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A spatial information technology approach for the mapping and quantification of gully erosion

J.A. Martínez-Casasnovas*

Department of Environment and Soil Science, University of Lleida, Rovira Roure 191, E25198 Lleida, Spain

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Abstract

In contrast to the effort during the last decades to investigate sheet (interrill) and rill soil erosion processes, relatively few studies have been focused on quantifying and/or predicting gully erosion. The extension of the use of modern spatial information technologies, such as geographical information systems (GIS), digital elevation modelling (DEM) and remote sensing, have created new possibilities for research in this field. A key issue to be addressed, as the basis for predicting the effects of global changes such as land use and climate changes, is the mapping and quantification of gully erosion rates, including rate of retreat of gully walls and rate of sediment production. This research work presents a method to compute the rate of retreat of gully walls and the associated rate of sediment production caused by gully erosion. The proposed method uses multitemporal aerial photographs and multitemporal digital elevation models, both of which have been processed using GIS techniques. The research was applied to a sample catchment of 25 km^2 located in Catalonia, Spain. Aerial photographs at scale of 1:30,000 from 1957 and orthophotos from 1993 were used to map gully erosion and determine erosion rates between 1957 and 1993. The rates of channel incision and sediment production were computed from the subtraction of multitemporal digital elevation models. The rate of gully walls retreat was 0.2 m $year^{-1}$, representing a rate of 0.9‰ m^2 $year^{-1}$. The maximum rate of channel incision (0.7–0.8 m $year^{-1}$) occurred at the head of the gully and at meandering zones. The rate of sediment production caused by gully erosion was 1322 ± 142 ton ha^{-1} $year^{-1}$. In comparison with other methods to compute sediment production caused by gully erosion processes, the proposed method integrates the losses due to overland flow, mass movements and gully deepening and supposes an improvement to locate the areas within the gullies with higher erosional activity.

Keywords: Gully erosion; Erosion rates; Airphoto interpretation; GIS; Digital elevation models

* Tel.: +34-973702615; fax: +34-973702613.

E-mail address: j.martinez@macs.udl.es (J.A. Martínez-Casasnovas).

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1. Introduction

Gully erosion is a serious problem in many parts of the world, and particularly in the Mediterranean basin, because of climate, lithology, soils, relief and land use/cover characteristics. The causes, processes, prediction and control of gully erosion have aroused the interest of many researchers in different environments. Most research has been addressed to analyse gully morphology and the stages of gully development as a first step in evaluating gully processes and assessing the potential for gully erosion (Ireland et al., 1939; Heede, 1979; Imeson and Kwaad, 1980; Crouch and Blong, 1989; Poesen, 1993). Gully erosion modelling has focused more on development of qualitative and empirical–statistical models than in the formulation of physically based models (Bocco, 1991) (see, among others, Thompson, 1964; Williams and Morgan, 1976; Stocking, 1980; Donker and Damen, 1984). Most recently, with the aid of digital elevation modelling, research has been addressed to predict the threshold contributing area and/or other topographic effects and limits on the initiation, distribution and location of ephemeral gullies in different conditions (Moore et al., 1988; Vandaele et al., 1997; Prosser and Abernethy, 1996; Desmet et al., 1999).

To study the typology of gullies and the effects of gully erosion (sediment production and land degradation), and to predict the risk of gully erosion and its environmental, social and economical effects, different approaches have been used. Those approaches include (a) mapping existing gullies and present erosional activity (Van Zuidam, 1986; Crouch and Blong, 1989; Palacio and López, 1994), (b) characterisation of the gully erosion degree on the basis of indices (Williams and Morgan, 1976), (c) mapping gully erosion hazard in actively eroding catchments on the basis of the threshold contributing area concept and/or other topographic factors as derived from high-resolution digital elevation models (Moore et al., 1988; Vandaele et al., 1997; Desmet et al., 1999) and (d) mapping of gully retreat rates and quantification of sediment production (Dymond and Hicks, 1986; DeRose et al., 1998).

Most of that previous research has been based on the use of remote sensing techniques, particularly airphoto interpretation and photogrammetry, which are considered to have great potential in data collection to map gully erosion, for continuous monitoring and for modelling (Bocco, 1991; Nachtergaele and Poesen, 1999). Satellite images may also offer interesting possibilities to investigate gully erosion provided that gullies affect areas wide enough to be covered by the resolution of the images (Giordano and Marchisio, 1991). In this respect, multispectral remote sensing techniques have been applied to map the extension of gully erosion phenomena (Solè et al., 1986; Bocco, 1990; Martínez-Casasnovas and Poch, 1998), and to map the present erosional activity of gully walls from the mapping of vegetation cover (Martínez-Casasnovas, 1998).

Large- and medium-scale multitemporal aerial photographs and videographic techniques have been used for gully and ephemeral gully growth monitoring and to compute gully retreat and sediment production rates, substituting or complementing the use of erosion pins or stakes (Palacio and López, 1994; Nachtergaele and Poesen, 1999; Oostwoud Wijdenes et al., 2000). Other authors have also investigated the application of photogrammetric techniques, using multitemporal aerial photographs, to map the volumetric changes in gullies and, subsequently, to compute the amount of eroded materials and the rate of concentrated-flow erosion in cropland or steepland (Thomas et al., 1986; Dymond and Hicks, 1986; Poesen et al., 1996). Most recently, the development and extension of photogrammetry, digital imaging technology and geographical information systems (GIS) have contributed to the use of multitemporal digital elevation models (DEM) to compute sediment production by gully erosion (Thomas et al., 1986; DeRose et al., 1998; Martínez-Casasnovas, 1998; Betts and DeRose, 1999). Analysis techniques used in these studies confirm the conclusions of other researchers who state that sediment production by gully erosion is far from negligible (Poesen et al., 1996), and suggest that the significance of gully erosion needs to be emphasised.

In spite of those studies, some authors still argue that in contrast to the effort that has been addressed during the last decades to investigate interrill and rill erosion processes, relatively few studies have been focused on quantifying and/or modelling gully erosion (Bocco, 1991; Poesen et al., 1998).

The present paper shows the methods and results of research carried out in the Penedès vineyard region (NE Spain) to compute the rate of gully walls retreat and the rate of sediment production caused by gully erosion. In this area, gully erosion is widespread and affects between 15% and 27% of the land (Porta et al., 1994; Martínez-Casasnovas, 1998). The proposed method uses multitemporal aerial photographs and multitemporal DEM that are processed by means of GIS techniques. Erosion rates are discussed in relation to results obtained by other researchers in different environments and by distinct methods of measuring.

2. The study area

The Penedès region is located in NE Spain, about 30 km southwest of Barcelona, between the Sierra Prelitoral mountains and the Anoia and Llobregat rivers. A representative catchment of this region, called The Rierussa catchment (about 25 km^2) was selected to carry out the research (Fig. 1).

The main agricultural uses are vineyards (35% of the area) and winter cereals (6% of the area) that alternate with vineyards. Other important land covers are grassland and shrubland (25% of the area) and forested shrubland (17% of the area), both mainly covering some parts of the gully walls or on high slope degree, areas that were abandoned for agricultural use some years after the advent of mechanisation. Other minority crops are almond, olive and peach tree plantations. This area is part of the Penedès Tertiary Depression, where calcilutites (marls) and occasional sandstones and conglomerates crop out as the lithological materials. The area is characterised by a temperate to maritime Mediterranean climate, with a mean annual rainfall ranging from 471 to 670 mm (Porta et al., 1994). Rainfall distribution is irregular, with high-intensity rainstorms during autumn after the dry season (i.e. >100 mm h^{-1} over short periods), with high erosive potential (the rainfall erosivity factor R varies between 1049 and 1200 MJ mm ha^{-1} h^{-1} year^{-1}). Soils are highly calcareous and are classified according to the Soil Taxonomy (Soil Survey Staff, 1998) as *Xerorthents typics*, *Calcixerepts typics*, *Calcixerepts petrocalcics* and *Haploxerepts fluventics* (Martínez-Casasnovas, 1998). The major part of soil profiles

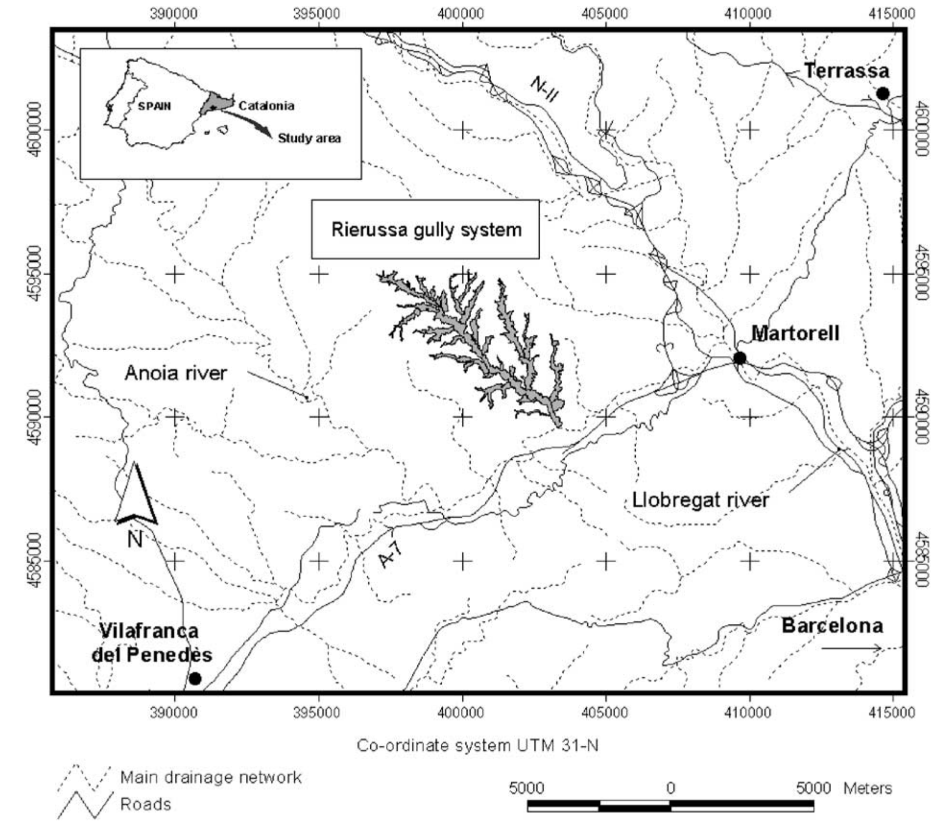

Fig. 1. Location of the study area.

has been truncated by hydric erosion and underlying horizons constitute, at present, the top layers.

One of the main characteristics of the area is the dissection of the landscape by a dense and deep network of gullies. Intergully areas are usually undulating to rolling. The average slope degree of this area is between 10% and 15%. The most frequent landforms are complex slopes (slope degree 5–15%) that alternate with rounded crests (slope degree 5–10%) and gullies. The gullies are characterised by vertical sidewalls and are between 11 and 60 m deep and 75 and 350 m wide (Martínez-Casasnovas, 1998). Gullies have a high degree of lateral expansion in relation to head retreat or linear advance. This is due to the frequent failure of gully walls and the retreat of gullies towards drainage ways of vineyard plots. Sediments mobilised from the walls are usually removed by flowing water after high-intensity rainstorms. In other cases, the sediments are deposited on the walls or on the gully bottom, which may lead to some degree of stabilisation. The cross-sectional shapes of the gullies are V- to U-shaped or U-shaped.

The development of the gully system has been favoured by the cropping of vineyards. Vines only cover partially the soil (about 50%) during the vegetation period. It causes large overland flows during high-intensity precipitation events. Surplus runoff is usually concentrated in hillside ditches (locally called “rases”) that flows either into main drainage channels or directly into gullies. This favours formation of gullies at the outlet of ditches or drainage ways and the gully network enlarges linearly. Large gullies grow by deepening in the unconsolidated Tertiary deposits. Mass movements on sidewalls produce parallel widening of gullies.

The period between the 1950s and the 1990s was important in the region since the agricultural system experienced a substantial transformation after the advent of mechanisation (after the 1950s). This change has led to increasing land degradation. Until the current work, erosion research in the Penedès region has not been addressed to determine gully erosion rates (retreat of walls and sediment production) or identified the most active gully erosion areas. Previous research has concentrated on other erosion processes: interrill and rill erosion rates at vineyard plots, with emphasis on the comparison between traditional and modern plantations (Sánchez-Bosch and Martínez-Casasnovas, 2000).

3. Materials and methods

The research was based on a multitemporal analysis of aerial photograph stereo pairs from 1957 (1:30,000 scale), orthophotos from 1993 (1:25,000 scale) and two DEMs (25-m resolution). The general methodological procedure is described in Fig. 2.

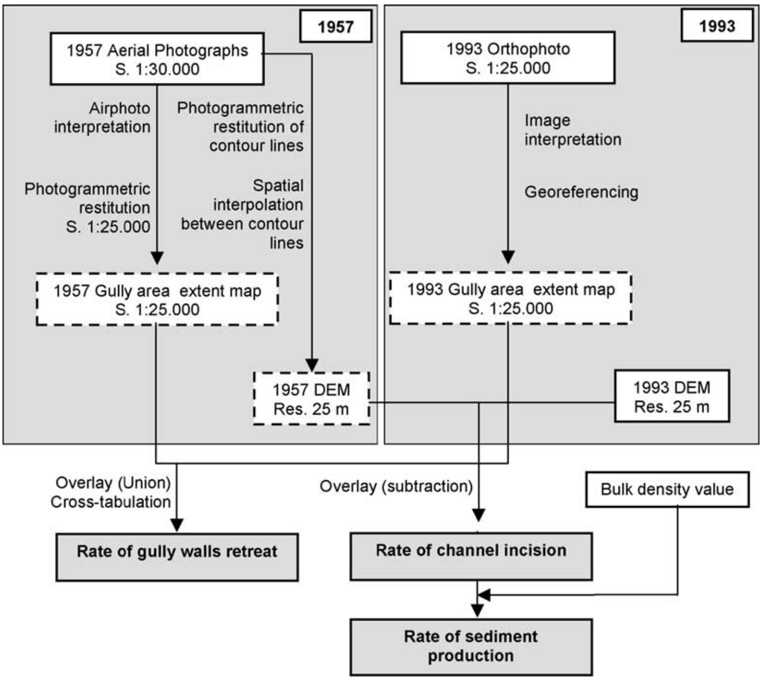

Fig. 2. Data flow diagram with the general methodological process applied.

3.1. Determination of the rate of gully walls retreat

The gullied area for 1957 was mapped by means of airphoto interpretation. The boundary of the eroded area was drawn along convex slope break lines that mark the incision of gullies in the unconsolidated Tertiary deposits. The result of the airphoto interpretation for 1957 was restituted by means of a digital photogrammetric process at scale of 1:25,000. This restitution was made by experts of the Geodisa team (a Spanish surveying and mapping company). The inner orientation of the airphotos was based on 15 tie points per stereo pair and the exterior orientation on 6 control points per stereo pair. The geometric transformation produced a RMS error of ± 0.5 m in both X and Y directions and ± 1 m in Z (altitude). The product was an ArcInfo (ESRI™) format polygon coverage. The gullied area for 1993 was drawn on a 1:25,000 orthophoto produced by the Cartographic Institute of Catalonia and digitised as an ArcInfo polygon coverage. Both coverages were geo-referenced according to the UTM 31N coordinate system.

The coverages were overlaid using ArcInfo's Union command. A contingence matrix was derived from the Union coverage. This matrix gives information about the area covered by each mapped class at the respective dates as well as about two-dimensional or planimetric changes among the classes in the considered period. From this matrix, the rate of gully walls retreat was computed.

3.2. Determination of the rates of channel incision and of sediment production

The rate of channel incision and of sediment production were computed from the subtraction of two digital elevation models in grid format (1993–1957). The 1957 DEM was constructed from 10-m spaced contour lines, and break lines: along convex slope break lines that mark the incision of gullies and streams. The contours and the break lines were drawn by means of photogrammetric restitution of the 1957 aerial photographs. The algorithm used for spatial interpolation was the Topogrid ArcInfo command. This method uses an iterative finite difference interpolation technique that produces DEMs without losing the surface continuity of methods such as kriging or splines. The horizontal resolution given to the DEM was 25 m, in order to be compared with the 25-m resolution 1993 DEM. The last was acquired from the Spanish "Servicio Geográfico del Ejército".

The 1957 DEM was corrected due to systematic errors. To estimate those errors, the 1957 DEM was compared with the 1993 DEM in control cells located over areas of stable terrain or without supposed changes (watershed divides and roads). The mean of the differences in those control cells was assumed to be the value of the systematic error. This value (5 m) was subtracted from the value of each cell of the 1957 DEM to correct the error.

The subtraction of the digital elevation models (1993–1957) produced a new grid with the altitude difference for each cell of the grid. A negative value in cells of the difference grid was interpreted as erosion (surface lowering or gully deepening), a positive value as filling or aggradation and a very low or zero value as stable areas. The altitude differences within the 95% confidence interval ($X \pm 2$ S.D., where X is the mean value of the differences and S.D. is the standard deviation) were used to compute the eroded material volume and the sediment production rate. The difference values from the 95% confidence interval were used to determine the range of variation. The sediment production rate was calculated according to Eq. (1) (Martínez-Casasnovas, 1998).

$$\mathrm{SPR} = (\mathrm{ED} \cdot \mathrm{GR}^2 \cdot \mathrm{Bd})/(AT) \tag{1}$$

where SPR = sediment production rate (ton ha^{-1} year^{-1}), ED = sum of the elevation differences (m), GR = horizontal grid resolution (m) (25 m in the present case), Bd = bulk density of the deposits (ton m^{-3}), A = surface (plane view) of the gully system area (ha), T = time of the studied period (years).

The deposits affected by gullying are mainly composed of Tertiary lutites (marls) and, to a minor extent, soils. An average bulk density value of lutites of 1.735 ton m^{-3}, computed from bulk density measurements carried out in the study area by Martínez-Casasnovas (1998) and Usón (1998), was used to estimate the mass of the eroded sediments.

4. Results

4.1. Gully area extent and rate of gully walls retreat

Image interpretation of the gullied area in 1957 and 1993 produced two gully area extent maps (Fig. 3). The numeric analysis of changes was performed from the contingence matrix of Table 1 that results from cross-tabulation of the 1957 and 1993 gully area extent maps. Two main information sets were extracted from Table 1: (a) new eroded areas resulting from gully retreat, and the retreat rate and (b) the gullied areas that were filled.

The total area affected by the retreat of gullies in the period 1957–1993 was 76.5 ha (shadowed cell in the contingence matrix, Table 1). The total area of existing gullies that was filled by farmers during this period, mainly to create new vineyard plots, was 38.8 ha (bold figure in the contingence matrix, Table 1). Both areas are also represented in Fig. 4. The main reason for the filling of gullies during this period was the high pressure on agricultural land since the 1970s to develop new urban and industrial areas. This pressure was associated with the degree of recognition and quality of the wines and ‘‘cavas’’ produced in the Penedès region. In turn, this revalued the vineyards and led to a shortfall of available land for further development. The only way for expansion of the crop was the use of marginal areas. In the study area, the filling of gullies represented, in 36 years, 6.4% of the gullied area. However, large investments that imply filling and levelling sometimes have a short life, since the first high-intensity rainfalls may produce the collapse of the filled areas.

According to Table 1, the balance of the area mapped as gully eroded during 1957–1993 is 37.7 ha. This figure does not represent, however, the gully walls retreat rate, since the filling of gullies does not mean a regression of the erosion process. Only the area affected by the retreat of gullies was used to compute the erosion rate (76.5 ha in 36 years). This represents a rate of 2.1 ha year^{-1} or in terms of the catchment area, 0.9‰ m^2 year^{-1}. The linear retreat of gully walls occurred at an average retreat rate of 0.2 m year^{-1} along the perimeter of the gullies of the Rierussa catchment. However, this represents

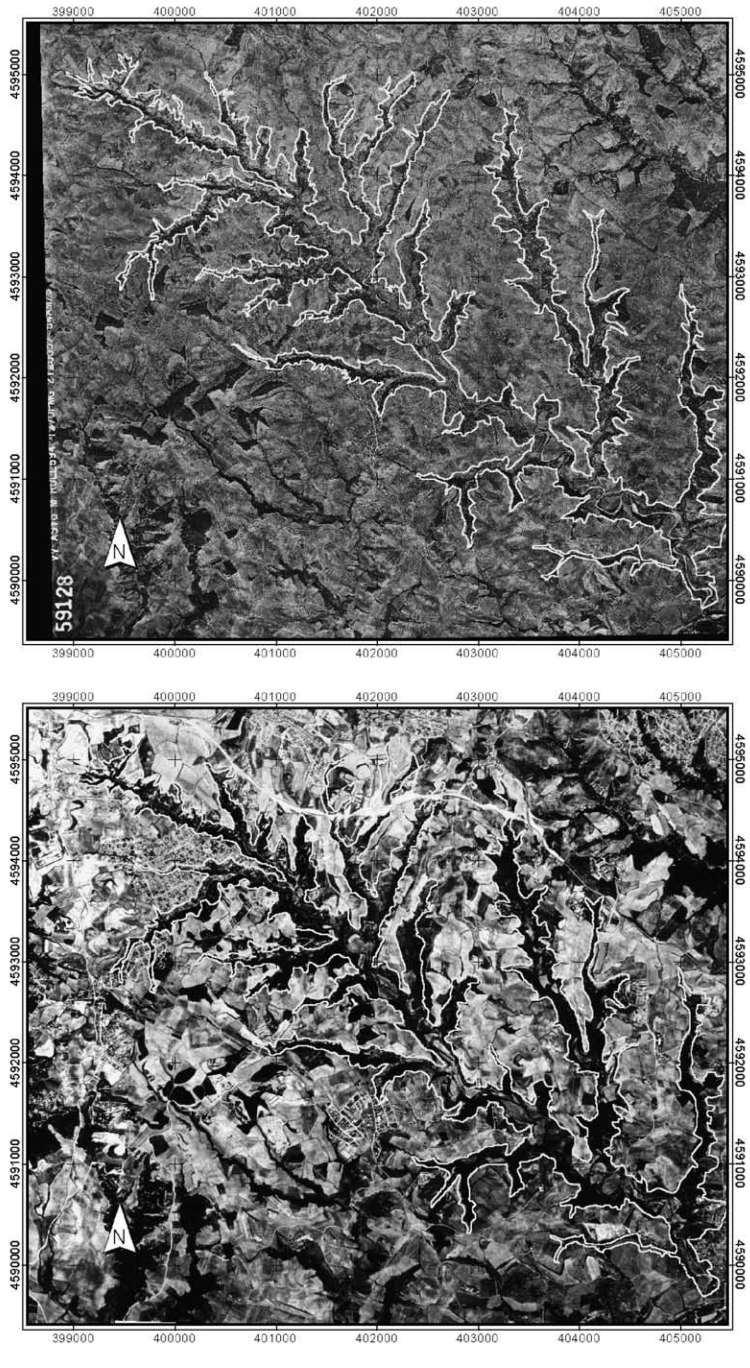

Fig. 3. Gully area extent maps of the 1957 and 1993 situations.

Table 1
Contingence matrix of gullied areas in 1957 and 1993

Year 1993 (ha)	Year 1957 (ha)		
	Gullied areas	Non-gullied areas	Total (year 1993)
Gullied areas	565.4	76.5	641.9
Non-gullied areas	**38.8**	1769.6	1808.4
Total (year 1957)	604.2	1846.1	2450.3

default rates since areas that were both eroded and filled within the studied period and, therefore, not detected in the image interpretation process, may be included.

The gully retreat rate measured in the Penedès region was compared with the rate measured in gully systems and badlands located in the Barasona reservoir basin (pre-

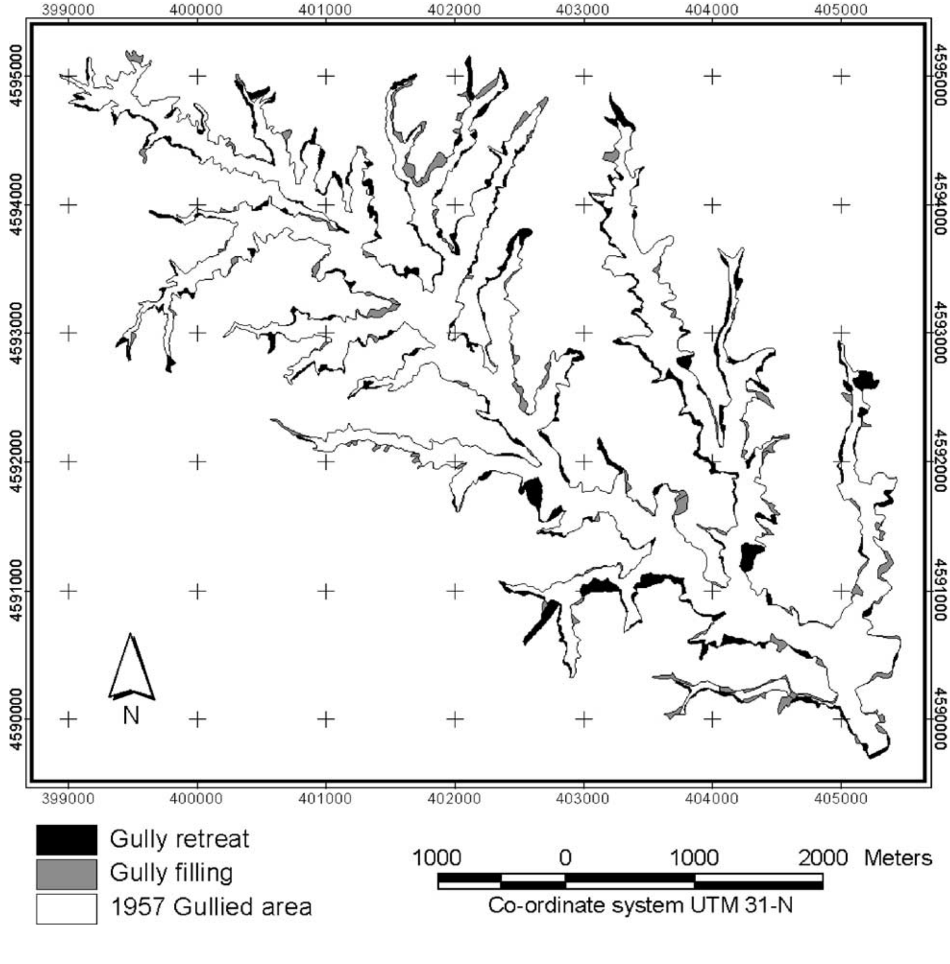

Fig. 4. Union map showing the gully retreat areas and filled areas within the studied period.

Pyrenean area—NE Spain, Martínez-Casasnovas and Poch, 1998). In those badlands, a rate of 2.8 ‰ m^2 $year^{-1}$ was measured, using a similar approach and considering a period of 28 years. Different conditions are given in the Barasona reservoir basin. This is a mountain area with very different land use orientation. The main land cover is natural forest (*Pinus halepensis*, *Pinus silvestrys* and *Quercus faginea*). Agriculture represents only a very marginal land use type (mainly rainfed crops for grazing) in some parts of the floodplain areas. Gully and badland development is not as influenced as in the Penedès region by human actions. Neither erosion control measures nor filling are common practices in the Barasona basin. Implementation of soil conservation measures could be one of the reasons that would have influenced the lower gully retreat rate in the Penedès. In this area, farmers have been controlling the retreat of gullies by means of stacks of stones and debris of the vines' cutout along the boundary between gullies and plots. These are not very effective measures to control gully retreat but restrain it to some extent (Martínez-Casasnovas, 1998; Usón, 1998). Associated clearing of forested shrubland and forested areas since the 16th century (Balcells, 1980), appears to a probable cause of disequilibrium responsible for higher runoff rates and gully erosion processes. After the advent of mechanisation in the 1950s and 1960s, changes to the traditional soil and water conservation measures have occurred (Porta et al., 1994) further aggravating the erosion problems.

4.2. Channel incision and sediment production rates

Fig. 5 shows the altitude difference map as result of the subtraction of the 1957 and 1993 digital elevation models in the gullied area. Negative cell values indicate erosion (surface lowering or gully deepening), positive cell values point to gully filling or aggradation, and a very low or zero value indicates stable areas.

The DEM difference map shows that the pattern of erosion within the gully is not uniform. The most active downcutting processes are clearly located at the head of the gully system and along the gully axis. The head (around 270 m above sea level) tends to reach the local base level (74 m above sea level), located in the outlet of the drainage system, producing important surface lowering. In this part of the gully, the maximum amount of surface lowering occurred (28.5 m in 36 years), representing a lowering rate of 0.8 m $year^{-1}$. High rates also occur in secondary headcuts located in the upper–middle section of the gully system (example: cross-section 1 in Fig. 6). The axis of the central section of the gully presented smaller lowering rates between 0.15 and 0.35 m $year^{-1}$. Other sections of the gully axis, located at meandering zones near the outlet, where downcutting and mass movements are the dominant processes, also presented a surface lowering rate similar to the one at the gully head (0.7 m $year^{-1}$) (cross-section 2 in Fig. 6). There were other sections that did not present significant changes (cross-section 3 in Fig. 6). Those are areas usually located in central and proximal sections of the gully axis (close to the outlet), where the gradient of the longitudinal profile is flatter.

Other authors have also used the method of subtracting multitemporal DEMs to compute rates of channel incision in gullies in different study areas (DeRose et al. 1998, in the Mangatu Forest, New Zealand). Despite the differences between intrinsic conditions of the Penedès region and the Mangatu Forest, the computed rates of channel

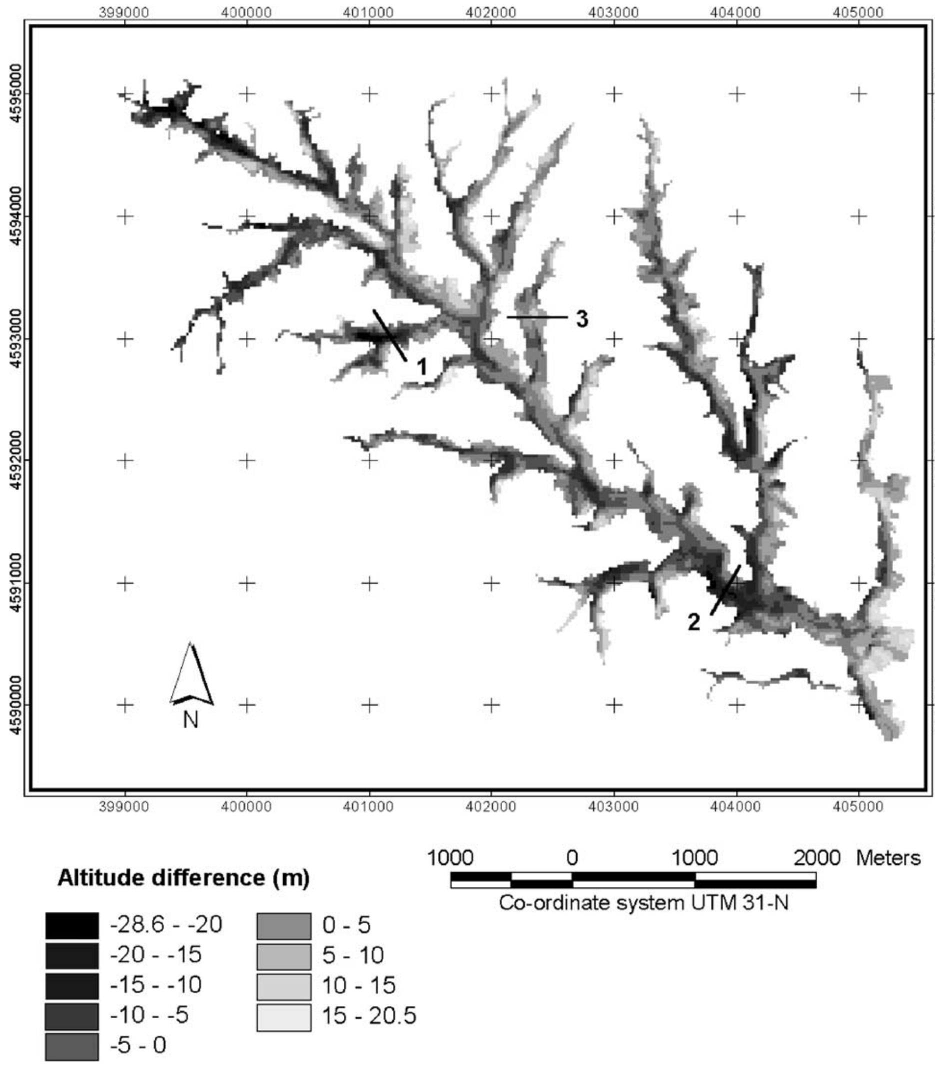

Fig. 5. Result of the subtraction of the 1957 and 1993 digital elevation models in the gullied area of the Rierusa catchment and location of the cross-sections represented in Fig. 6.

incision in the Penedès are similar to the rates computed for the period 1958–1992 (0.77–0.79 m $year^{-1}$) in the Mangatu Forest. DeRose et al. (1998) also computed the lowering rate for the period 1938–1958 in the Mangatu Forest (1.3–2.3 m $year^{-1}$), revealing nonuniform temporal changes, with impacts produced by the reforestation of the gully system catchment between 1958 and 1992. In the Penedès region, although it was not possible to determine the channel incision rate for the period before 1957 because of the unavailability of earlier aerial photographs, a related research also points out to nonuniform temporal gully erosion rates. Sánchez-Bosch and Martínez-Casasnovas (2000)

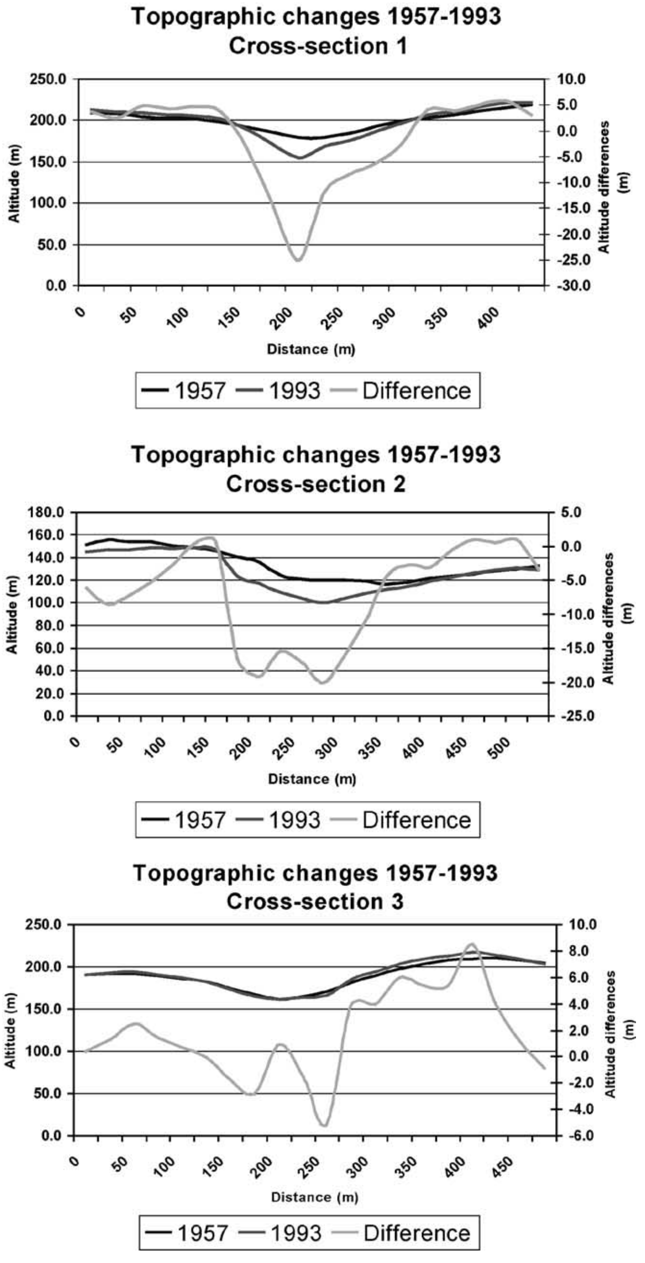

Fig. 6. Cross-sections of the 1957 and 1993 digital elevation models and altitude differences showing examples of significant changes produced in the Rierusa catchment (cross-sections 1 and 2) and of not significant changes (cross-section 3).

analysed changes in the land use/cover and conservation practices that occurred in the study area in the years 1957–1992 and their relation to soil losses. A clear negative balance of soil loss rates was apparent, with 12.6% of agricultural land experiencing major negative changes (between 50% and 300% increase of soil loss). The main reason for this negative balance was the management practices used to establish new vineyard plantations rather than the increase in area dedicated to vineyards. These results indicate that, as well as soil loss increased at plots in 1992 in contrast to 1957, gully erosion rates would have also increased with respect to the period before the advent of mechanisation (represented by the 1957 situation), when traditional conservation practices were maintained.

The altitude differences within the gully system between 1957 and 1993 presented a negative balance. This indicates the production of sediments during the studied period, as estimated according to Eq. (1). The total production of sediments in the 36-year period was $29.2 \pm 3.1 \times 10^6$ ton. This represented a mean annual rate of $0.8 \pm 0.1 \times 10^6$ ton year^{-1} in the gully system and a surface unit rate of 1322 ± 142 ton ha^{-1} year^{-1}. If referred to the Rierussa catchment area the gully erosion rate was 331 ± 35.5 ton ha^{-1} year^{-1}. These figures represent erosion rates by default since farmers contribute to modify the real rate by the filling of some parts of the gullies to crop vineyards. To minimise the influence of gully filling in the calculus of the sediment production rate, the areas filled during the studied period were not considered. So, the rate was computed from the area affected by the retreat of gullies and the intersection of the gullied areas in both years: 1957 and 1993.

In contrast to sediment production rates measured in other areas of the Mediterranean basin, as for example the 190 ton ha^{-1} year^{-1} measured in badlands in the SE France (Bufalo and Nahon, 1992) or the 302–455 ton ha^{-1} year^{-1} measured in badlands in the Barasona reservoir basin (NE Spain) (Martínez-Casasnovas and Poch, 1998), the computed rate in the gully system of the Penedès (1322 ± 142 ton ha year^{-1}) is significantly higher. Out of the Mediterranean basin, DeRose et al. (1998) found in the Mangatu Forest (New Zealand) sediment productions rates of the same magnitude (1550 ± 50–2480 ± 80 ton ha year^{-1}). The reasons for the difference in the order of magnitude of the sediment production rates are found in the methods applied to determine them. The methods used by Bufalo and Nahon (1992) or by Martínez-Casasnovas and Poch (1998) only include sediment production due to overland flow processes. The method applied in the present case study, and by DeRose et al. (1998), includes the sediments produced by several processes: overland flow (causing sheet erosion), downcutting (causing channel incision), headcutting (causing retreat of gullies into ungullied headwater areas) and mass movements and bank erosion (producing undercutting and collapse of gully walls). This means that sediment production rates computed by different methods are not directly comparable since they do not consider the same erosion processes. Difficulties in determining the extent to which each erosion process contributes to the total sediment production can be viewed as a limitation of the DEM subtraction method.

5. Conclusions

This paper presented a method based on the subtraction of different date altitude values that helps to identify active gully erosion areas. In comparison to other traditional methods of measuring sediment production, the proposed method computes a rate that is one order of magnitude higher than results from other studies. This is because this method integrates losses due to overland flow, mass movements, bank erosion, downcutting and headcutting. Differentiation of the sediment production due to each of those processes needs additional airphoto interpretation and field work to map the areas within the gullies where each process mainly occur.

The application of the multitemporal analysis of aerial photographs and DEMs to the Penedès vineyard region confirmed the acceleration of erosion in the recent past since the advent of mechanisation. For the period 1957–1993, the retreat of gully wall rate was 0.2 m year^{-1}, with a surface rate of 0.9‰ m^2 year^{-1}. The rate of sediment production caused by gully erosion was 1322 ± 142 ton ha^{-1} year^{-1}. In the present application, those figures represent rates by default. This is due to the filling of some gullied areas by farmers to crop vineyards that impedes knowing the areas that were affected by the retreat of gullies during the period 1957–1993 and that were also filled during the same period.

The estimated sediment production could not be validated with sediment yield measurements. The subtraction of digital elevation data, however, only showed significant changes in the gully affected areas. This indicated that no significant errors existed in the subtraction of DEMs and supported the validity of the implemented technique.

Acknowledgements

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References

Balcells, A., 1980. El problema agrario en Cataluña. La cuestión rabassaire (1890–1936). Serie de Estudios. Servicio de Publicaciones Agrarias, Ministerio de Agricultura, Pesca y Alimentación, Madrid.

Betts, H.D., DeRose, R.C., 1999. Digital elevation models as a tool for monitoring and measuring gully erosion. International Journal of Applied Earth Observation and Geoinformation 1 (2), 91–101.

Bocco, G., 1990. Gully erosion analysis using remote sensing and GIS. PhD thesis, University of Amsterdam, Amsterdam.

Bocco, G., 1991. Gully erosion: processes and models. Progress in Physical Geography 15 (4), 392–406.

Bufalo, M., Nahon, D., 1992. Erosional processes of Mediterranean badlands: a new erosivity index for predicting sediment yield from gully erosion. Geoderma 52, 133–147.

Crouch, R.J., Blong, R.J., 1989. Gully sidewall classification: methods and applications. Zeitschrift fur Geomorphologie, N.F. 33, 291–305.

DeRose, R.C., Gómez, B., Marden, M., Trustrum, N.A., 1998. Gully erosion in Mangatu forest, New Zealand, estimated from digital elevation models. Earth Surface Processes and Landforms 23, 1045–1053.

Desmet, P.J.J., Poesen, J., Govers, G., Vandaele, K., 1999. Importance of slope gradient and contributing area for optimal prediction of the initiation and trajectory of ephemeral gullies. Catena 37, 377–392.

Donker, N.H.W., Damen, C.J., 1984. Gully system development and assessment of gully initiation risk in Miocene deposits near Daroca-Spain. Zeitschrift fur Geomorphologie, N.F., Supplementband 49, 37–50.

Dymond, R.J., Hicks, D.L., 1986. Steepland erosion measured from historical aerial photographs. Journal of Soil and Water Conservation 41, 252–255.

Giordano, A., Marchisio, C., 1991. Analysis and correlation of the existing soil erosion maps in the Mediterranean basin. Quaderni di Scienza del Suolo 3, 97–132.

Heede, H., 1979. Gully development and control. USDA Forest Service Research Paper RM-169, Second edition, Fort Collins.

Imeson, A.C., Kwaad, F.J.P.M., 1980. Gully types and gully prediction. K.N.A.G. Geografisch Tijdschrift XVI (1980) 5, 430–441.

Ireland, H.A., Sharpe, C.F., Eargle, D.H., 1939. Principles of gully erosion in the Piedmont of South Carolina. US Department of Agriculture, Technical Bulletin 63, 1–143.

Martínez-Casasnovas, J.A., 1998. Soil–landscape–erosion. Gully erosion in the Alt Penedès-Anoia (Catalonia, Spain). A spatial information technology approach: spatial databases, GIS and remote sensing. PhD thesis, University of Lleida, Lleida, Spain.

Martínez-Casasnovas, J.A., Poch, R.M., 1998. Estado de conservación de los suelos de la cuenca del embalse Joaquín Costa. Limnetica 14, 83–91.

Moore, I.D., Burch, G.J., Mackenzie, D.H., 1988. Topographic effects on the distribution of surface soil water and the location of ephemeral gullies. Transactions of the ASAE 31 (4), 1098–1107.

Nachtergaele, J., Poesen, J., 1999. Assessment of soil losses by ephemeral gully erosion using high-altitude (stereo) aerial photographs. Earth Surface Processes and Landforms 24, 693–706.

Oostwoud Wijdenes, D.J., Poesen, J., Vandekerckhove, L., Ghesquiere, M., 2000. Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. Catena 39, 147–167.

Palacio, J.L., López, J., 1994. Videography: an alternative remote sensing tool for monitoring gully erosion. ITC Journal 1994-3, 233–237.

Poesen, J.W., 1993. Gully typology and gully control measures in the European loess belt. In: Wicherek, S. (Ed.), Farm Land Erosion in Temperate Plains Environment and Hills. Elsevier Sciences Publishers, Amsterdam, The Netherlands, pp. 221–239.

Poesen, J.W., Vandaele, K., van Wesemael, B., 1996. Contribution of gully erosion to sediment production on cultivated lands and rangelands. In: Walling, D.E., Webb, B.W. (Eds.), Erosion and Sediment Yield: Global and Regional Perspectives. IAHS Publication, vol. 236. IAHS Press, Wallingford, pp. 251–266.

Poesen, J.W., Vandaele, K., van Wesemael, B., 1998. Gully erosion: importance and model implications. In: Boardman, J., Favis-Mortlock, D. (Eds.), Modelling Soil Erosion by Water. NATO ASI Series, vol. I 55. Springer-Verlag, Berlin, pp. 285–311.

Porta, J., Ramos, M.C., Boixadera, J., 1994. Mechanical measures for runoff management and erosion control in the vineyards of North East Spain. In: Rickson, R.J. (Ed.), Conserving Soil Resources: European Perspective. CAB International, Wallingford, pp. 369–378.

Prosser, I.P., Abernethy, B., 1996. Predicting the topographic limits to a gully network using a digital terrain model and process thresholds. Water Resources Research 32, 2289–2298.

Sánchez-Bosch, I., Martínez-Casasnovas, J.A., 2000. Influence of land use changes and traditional soil conservation practices on erosion in the Penedès vineyard region (Catalonia). Third International ESSC Congress, "Man and Soil in the Third Millennium", Book of Abstracts, Valencia, 28 March–1 April 2000. European Society for Soil Conservation (ESSC). 197 pp.

Soil Survey Staff, 1998. Keys to Soil Taxonomy, 8th ed. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

Solè, Ll., Clotet, N., Gallart, F., Sala, I., 1986. Análisis de las posibilidades de las imágenes TM en la detección de áreas degradadas en sectores montañosos. In: Clotet, N., Solè, Ll. (Eds.), Coumunicaciones Científicas de la I Reunión Científica del Grupo de Trabajo de Teledetección. Institut d'Investigacions Geològiques Jaume Almera, Barcelona, pp. 335–363.

Stocking, M.A., 1980. Examination of the factors controlling gully growth. In: De Boodt, M., Gabriels, D. (Eds.), Assessment of Erosion. Wiley, Chichester, pp. 505–520.

Thomas, A.W., Welch, R., Jordan, T.R., 1986. Quantifying concentrated-flow erosion on cropland with aerial photogrammetry. Journal of Soil and Water Conservation 41, 249–252.

Thompson, J.R., 1964. Quantitative effect of watershed variables on rate of gully head advancement. Transactions of the ASAE 7, 54–55.

Usón, A., 1998. Medidas de control de la erosión en suelos de viña de las comarcas Anoia-Alt Penedès (Barcelona): efectividad y viabilidad. PhD thesis, University of Lleida, Lleida.

Van Zuidam, R.A., 1986. Aerial Photo-Interpretation in Terrain Analysis and Geomorphologic Mapping. Smits Publishers, The Hague.

Vandaele, K., Poesen, J.W., Marques de Silva, J.R., Govers, G., Desmet, P., 1997. Assessment of factors controlling ephemeral gully erosion in Southern Portugal and Central Belgium using aerial photographs. Zeitschrift fur Geomorphologie, N.F. 41 (3), 273–287.

Williams, A.R., Morgan, R.P.C., 1976. Geomorphological mapping applied to erosion evaluation. Journal of Soil and Water Conservation 31, 164–168.