

## **Contribution of gully erosion to sediment production on cultivated lands and rangelands**

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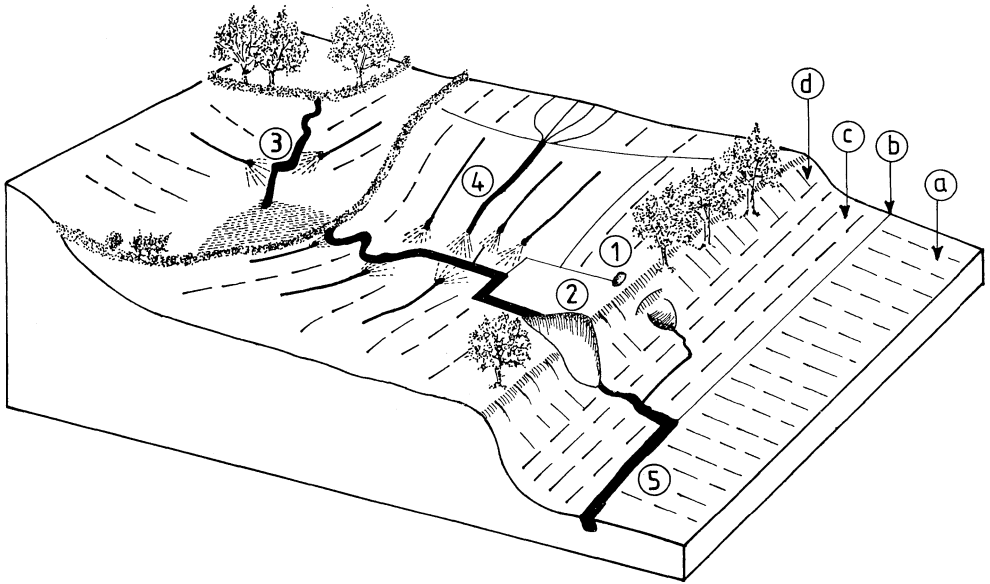
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**Abstract** Sediment production by gully erosion and by interrill and rill erosion in three study areas, representing contrasting agricultural environments (i.e. central Belgium, southeast Portugal and southeast Spain), is assessed through soil erosion mapping and analysis of aerial photos. The data indicate that mean annual soil losses due to ephemeral gully erosion are far from negligible in the studied environments: i.e.  $3.6 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  in central Belgium,  $3.2 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  in southeast Portugal and  $9.7 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  in southeast Spain. Mean sediment production by ephemeral gully erosion represents 44% of total sediment produced in intensively cultivated small catchments with loess-derived soils, but 80% or more in Mediterranean areas with stony soils. These figures are not constant for the studied environments but vary over time with rainfall intensity and land-use. The limited data available indicate that sediment production due to bank gully erosion is about one order of magnitude smaller than sediment produced by ephemeral gully erosion in central Belgium. The results obtained indicate that more attention should be given to the rate of ephemeral gully erosion when assessing and modelling the impact of environmental change on sediment production.

### **BACKGROUND**

When measuring and modelling sediment production due to water erosion on agricultural land, most attention has hitherto been given to interrill (sheet) and rill erosion. Gully erosion has received much less attention, particularly in Europe. However, field observations in a variety of agricultural environments made over the last decade indicate that, besides interrill and rill erosion, gully erosion is often an important sediment source.

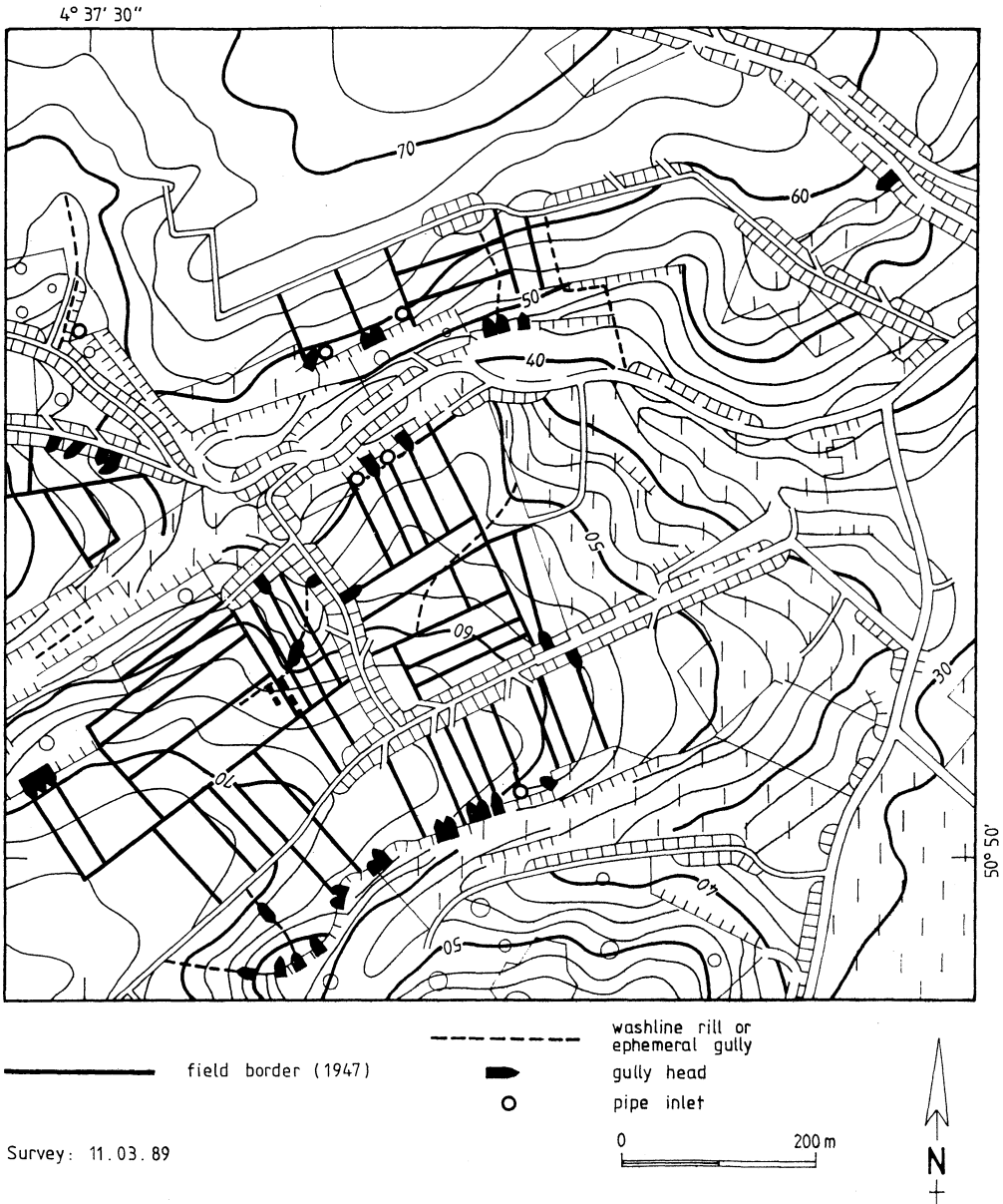
A gully has been defined as a steep-sided channel, often with a steeply sloping and actively eroding head scarp, caused by erosion due to the intermittent flow of water, usually during and immediately following heavy rains. In some cases ephemeral gullies have been observed to have formed by concentrated saturation overland flow or even snowmelt. These channels are deep enough to interfere with, and not to be obliterated by, normal tillage operations (Bradford & Piest, 1980; Soil Science Society of America, 1984). Because "normal" tillage operations vary both in space and time, there are no widely agreed upon dimensions for distinguishing gullies from rills. In this study we use



**Fig. 1** Sketch illustrating various gully types on agricultural lands (partly after Farres *et al.*, 1993). 1 = pipe inlet; 2 = bank gully; 3 = ephemeral gully in valley-bottom; 4 = ephemeral gully in valley-side; 5 = ephemeral gully in linear landscape element; a = tillage direction; b = limit of headland; c = headland; d = bank (lynchet).

the more rigorous definition proposed by Hauge (1977): i.e. gullies are distinguished from rills by a critical channel cross-sectional area of one foot<sup>2</sup> (= 929 cm<sup>2</sup>). This threshold is also perceived by farmers as a critical channel size above which the channels start to interfere with the trafficability of the land (Souchère, 1995). Based on their location in the landscape and on their morphology, as well as on the dominant erosion process leading to their formation, two main gully types have been recognized in European agricultural lands (Poesen, 1989, 1995; Poesen & Govers, 1990): ephemeral gullies and bank gullies. Figures 1 and 2 illustrate their characteristic location in the landscape. Although Fig. 1 was based on observations made in Northern Europe, it can be safely said that both gully types are also found in other agricultural environments such as those of the Mediterranean (Poesen, 1995).

Ephemeral gullies form where overland flow concentrates, i.e. either in natural drainage-lines (thalwegs of zero order basins or hollows) or along (or in) linear landscape elements such as, for instance, drill lines, dead furrows coinciding with parcel borders or at the limit of headlands, tractor ruts, unpaved access roads, etc... (Poesen 1989, 1993; Poesen & Govers 1990). These erosion features are continuous, temporary channels, which are often erased by tillage operations. By applying the definition of Hauge (1977), the boundary between a rill and an (ephemeral) gully becomes clear-cut. Ephemeral gullies seem to result essentially from hydraulic erosion by concentrated overland flow. This implies that sediment detachment and removal is essentially a function of flow intensity. Ephemeral gullies can be further classified on the basis of their topographic location as valley-side, valley-head and valley-bottom gullies (Brice, 1966). Practical considerations suggest subdivision of ephemeral gullies according to their width-depth ratio ( $w/d$ ) (Poesen & Govers, 1990; Poesen, 1993). Wide ephemeral



**Fig. 2** Excerpt of topographic map (Korbeek-Dijle, Belgium) showing typical locations of ephemeral gullies and bank gullies in central Belgium (after Poesen, 1993). All gully heads located on a bank are bank gullies. Note that the positions of a number of bank gullies coincide with the position of old field borders mapped from aerial photos (1947; after Vandaele, 1996).

gullies with a  $w/d \gg 1$  cause important crop damage. In addition, a high percentage of total soil lost through gully erosion consists of fertile topsoil with a high organic matter and fertilizer content. These gullies are, however, easily erased by conventional tillage. On the other hand, narrow and deeper ephemeral gullies with a  $w/d = 1$  or even  $< 1$  cause

relatively little crop damage and the percentage of total soil loss consisting of fertile topsoil is significantly less compared to fertile topsoil losses for wide gullies. The deep and narrow gullies, however, are not easily erased by conventional tillage and often heavy equipment is required to reshape the areas where they form. The infilling of these gullies often creates topographic depressions in which new gullies will develop subsequently.

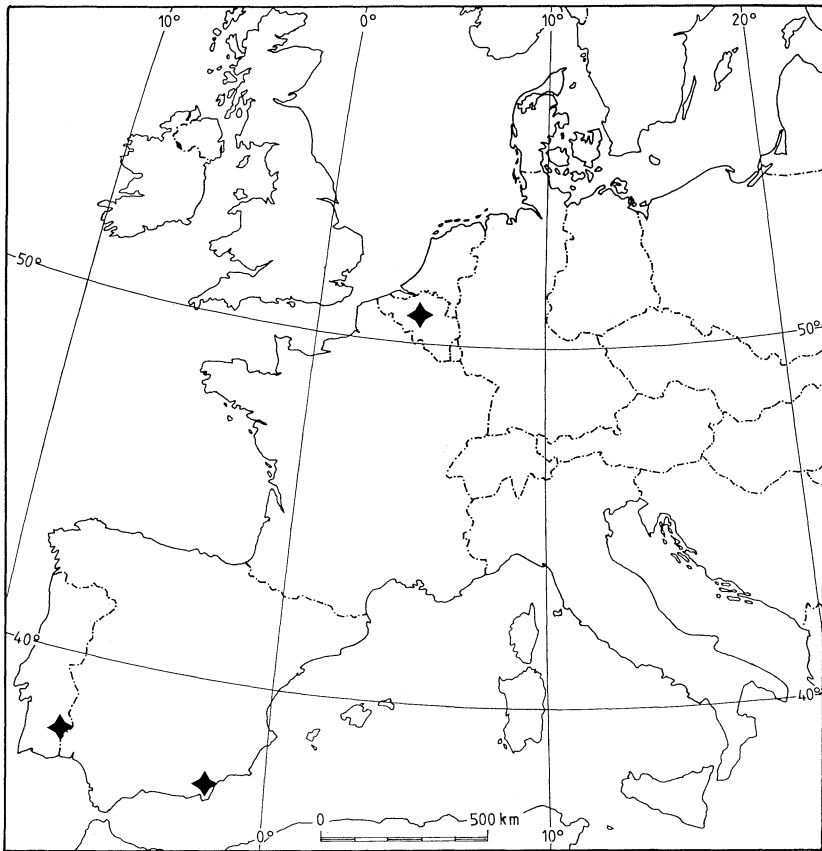
Bank gullies form where a wash-line, a rill, a dead furrow or an ephemeral gully crosses an earth bank (e.g. a terrace bank, a lynchet, an exploitation shoulder or a sunken lane bank) (Figs 1 and 2). These features are discontinuous, permanent channels which usually cannot be obliterated by conventional tillage operations. This gully type was first described in northern Europe (Poesen, 1989; Poesen & Govers, 1990, Farres *et al.*, 1993) and later also in Mediterranean environments (Poesen, 1995). Bank gully erosion seems to be less controlled by overland flow intensity and more by factors controlling piping and mass movement (i.e. slumping and soil fall). The latter processes are less controlled by the catchment size but depend more on the local site characteristics, such as the presence and density of biopores and cracks, and soil type. This implies that prediction of the exact location and the volume eroded by bank gullies is more difficult than for ephemeral gullies (Poesen, 1989, 1993). However, bank gullies often develop where a bank crosses a dead furrow (on a parcel border) which intercepts overland flow and directs this flow to the bank (Fig. 2).

In the framework of environmental change studies, there is a need to predict more accurately the contribution of various soil erosion processes to sediment production at the catchment scale. Therefore, this paper attempts to quantify the contribution of the two gully erosion types to sediment production in cultivated lands and rangelands of western Europe and to elucidate the controlling factors. In order to assess the contribution of (ephemeral) gully erosion to sediment production, soil losses due to interrill-, rill and (ephemeral) gully erosion were assessed in three contrasting European environments with increasing aridity: i.e. a temperate humid environment (central Belgium), a Mediterranean environment (southeast Portugal) and an arid environment (southeast Spain) (Fig. 3). The sediment production by bank gully erosion is quantified for a study area in central Belgium. Before discussing the methodology and the results, the studied environments are briefly described. More information regarding the Belgian study sites can be found in Vandaele & Poesen (1995) and in Vandaele *et al.* (in press).

## DESCRIPTION OF STUDY SITES

### Central Belgium

The study area in central Belgium is located between Leuven and Brussels and is part of the north European loess belt (Fig. 3). The depth of the loess cover ranges between a few cm and 10 m. The loess sheet covers Tertiary sandy deposits. Topsoils have a very high silt content (70-80%) and a moderate clay content (10-20%). The study area is characterized by a dense network of dry valleys. The land in this region has been under cultivation for at least 1000 years and is presently used for the production of winter wheat and barley (autumn sown), sugar beet, potatoes, maize and chicory (spring sown).



**Fig. 3** Location of three study sites in western Europe: i.e. central Belgium, southeast Portugal and southeast Spain.

About 4% of the study area has slopes exceeding 10%. Mean annual precipitation ranges between 700 and 850 mm and precipitation is relatively well distributed over the year.

### **Southeast Portugal**

The study area in Portugal is located in the Alentejo region, 5 km east of Mertola (Vandaele *et al.*, in press, Fig. 3). The typical red schist soils are very shallow (depth ranges between several centimetres and several decimetres) due to intense erosion by water as well as tillage erosion which took place since the 1930s (Poesen & Lavee, 1994). The rock fragment content by mass equals about 30%. The area is characterized by a network of dry valleys, while most valley-bottoms are incised by an intermittent stream network. Around the 1930s, the matorral (scrub and oak vegetation) was cleared on a large scale for autumn-sown winter wheat and barley production (Tomas & Coutinho, 1994). The traditional and most widely-spread crop rotation is wheat-fallow (de Lima, 1989). Slopes in this study area are gentle with only 8% of the area having slopes exceeding 10%. The climate is typical Mediterranean with a mean annual

precipitation of 560 mm (Beja) and a maximum rainfall between October and March. This means that the fields are unprotected during the period with the highest rainfall amounts.

### **Southeast Spain**

The study area in southeast Spain is located 25 km east of the town of Almeria at the footslopes of the Sierra de Gata (Fig. 3). These footslopes are typical piedmonts with a coarse weathering mantle on andesitic rock and, in their basal part, extensive alluvial fan systems of late Pleistocene age (Harvey, 1987). Soil depth ranges between 25 cm in the upper parts to more than 1 m in the lower parts (Poesen *et al.*, in preparation). There is an abundance of angular rock fragments in the upper parts (20 to 50% rock fragment cover). The soils have a sandy loam texture and an organic rich topsoil (mollic epipedon). Before 1983, the study area was cultivated for rainfed cereal production. Since 1983, this land became abandoned and was used as rangeland (regular grazing by sheep and goats). It is sparsely vegetated with annuals and bushes (e.g. *Thymelaea hirsuta*). Since land abandonment, a dense rill and gully network developed which was mapped in 1993. Slopes range between 3% in the lower parts and 20-25% in the upper parts. 30% of the study area has slopes exceeding 10%. Mean annual precipitation is 180 mm and rains are concentrated in winter and early spring.

### **METHODS**

Different techniques were used to assess soil losses by gully erosion as well as by rill and interrill erosion in the three study sites.

For the study site in central Belgium, two techniques were used: i.e. mapping of all erosion features in the field and an analysis of aerial photos. Detailed seasonal mapping at a scale of 1:5000 of all rills and gullies observed in an intensively cultivated 25 ha catchment (Hammeveld-1 catchment, Vandaele & Poesen, 1995) was conducted during a three year monitoring period (October 1989-October 1992). At the same time, measurements of the cross-section of erosion channels (rills and gullies) with a minimum depth of 1 cm and a minimum length of 10 m as well as their total length were made. Next, eroded volumes were calculated. It should be kept in mind that the calculated soil volumes eroded by ephemeral gullying represent minimum values, since most ephemeral gullies experience repeated cycles of cut and fill between tillage events, so that the actual soil loss due to concentrated flow may be several times the volume indicated by the periodic measurement of channel cross-sectional area (Thorne *et al.*, 1986). Secondly, detailed measurements of the length of ephemeral gullies in a study area ranging between 272 and 1074 ha using aerial photos at a scale varying between 1:15 000 and 1:21 000 were made (Vandaele *et al.*, in press). The aerial photos were taken in 1963, 1969, 1971, 1981 and 1986. These photos are considered to be a random sample of the time series. Only ephemeral gullies with a width greater than about 1.0 m could be detected on these photos. Since ephemeral gullies with a width less than 1.0 m were not included in these calculations, and since aerial photos were not taken at the optimal period for detecting ephemeral gullies, a percentage of the existing gullies in that year

were no longer visible on the photos (for instance, because they were already filled in by the farmers or because they were overgrown by weeds), and the values obtained using this method are rather conservative. Based on numerous field measurements of mean ephemeral gully cross-sections, volumes eroded by ephemeral gullies were calculated using two sets of cross-sectional data (depth  $\times$  width): i.e.  $0.20 \times 1.00 \text{ m}^2$  and  $0.30 \times 1.50 \text{ m}^2$  (Vandaele *et al.*, in press). These data were compared with published interrill and rill soil loss data obtained from field plots in the study area.

In southeast Portugal, detailed measurements of the length of ephemeral gullies in a study area ranging between 270 and 553 ha were made using aerial photos at a scale of 1:15 000 (Vandaele *et al.*, in press). The aerial photos were taken in 1970, 1978 and 1985. Based on field measurements of mean ephemeral gully cross-sections, volumes eroded by ephemeral gullies were calculated using two sets of cross-sectional data (depth  $\times$  width): i.e.  $0.15 \times 0.50 \text{ m}^2$  and  $0.25 \times 1.50 \text{ m}^2$  (Vandaele *et al.*, in press). For the reasons outlined for the aerial photo-analysis in central Belgium, the soil loss data for ephemeral gully erosion in southeast Portugal are rather conservative. Data on sediment production by ephemeral gully erosion were compared to reported interrill and rill soil loss data collected from field plots ( $20 \times 8.3 \text{ m}^2$ ) in the study area ("Vale Formoso" experimental station, Tomas, 1992).

Finally, in southeast Spain, detailed mapping at a scale of 1:500 of all rills and gullies on a representative 10 ha footslope section (Cerro Pistolas, Sierra de Gata, Almeria) was conducted (Poesen *et al.*, in preparation). The rills and gullies developed during a period of 10 years (1983 = year of abandonment; 1993 = year of erosion mapping). Transects, 200 m long, were established parallel to the contour every 10 m along the slope over a length of 500 m. Along each transect, location, width and depth of all rills and gullies (minimum depth = 1 cm) were recorded. The sum of rill and gully cross-sections was calculated for each transect. Total soil loss due to rill and gully erosion was calculated by multiplying the sum of rill and gully cross-sections with a slope length of 10 m per transect, and summing these values over the entire 10 ha field area.

## CONTRIBUTION OF EPHEMERAL GULLY EROSION TO SEDIMENT PRODUCTION IN THE THREE STUDY AREAS

### Central Belgium

Table 1 shows a good agreement between ephemeral gully soil loss data obtained by detailed field monitoring and data extracted from aerial photos. The data in Table 1 indicate that mean soil loss due to ephemeral gully erosion is far from negligible and is, on average, 44% of total soil lost. For the Ganspoel catchment in central Belgium, Vandaele (1996) reported this fraction to amount to 55% of total sediment produced in a three year study period (1989-1992). Quine *et al.* (1994) calculated, on the basis of caesium-137 patterns, that ephemeral gullying in the thalweg of a 2.3 ha zero-order catchment in central Belgium, accounted for 60% of the total long-term sediment export by water erosion.

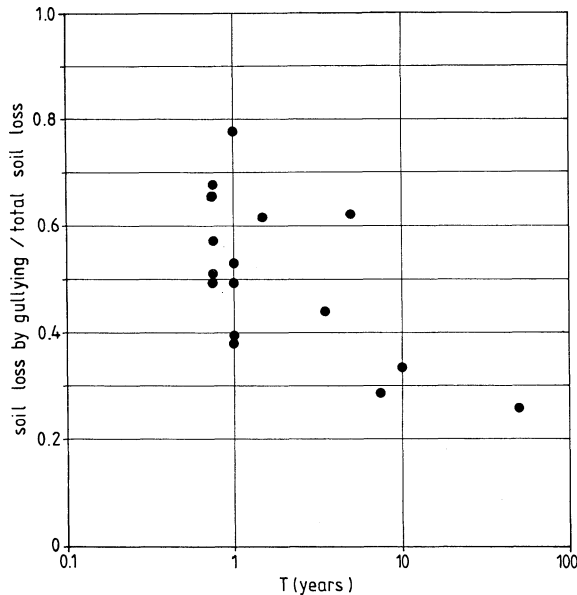
Vandaele & Poesen (1995) also showed that this percentage varies throughout the year and obviously between erosion events. Figure 4 shows that the ratio between soil loss by gullying and total soil loss from three small catchments in central Belgium

**Table 1** Sediment production by various water erosion processes in central Belgium.

Method	Observation period (years)	Ephemeral gully <sup>a</sup> (m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup> )	Interrill and rill <sup>a</sup> (m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup> )	% Gully <sup>b</sup> Source
Field mapping	3	3.4	4.0*	46 Vandaele & Poesen (1995)
Aerial photos	5	2.3-5.1**		Vandaele <i>et al.</i> (in press)
Runoff plots	5		5.8	Bollinne (1982)
Field mapping	3		4.0*	Govers (1991)***
Mean		3.6	4.6	44

<sup>a</sup> Figures for interrill and rill as well as for ephemeral gully erosion are average values for the observation period.  
<sup>b</sup> % Gully equals the percentage of total soil loss due to ephemeral gully erosion.  
 \* Soil loss due to interrill erosion was assumed to be 10% of total soil lost. This figure is based on data reported in the literature for comparable conditions (Govers & Poesen, 1988).  
 \*\* Eroded volumes by ephemeral gully erosion were calculated using two sets of cross-sectional data (depth × width): i.e. 0.20 × 1.00 m<sup>2</sup> and 0.30 × 1.50 m<sup>2</sup>.  
 \*\*\* These data only include observations made during the winter period.

decreases with an increasing return period of the rainstorm (Vandaele, 1996). In other words, the relative contribution of gully erosion to total sediment production within the catchments decreases when the 30 minute rainstorm intensity increases. This is attributed to a corresponding increase in rill erosion rates on the hillslopes within the catchment.



**Fig. 4** Relation between return period (T) of rainstorms and ratio of soil loss by gully erosion and total soil loss (i.e. due to interrill, rill and gully erosion) in small (25 ha) catchments of central Belgium. Return periods are for 30 min rainfall intensity values. Data are compiled by Vandaele (1996).



Since low intensity rains in the study area prevail in the winter period, the relative contribution of gully erosion to total sediment production is higher during that period compared to the spring and summer periods which are characterized by more intense rainstorms (Vandaele & Poesen, 1995).

Beside rainfall regime, vegetation cover and pattern within the catchment seem also to control the percentage of total soil loss due to ephemeral gully erosion. For instance, during an extreme rainstorm in the early summer of 1991 (26 mm of rain in 30 min, with a return period of about 50 years) in central Belgium, the contribution of ephemeral gully erosion to total sediment production in the studied catchment was only 24% (Fig. 4) because the hillslopes under sugar beet, potatoes and chicory exhibited intense interrill and rill erosion (Vandaele, 1995). However, a high intensity rainfall event (20 mm in 20 min, total rain = 80 mm) at the end of August 1995 produced limited interrill and rill erosion on the hillslopes but considerable gully erosion in thalwegs and dead furrows under sugar beet or maize. This is attributed to the high vegetation cover (stubble and straw mulch) on most hillslopes at that time of the year.

### Southeast Portugal

The mean contribution of ephemeral gully erosion to total sediment production amounts to 80% (Table 2) and is thus more important than the gully contribution found for central Belgium. One of the reasons is the fairly high rock fragment contents of Portuguese soils (30% by mass on average) which reduces interrill and rill erosion (Poesen *et al.*, 1994) but not necessarily overland flow production. This overland flow causes ephemeral gully erosion to occur more downslope in topographic concavities (hollows) and in linear landscape elements.

**Table 2** Sediment production by various water erosion processes in southeast Portugal.

Method	Observation period (years)	Ephemeral gully <sup>a</sup> (m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup> )	Interrill and rill <sup>a</sup> (m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup> )	% Gully <sup>b</sup>	Source
Aerial photos	3	1.1-5.3*			Vandaele <i>et al.</i> (in press)
Runoff plots	20		0.2-1.3		Tomas (1992)**
Mean		3.2	0.8	80	

<sup>a</sup> Figures for interrill and rill as well as for ephemeral gully erosion are average values for the observation period.

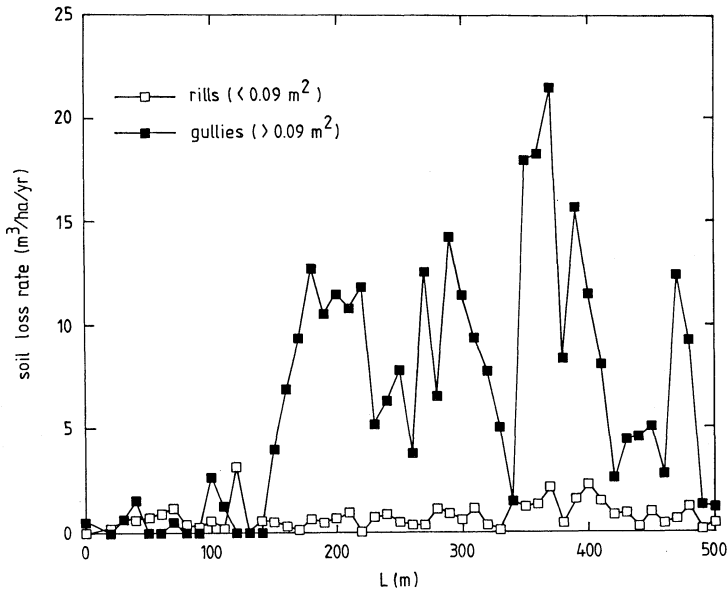
<sup>b</sup> % Gully equals the percentage of total soil loss due to ephemeral gully erosion.

\* Eroded volumes by ephemeral gullies were calculated using two sets of cross-sectional data (depth x width): i.e. 0.15 x 0.50 m and 0.25 x 1.50 m.

\*\* Soil loss data are means for 13 plots with different crop rotations (wheat-leguminosa-wheat, wheat-leguminosa, fallow-wheat).

### Southeast Spain

Figure 5 shows the rates of soil loss by rill erosion and by gully erosion along the hill-slope at the Spanish study site. From 0 to 140 m, rill and gully erosion rates are of equal



**Fig. 5** Rates of soil loss due to rill erosion and due to gully erosion as a function of position along the study hillslope in southeast Spain. L is length measured from upper part of the abandoned field plot.

importance, i.e.  $1\text{--}2\text{ m}^3\text{ ha}^{-1}\text{ year}^{-1}$ . However, for slope lengths  $> 140\text{ m}$ , gully erosion rates (i.e. up to  $20\text{ m}^3\text{ ha}^{-1}\text{ year}^{-1}$ ) become far more important than rill erosion rates.

The calculated mean interrill and rill soil loss for the studied abandoned hillslope (Table 3:  $2.0\text{ m}^3\text{ ha}^{-1}\text{ year}^{-1}$ ) are higher than those reported for similar land-uses elsewhere in the Mediterranean: i.e.  $0.01\text{--}1.5\text{ m}^3\text{ ha}^{-1}\text{ year}^{-1}$  (Poesen *et al.*, in preparation). One of the possible reasons is that the vegetation cover on our studied slope was significantly lower than the vegetation cover on abandoned agricultural land in the other studies.

The results from the three study sites indicate that soil loss due to ephemeral gullying is far from negligible: mean ephemeral gully erosion rates are almost as important as interrill and rill erosion rates in central Belgium, but are more important in

**Table 3** Sediment production by various water erosion processes in southeast Spain.

Method	Observation period (years)	Ephemeral gully <sup>a</sup> ( $\text{m}^3\text{ ha}^{-1}\text{ year}^{-1}$ )	Interrill and rill <sup>a</sup> ( $\text{m}^3\text{ ha}^{-1}\text{ year}^{-1}$ )	% Gully <sup>b</sup>	Source
Field map	10	9.7	2.0*	83	Poesen <i>et al.</i> (in preparation)

<sup>a</sup> Figures for interrill and rill as well as for ephemeral gully erosion are average values for the observation period.

<sup>b</sup> % Gully equals the percentage of total soil loss due to ephemeral gully erosion.

\* Soil loss due to interrill erosion was assumed to be 10% of total soil lost. This figure is based on data reported in the literature for comparable conditions (Govers & Poesen, 1988).

Mediterranean environments, particularly in abandoned cultivated land (rangelands). Furthermore, it should not be forgotten that data on ephemeral gullying extracted from aerial photos result in conservative figures (see above). For rangelands on abandoned cultivated lands, it is assumed that interrill and rill erosion are drastically reduced by the vegetation cover, but also by the presence of a well-developed erosion pavement. Hence, sediment concentrations in overland flow generated on the intergully areas will be quite low. More downslope, this overland flow is often responsible for rapid gully development, mainly due to the clearwater effect.

The scarce data available indicate that the contribution of gully erosion to total soil loss from agricultural catchments can vary considerable in space and in time. More research is needed to elucidate how various factors such as precipitation, topography, soils and land-use affect this contribution.

One implication of these results is that they indicate whether valley incision or valley aggradation will dominate: interrill and rill erosion mainly occur on upland areas whereas ephemeral gully erosion dominantly occurs in valley bottoms of zero order catchments (Vandaele & Poesen, 1995). If the contribution of gully erosion to total soil loss exceeds 50% (such as for instance in southeast Portugal and in southeast Spain), one may expect the valley bottoms to deepen if no other erosion process takes place (such as for instance tillage erosion). If, on the other hand, the gully contribution is less than 50%, one may expect valley aggradation to take place. If one looks at the figures for central Belgium, one may expect slight valley aggradation to take place in central Belgium and a deepening of the valley bottoms in southeast Portugal and in southeast Spain, assuming that no other erosion process produces sediment on the slopes. If land abandonment takes place, valley-floor lowering dominates, because less sediment is produced by interrill and rill erosion on the slopes, and concentrated overland flow will incise valley bottoms. The latter situation has been observed on many abandoned lands throughout the Mediterranean where abandoned slopes become covered by matorral and rock fragments (erosion pavements).

## **COMPARISON OF OBSERVED DATA ON EPHEMERAL GULLY EROSION WITH PUBLISHED DATA FOR OTHER AREAS**

Published data on soil losses by various water erosion processes in other study areas in Europe and North America allow the contribution of (ephemeral) gully erosion to sediment production in small agricultural catchments to be calculated. These results should, however, be used with caution because they are partly based on methods and models involving a high degree of uncertainty.

In northern France (Pays de Caux), an area with loess-derived soils, Souchère (1995) obtained a mean soil loss figure for ephemeral gullies (which developed only in valley-bottoms) of  $2 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  for 18 small catchments (3.5-64 ha) during observation periods ranging between 1 to 8 months only (1991-1993). This value is of the same order of magnitude as the values reported in this study for the study site in central Belgium with similar soils and land use (Table 1).

Table 4 lists some values for the percentage of total soil loss due to ephemeral gully erosion for two different areas in Europe with loess-derived soils. From this table one can deduce that the percentage of total soil loss due to ephemeral gully erosion ranges

**Table 4** Contribution of gully erosion to sediment production in different European areas with loess-derived soils.

Location	Study area	% Gully <sup>a</sup>	Source
North France	Loess-derived soils, winter and summer crops, conventional tillage	10-45	Ludwig <i>et al.</i> (1992)
North France	Loess-derived soils, winter and summer crops, conventional tillage, various catchments with a mean size of 34 ha, slopes 7-11% (1988-1990)	44-46	Auzet, personal communication in Vandaele & Poesen (1995)
Southwest Germany	Loess-derived soils, winter and summer crops, conventional tillage, 2.8 ha, slopes = 7-12% (1991-1992)	36	Baade (1994)
Range		10-46	

<sup>a</sup> % Gully equals the percentage of total soil loss due to ephemeral gully erosion

between 10 and 46%, which is also in accordance with the data reported in this study for central Belgium (Table 1). Bogen *et al.* (1994) reported gully erosion on agricultural land and bank erosion to contribute 55% of the total sediment load of the River Leira in southern Norway.

Data on the contribution of gully erosion to total sediment production in North America range between 19 and 81% (Table 5). Glymph (1957) calculated that gully erosion was from zero to 89% of the sediment yield from 113 watersheds in various parts of the USA. Few data on this parameter exist outside North America and Europe. Heusch (1980) reported that in the semiarid part of Niger (Ader Dutchi Massif), gullying produced almost 80% of the annual sediment yield. Oostwoud Wijdenes & Bryan (1994) found that sediment produced from gully headcut retreat in a 1.2 ha catchment in the semiarid part of Kenya represented 53% of the total sediment output of the catchment. For an arid environment in Argentina, Coronato & del Valle (1993) reported that gullying in a 1152 ha study area was responsible for 58% of total sediment production.

From Tables 1, 2, 3, 4 and 5, the following conclusions can be drawn.

- (a) The calculated values for the gully contribution to sediment production for the European study sites (Tables 1, 2 and 3) fit fairly well with calculated data from other areas (Tables 4 and 5).
- (b) Despite the fact that the methods used in most studies produce conservative figures for soil loss by ephemeral gullying, the data indicate that the gully contribution is far from negligible in all environments. The percentage of total soil loss due to (ephemeral) gully erosion exceeds 10% in all studies. In particular environments, such as in the Mediterranean and on rangelands, gully erosion seems to be the main source of sediment in upland areas, producing up to 83% of the total sediment production in small catchments (Tables 3 and 5).
- (c) For catchments with slopes producing low amounts of sediment by interrill and rill erosion, such as for instance slopes under grassland (Table 5: Bradford & Piest, 1980), or slopes under rangeland with well-developed erosion pavements (Table 3: Poesen *et al.*, in preparation; Table 5: Osborn & Simanton, 1989) gullies contribute significantly more to sediment yield (63-81%) than if the slopes produced large

**Table 5** Contribution of gully erosion to sediment production in North America.

Location	Study area	% Gully <sup>a</sup>	Source
USA (Athens, Georgia)	Sandy loam soils, conventional tilled soybeans and untilled fallow during winter, 3 ha, slopes = 5-6%	28	Thomas & Welch (1988); Lafflen (1985)
USA (Athens, Georgia)	Sandy loam soils, double-cropped soybeans and winter wheat, 2-8 ha, slopes = 6%	30	Thomas <i>et al.</i> (1986); Lafflen (1985)
USA (Iowa)	Loess soil, 8 ha, slopes = 3-11%	20	Lafflen (1985)
USA (Iowa)	Glacial till, 4 ha, slopes = 2%	19	Lafflen (1985)
USA (Iowa)	Loess soil, conservation tillage, continuous corn on contour, 43 ha, steep slopes (1972-1983)	35	Lafflen (1985); Spomer & Hjelmfelt (1985)
USA (Iowa)	Loess soil, conventional tillage, continuous corn on contour, 24 ha, steep slopes (1964-1983)	22	Lafflen (1985); Spomer & Hjelmfelt (1985)
USA (Iowa)	Loess soil, continuous corn, field contoured, 30-33.5 ha (1964-1976)	19-21	Bradford & Piest (1980)
USA (Iowa)	Loess soil, pasture grass (bromegrass) rotation-grazed, 43 ha (1964-1972)	63	Bradford & Piest (1980)
USA (Alabama)	Soils from hydrologic group A	60	Lafflen (1985)
USA (Alabama)	Soils from hydrologic group B	50	Lafflen (1985)
USA (Mississippi)	Loess soil, conventional tilled soybeans, 1.9 ha (1985-1987)	60	Grissinger & Murphey (1989)
USA (Arizona)	Gravelly loam soils, rangeland (discontinuous cattle grazing), slopes = 3-15%, 3.7-4.4 ha (1973-1980)	60-81	Osborn & Simanton (1989)
Range		19-81	

<sup>a</sup> % Gully equals the percentage of total soil loss due to ephemeral gully erosion

amounts of sediment, such as in the several areas investigated with cropland on loess-derived soils (10-46%, Tables 1 and 4).

- (d) From the data it becomes clear that the relative contribution of gully erosion to total sediment production is not a constant for a given catchment. This relative contribution seems to vary with topography, rainfall intensity (Fig. 4), soil type, soil surface conditions and land use, amongst other factors. For instance, field data collected by Evans (1993) in the UK revealed that the contribution of gully erosion in valley-bottoms to total soil loss is most important in localities with dominantly heavier textured soils. Where soils were mostly silty, coarse loamy or sandy, rill erosion on the hillslopes became more important, reducing the relative contribution of ephemeral gully erosion in valley-bottoms to overall sediment production.
- (e) Given that gully erosion contributes significantly to sediment yield in small agricultural catchments, and that in particular environments it is even more important than interrill and rill erosion, more attention should be given to the study and prediction of (ephemeral) gully erosion and to how the intensity of this soil degradation process is affected by environmental change (climatic and land-use changes).

- (f) This study indicates that ephemeral gully erosion causes considerable on-site soil loss. In addition, sediment produced by ephemeral gully erosion and leaving the field or catchment can cause more off-site damage than would be expected by considering only interrill and rill erosion in the field or in the catchment.
- (g) Ephemeral gully erosion operates at spatial units which are larger than that occupied by the traditional runoff plot. Therefore, appropriate and standardized methods to study ephemeral gully erosion should be developed.

## SEDIMENT PRODUCTION BY BANK GULLY EROSION

The intensity of bank gully erosion in a given area depends on a number of factors such as the density of banks in the landscape, bank type, and the conditions favourable for bank gully initiation (e.g. production of overland flow and piping). However, few data exist on the importance of bank gully erosion. In order to assess their contribution to annual soil loss, data from two erosion surveys, made in central Belgium, are used (Poesen, 1989, 1993; Table 6). The areas are characterized by a moderate to high bank density (sunken lane banks, lynchets, old quarry banks). The results indicate that in such areas, bank gullies can produce significant amounts of sediment which can be as high as  $228 \text{ m}^3 \text{ ha}^{-1}$  of area draining into the bank gully. However, since bank gullies are seldom immediately erased, they remain visible during subsequent years. Hence, the measured bank gully volumes were assumed to have formed over a period ranging between 10 to 20 years. This results in soil loss rates due to bank gully erosion of  $0.2$  to  $0.5 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , which are one order of magnitude smaller than soil loss rates due to ephemeral gully erosion in this study area (Table 1:  $2.3$ - $5.1 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ).

**Table 6** Bank characteristics and sediment production by bank gully erosion in central Belgium.

Site	Area (ha)	Bank density ( $\text{m ha}^{-1}$ )	Bank gully volume ( $\text{m}^3$ )	Soil loss ( $\text{m}^3 \text{ ha}^{-1}$ )	Soil loss rate <sup>a</sup> ( $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ )	Source
Ormendaal	126	45.6	641.5	5.1	0.25-0.5	Poesen (1989)
Kinderveld	100	75.7	404	4.0	0.2-0.4	Poesen (1993)

<sup>a</sup> Soil loss rates are calculated assuming that the observed bank gullies formed in a period ranging between 20 and 10 years preceding the year of surveying.

Field observations in the Mediterranean reveal that bank gully erosion can be quite active on terraced land (Poesen, 1995). This is best seen once land abandonment has taken place. However, so far no data are available indicating the contribution of bank gully erosion to sediment production in such environments.

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