculations of sediment displaced by the storm. Systematic errors are mainly generated by imprecise positioning of the total station and imprecise determination of the prism elevation. The evaluation of systematic errors was made by comparing the elevation differences over the areas of stable terrain: interfluve areas within the plot, where rills were not observed after the storm. Those areas mainly occurred on the left side (down slope) of the plot. In those areas, and in the absence of errors, the mean and variance of differences in elevation, computed from the multi-date DEMs, should be negligible (DeRose, 1998). We established six control sites (areas), representing 1% of the surface of the plot. The mean of the elevation differences in the control areas [DEM(20/06/00) − DEM(17/03/00)] was 0.0026 m. It means that the DEM(20/06/00) was, on average, slightly higher than the DEM(17/03/00). This figure was subtracted from the DEM(20/06/00) to compensate it for the systematic error detected. The accuracy on mean differences in elevation (elevation error) was estimated as twice the standard deviation of the mean elevation differences for the control areas. This error was ± 0.0017 m, which represents the 95% confidence limits for erosion results.

After the correction for systematic errors, the subtraction of the grids, [DEM(20/06/00) − DEM(17/03/00)], produced a new grid with the altitude difference for each cell of the grid. A negative value in the cells of that grid was interpreted as erosion (surface lowering), a positive value as deposition, and a very low or zero value as no change. The sediment production rate by area unit

(1 ha) was calculated according to Eq. (2) as proposed by (Martínez-Casasnovas, 2000).

$$\mathrm{SPR} = (\mathrm{ED} \cdot \mathrm{GR}^2 \cdot \mathrm{Bd})/\mathrm{A} \quad (2)$$

where, SPR = sediment produced by the rainfall event (Mg ha^{-1}), ED = sum of the elevation differences (m), GR = grid resolution (m) (0.2 m in the present case study), Bd = bulk density of the soil top layer Mg m^{-3}, and A = surface of the plot (ha).

An average value of 1.25 Mg m^{-3}, computed from bulk density measurements carried out in the study area by Martínez-Casasnovas (1998) and Usón (1998), was considered as the bulk density value of the soil top layer in order to estimate the weight of the produced sediments.

No soil movement or levelling was made by the farmer in the period between the surveys, only the usual tillage operations: mechanical and chemical weeding and application of pesticides. During the low intensity rainfalls recorded between the two dates (107 mm), most of the water was infiltrated without causing significant soil loss. This means that the altitude differences between the two surveys was due to soil erosion or deposition caused by the study storm.

4. Results and discussion

4.1. Rainfall event

The total rainfall recorded on 10 June 2000 in the raingauge station located in the analysed vineyard was 215 mm, 205 mm of which fell in 2 h 15 min. The analysis of historical rainfall data in this area, referred to as 24-h rainfall in four observatories (Table 1), shows that this rainfall of 215 mm has a return period

Table 1
24-h-rainfall [P (mm) for different return periods (years) for four observatories located in the studied area and its respective standard error (se)

Observatory	P_2 (mm), SE_2 (mm)	P_5 (mm), SE_5 (mm)	P_{10} (mm), SE_{10} (mm)	P_{20} (mm), SE_{20} (mm)	P_{30} (mm), SE_{30} (mm)	P_{50} (mm), SE_{50}(mm)	P_{100} (mm), SE_{100} (mm)
Piera	64.8	81.6	92.7	103.4	109.5	117.1	127.5
	4.0	6.4	9.1	14.9	16.6	16.6	16.6
Gelida	71.2	95.7	111.9	127.5	136.5	147.5	162.8
	10.3	16.2	23.5	33.0	39.3	39.3	39.3
Esparreguera	66.0	105.4	131.1	156.3	179.9	188.9	213.2
	14.3	22.7	32.5	45.7	63.3	63.3	63.3
Sant Sadurní	63.6	87.1	102.6	117.5	126.1	136.9	151.4
d'Anoia	8.0	12.8	18.2	25.6	37.7	37.7	37.7

higher than 100 years. The analysis of the distribution of maximum 24-h rainfall shows that 90% of the data are below 72 mm, with an average value of 55 mm. The 24-h rainfall of this event represents 42% of the annual rainfall recorded that year. The PCI for the daily rainfall for the year 2000 was 19.2, while in previous years this index ranged between 5.3 and 7.3 for similar annual rainfalls. This gives an idea of the importance of the study storm.

However, the most relevant characteristic of this event was its intensity.

The average intensity of the downpour was 91.8 mm h^{-1}, with a maximum intensity in 30-min periods of up to 170 mm h^{-1}. The maximum intensity in a 5-min period reached 180 mm h^{-1}. According to the Magister criteria (Magister, 1991), the storm was bimodal, with two peaks, in which 1-min intensities higher than 250 mm h^{-1} were recorded (Fig. 3). The available information on rainfall intensities in this area shows that the maximum average intensity values, referred to as one event, recorded during the last 20 years are about 40 mm h^{-1}, although in shorter periods of time the intensities had frequently reached values of 125 mm h^{-1} (Ramos and Porta, 1994). Thus, this rainfall event is extraordinary, not only because of the amount of rainfall and the season of the year in which it occurs, but because of its high intensity.

The total kinetic energy of the storm, calculated using the equations obtained for this specific area (Ramos, 1999) was 69,995 J m^{-2}, and the rainfall erosivity of this storm, evaluated by the erosivity index R, calculated as the product of kinetic energy and the maximum intensity in 30 min, reached a value of 11,756 MJ ha^{-2} mm h^{-1}. This value is 10 times greater than the annual value for this area (Ramos and Porta, 1994), which gives an idea of the very high erosive potentiality of this storm.

4.2. Soil loss

The subtraction of the two analysed grids yielded a new grid with the altitude differences (Fig. 4). This grid clearly shows the areas that suffered soil loss (negative difference values) and the areas where sedimentation occurred (positive difference values). The sum of the negative values represents a minimum for the amount of soil that was mobilised in the plot by the surface runoff generated. This totalled 828 ± 19 m^3, equivalent to 1035 ± 28 Mg or a specific rate of 487 ± 13 Mg ha^{-1}. A proportion of the sediment generated, 57% of this material, 476 ± 17 m^3, equivalent to 595 ± 21 Mg or 280 ± 10 Mg ha^{-1}, was deposited elsewhere within the same plot. The sum of both figures, negative and positive values, gives the net amount of soil loss or deposition. In the present case, the balance was negative, with a total of 352 ± 36 m^3 (440 ± 45 Mg) of soil loss in the plot, representing a specific loss of 207 ± 21 Mg ha^{-1}.

Most of this sediment was produced by concentrated surface runoff, which developed ephemeral gullies in topographic depressions within the plot (Fig. 4). Ephemeral gullying was considered for incision higher than 0.1 m. The soil

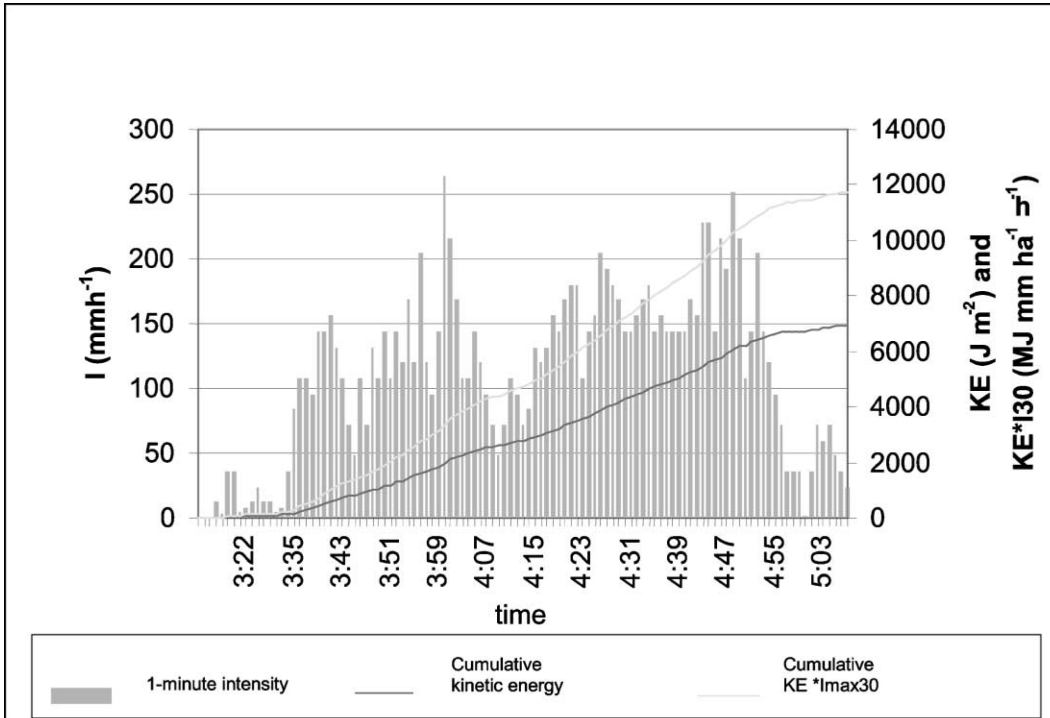

Fig. 3. Characteristics of the rainfall event registered on 10 June 2000 in the study area. One-minute intensity, cumulative kinetic energy and erosivity index $(KE*I30)$ proposed by Wischmeier and Smith (1978).

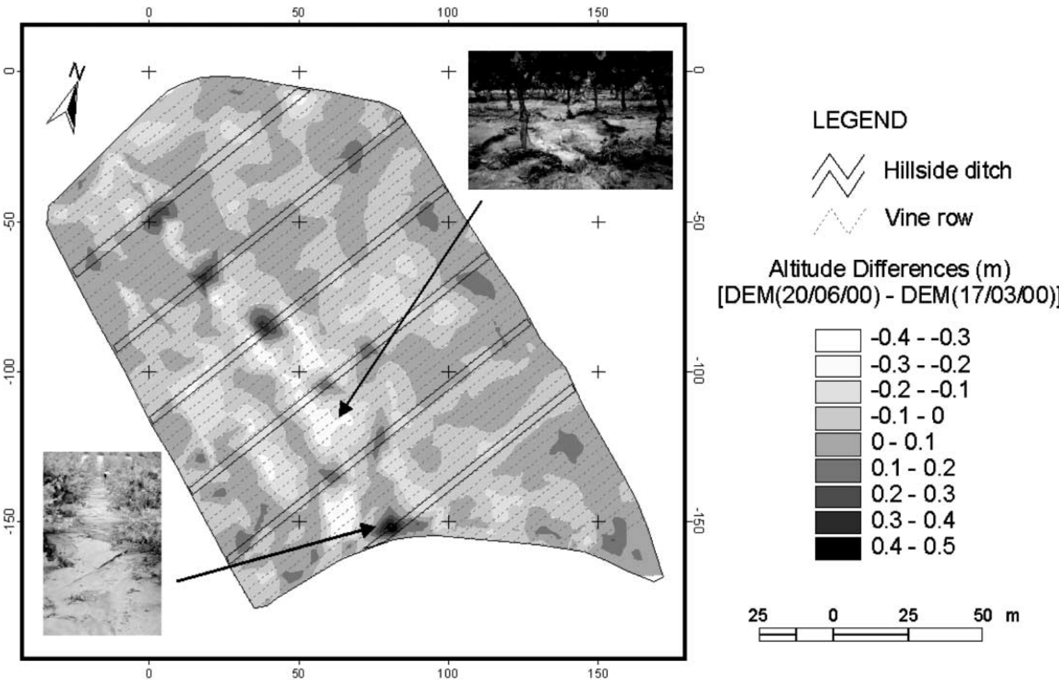

Fig. 4. Map of the altitude differences. Detail of the ephemeral gully originated in the central part of the plot and of the sedimentation produced near the hillside ditch in the lowest part of the plot.

detached by gullying affected approximately 3100 m^2, which represents 15% of the surface of the plot. This accounted for approximately 58% of the total soil detached (478 ± 6 m^3 out of 828 ± 22 m^3). A specific surveying of the boundaries of ephemeral gullies would have made possible to compute their contribution to the total soil loss produced with a higher precision. The rest of the soil detached (42% of the total) was due to rill and inter-rill erosion. Those erosion processes mainly affected 8320 m^2 (39% of the plot), displacing 350 ± 4 m^3 of sediments.

Deposition of sediment occurred preferentially in the hillside ditches and at the lowest areas of the plot, close to the border between the vineyard plot and the large gully which drains the plot. The sediment deposited in the hillside ditches accounted for 23% of the total deposits produced (111 ± 2 m^3 out of 476 ± 17 m^3). Although the main function of the hillside ditches is to intercept surface runoff and convey it out of the plot (Porta et al., 1994), in the present case they also acted to retain sediment in some pools that occur within the ditches. In other topographic conditions, such where there are no depressions within the ditches, the sediment would have been transported out of the plot via the drainage ways and the soil loss would have increased by 31.5% on that actually observed.

In comparison with soil loss rates measured in the same study area (Alt Penedès–Anoia region) (Table 2), a specific loss of 32 Mg ha^{-1} was measured in a 22-m-long, 5-m-wide plot, after an event of 71.5 mm (registered in the same study farm on 21 September 1995); or 18–22 Mg ha^{-1} measured only from rills after the rainfalls recorded during September–November (total rainfall was about 270 mm, with maximum 24-h rainfall of 127.9 mm) (Ramos and Porta, 1997). The computed soil loss in the present case study exceeded those figures by about 170–190 Mg ha^{-1}. The two main reasons are: the different magnitude of the rainfall events and the erosion processes accounted for by the different measurement methods used. In the first case, average rainfall intensities are typically < 30 mm h^{-1}, although in short periods of time there were also recorded intensities higher than 100 mm h^{-1}, but these are still much less than in the extreme event presented here. With respect to the second point, the methods used to evaluate soil losses are completely different. In previous studies, soil loss was measured in sample plots, which allowed measurement of inter-rill and rill erosion. In addition, only rill erosion was taken into account by profiling rills in several sections and measuring the total length of rills (Ramos and Porta, 1997). In the present case study, however, soil loss by concentrated surface runoff (gully erosion) is included in addition to that produced by overland flow (inter-rill and rill erosion). The measurement was made considering the agricultural field as the unit of measurement.

In comparison with soil loss rates measured in vineyards in other study areas (Table 2), e.g., 47–70 Mg ha^{-1} $year^{-1}$ (Tropeano, 1983), 35 Mg ha^{-1} $year^{-1}$ (Wicherek, 1991), and 34 Mg ha^{-1} in a single extreme rainfall event

Table 2
Comparison of soil losses produced in vineyards in the Mediterranean region

Region	Soil loss ($Mg\ ha^{-1}$)	Period	Reference
NW Italy	47–70	Year	Tropeano (1983)
Mid Aisne region (France)	35	Year	Wicherek (1991)
Alt Penedès–Anoia (Spain)	22	Year	Usón (1998)
SE France	34	One extreme rainfall event (24-h rainfall 243–316 mm)	Wainwright (1996a,b)
Alt Penedès–Anoia (Spain)	18–22 (only rill erosion)	September–November (maximum 24-h rainfall 127.9 mm)	Ramos and Porta (1997)
Alt Penedès–Anoia (Spain)	32 (measured on a plot 22×5 m, bare soil)	One rainfall event (71.5 mm)	Own unpublished data
Alt Penedès–Anoia (Spain)	207	One extreme rainfall event (215 mm)	Present study

(Wainwright, 1996a,b), the 207 ± 21 Mg ha^{-1} measured in the present study is substantially greater. Besides the differences in measurement methodology, the measured rate confirms the very high erosive potentiality of this storm, 10 times higher than the annual value.

If it is assumed that soil loss is proportional to the square daily rainfall, the soil loss in this event represents 92% of the annual loss. This percentage is higher than in other maximum 24-h rainfalls recorded in the same area, which range between 19% and 78%. Unfortunately, in the study area, regular information about soil loss by extreme events for all those years does not exist. The only available information refers to the soil loss (32 Mg ha^{-1}) that was measured during the maximum event recorded in 1995 (maximum rainfall 71.5 mm) (Table 2). According to the previous assumption, the loss represents 30% of the annual potential soil loss (105 Mg ha^{-1} $year^{-1}$, according to this estimation). This value of the 24-h rainfall has a return period of 5 years, and it significantly contributes to the total annual soil loss. Nevertheless, the characteristics of the study event (20 June 2000) are very particular because of the high intensity, and both results are not comparable.

The soil loss rate computed in the Alt Penedès–Anoia region at vineyard plot scales, together with the gully erosion rate of 1322 ± 142 Mg ha $year^{-1}$ computed by means of the same subtraction technique from medium resolution multi-temporal DEMs (Martínez-Casasnovas, 2000), confirms that this region is one of the most severely affected by water erosion in the Mediterranean basin.

5. Conclusions

This research presents a step forward in the mapping and quantification of soil erosion and sedimentation at agricultural plot scales caused by overland flow and concentrated surface runoff, as distinguished from measurements at small sample plots or estimations by prediction models. The proposed method may be suitable when important soil detachment is produced, especially during extreme rainfall events. In those cases, most of the soil is lost by concentrated surface runoff in specific waterways along the slope, which is difficult to evaluate using sample plots as methods of measurement. Among other, one of the most important qualities of the method is that it can provide a measure of the real soil volume lost. In addition, part of the detached and eroded material is deposited in other parts of the plot, which also can be evaluated with the proposed method.

The spectacular soil losses caused by the analysed rainfall event (207 Mg ha^{-1}) agree with the erosivity index (R) of the event, 10 times greater than the annual value for this area. This gives an idea of the very high erosive potential that the storm caused. This storm brought significant economic losses to farmers, not only in tillage works and rehabilitation of the drainage channels and the hillside ditches, but also losses in nutrients, as well as direct loss of topsoil.

The research also revealed information about the functioning of the soil and water conservation measures (hillside ditches). The existence of topographical depressions within the hillside ditches reduced soil losses relative to losses that would have otherwise occurred if the topography of the field had favoured more efficient drainage of runoff to the main drainage ways. This is an important factor in the future redesign of conservation measures in order to assist with the retention of sediments within the vineyard plots.

The surveying errors were minimised as much as possible in the present study (same surveying team and equipment, and almost the same number of height points acquired in each survey), and they had little influence on the results. If accuracy in height determination (random error) is taken as reference (± 0.018 m, as maximum in our case), that makes the method specially suitable for soil loss monitoring due to rill and ephemeral gully erosions, which produce significant surface lowering and important soil detachment. Inter-rill erosion can be also monitored in case of special extreme events, when important soil detachment is produced. Further research, studying other events of different magnitudes, is necessary to determine the sensitivity of the method to determine the minimum magnitude of event that may be monitored.

Acknowledgements

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