2.5

Gully Erosion in Europe

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2.5.1 INTRODUCTION

Soil erosion by water has received and still receives a lot of attention from scientists, soil conservationists and policymakers in Europe. However, when dealing with this soil degradation process, attention has merely been focused on sheet (interrill) and rill erosion rather than on gully erosion. This is reflected in the scientific literature, where more than 2200 plot-year data on soil loss by sheet and rill erosion in Europe have been published (see Chapter 2.4). Such data have been and are still being used to assess the impacts of land use on soil loss by water erosion or to develop, calibrate and validate various empirical and process-based water erosion models (addressing mainly sheet and rill erosion). Such models are then used for assessing soil erosion under global change or for establishing soil erosion risk maps at various scales (e.g. Van der Knijff *et al*., 2000). However, in many European landscapes under different pedo-climatic conditions and with different land uses one can observe the presence and dynamics of various gully types, e.g. ephemeral gullies, permanent or classical gullies and bank gullies. Field-based evidence suggests that sheet and rill erosion as measured on runoff plots are not always realistic indicators of total catchment erosion in Europe, nor do they indicate adequately the redistribution of eroded soil within a field. It is through (ephemeral) gully erosion that a large fraction of soil eroded within a field or catchment is redistributed and delivered to water courses (e.g. Evans, 1993; Martínez-Casasnovas *et al*., 2002).

Gully erosion in Europe has received much less attention than sheet and rill erosion, despite the fact that pictures from large or deep gullies are often shown to illustrate the seriousness of soil erosion by water in

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particular European study areas. Most studies, however, then zoom in on processes of runoff generation, splash erosion, interrill and rill erosion operating within the intergully zones without bothering too much about how these processes relate to gully erosion. Several reasons for the limited attention given to gully erosion can be put forward: (1) runoff plot research and available soil erosion models have focused the attention of people mainly on sheet and rill erosion, (2) gully erosion often occurs at spatial scales, which are beyond the traditional scale for investigating soil erosion by water (e.g. cultivated plots or parcels), (3) as gully erosion often occurs outside the boundaries of a field parcel, gully erosion is often not seen by farmers as a problem of their concern, (4) gully erosion is usually caused by more intense and hence less frequent climatic events and is therefore more difficult to measure and (5) gully erosion is apparently difficult to model.

Recent field-based studies indicate that (1) gully erosion is an important soil degradation process in a range of European environments, causing considerable soil losses and producing large volumes of sediment (e.g. Poesen and Valentin, 2003) and (2) (ephemeral) gully development increases the sediment connectivity in the landscape and hence also the sediment delivery to lowlands and permanent water courses where gullies aggravate off-site effects of water erosion (such as sediment deposition, flooding and pollution; e.g. Poesen and Hooke, 1997; Poesen *et al.*, 2003). Many cases of sediment and chemical pollution of watercourses and damage to properties by runoff from agricultural land relate to the occurrence of (ephemeral) gully erosion (e.g. Verstraeten and Poesen, 1999; Boardman, 2001; Ramos and Martínez-Casasnovas, 2004). However, soil losses caused by (ephemeral) gully erosion are rarely accounted for in current soil loss assessment programmes in Europe. For recent literature reviews on gully erosion in general, the reader is referred to Bull and Kirkby (2002) and Poesen *et al.* (2002, 2003).

The objective of this chapter is to provide more insight into the phenomenon of gully erosion in Europe by addressing the following questions.

1. What is gully erosion?
2. Where do gullies typically occur in Europe?
3. Is gully erosion a recent phenomenon in Europe?
4. How important is gully erosion in Europe?
5. What are the major consequences of gully erosion in Europe?
6. What are major triggering and controlling factors of gully erosion?
7. Do we have reliable gully erosion models in Europe?
8. How can gully erosion be prevented or controlled?
9. What are the main research needs for a better understanding of gully erosion and its control?

2.5.2 WHAT IS GULLY EROSION?

Gully erosion is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths (Figure 2.5.1). Permanent *gullies* (e.g. Figure 2.5.2) are often defined for agricultural land in terms of channels too deep to easily obliterate with ordinary farm tillage equipment, typically ranging from 0.5 to as much as 25–30 m in depth (Soil Science Society of America, 2001).

In the 1980s, the term *ephemeral gully erosion* (e.g. Figure 2.5.1 and 2.5.3) was introduced to include concentrated flow erosion phenomena larger than rill erosion but less than classical gully erosion, as a consequence of the growing concern that this sediment source used to be overlooked in traditional soil erosion assessments (Foster, 1986; Grissinger, 1996a,b). Even though in the literature ephemeral gullies are recorded on many photographs of erosion, it is only during the last two decades that these erosion phenomena have been recognised as being a

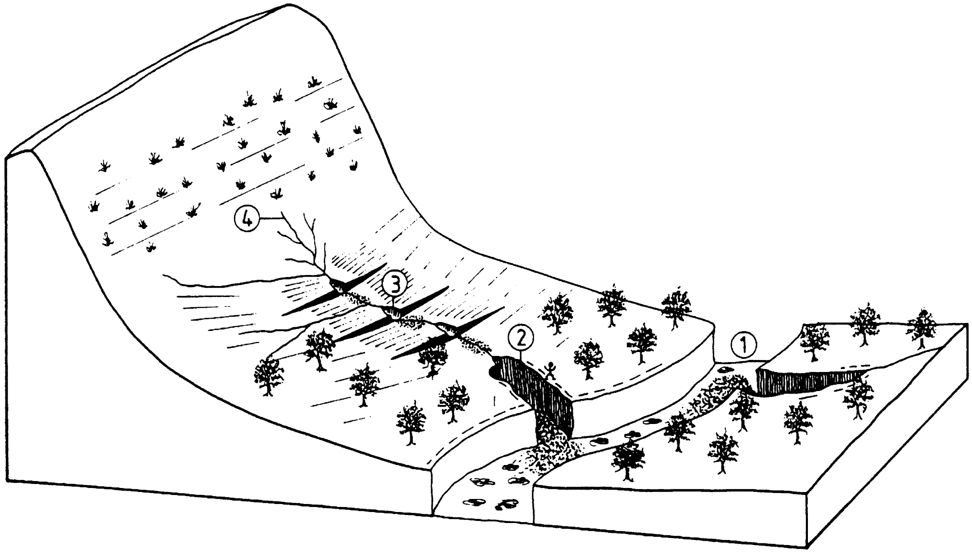

Figure 2.5.1 Sketch of a south European landscape illustrating the typical location of the various gully types discussed in this chapter. 1, River channel; 2, bank gully that developed in a river bank and the gully head that retreated in an orchard; 3, bank gully that developed in a terrace bank; and 4, ephemeral gully in cultivated land or permanent gully in rangeland. [From Poesen J *et al.*, Gully erosion in dryland environments, in *Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels*, Bull LJ, Kirkby MJ (eds), 2002, 229–262. Copyright John Wiley & Sons, Ltd. Reproduced with permission]

Figure 2.5.2 Permanent gully that developed in abandoned cropland (nowadays degraded rangeland) on a pediment (September 1996, El Nazareno, Almeria, Spain)

Figure 2.5.3 Ephemeral gully that developed in a maize field (July 1997, Bertem, central Belgium). Since the soil profile in the concentrated flow zone has locally been truncated, no resistant Bt horizon is present which resulted in a channel incision up to 0.80 m

major part of the erosional systems on cropland (Evans, 1993). According to the Soil Science Society of America (2001), *ephemeral gullies* are small channels eroded by concentrated overland flow that can be easily filled by normal tillage, only to form again in the same location by additional runoff events. Poesen (1993) observed ephemeral gullies to form in concentrated flow zones, located not only in natural drainage lines (thalwegs of zero-order basins or hollows) but also along (or in) linear landscape elements (e.g. drill lines, dead furrows, headlands, parcel borders, access roads). Channel incisions in linear landscape elements are usually classified as rills according to the traditional definitions that associate rill formation with the micro-relief generated by tillage or land forming operations (Haan *et al.*, 1994). However, such incisions may also become very large, so this classification seems unsuitable. In order to account for any type of concentrated flow channel that would never develop in a conventional runoff plot (used to measure rates of interrill and rill erosion), Poesen (1993) distinguishes rills from (ephemeral) gullies by a critical cross-sectional area of 929 cm^2 (square foot criterion). Hauge (1977) first used this criterion. Other criteria include a minimum width of 0.3 m and a minimum depth of about 0.6 m (Brice, 1966), or a minimum depth of 0.5 m (Imeson and Kwaad, 1980). As to the upper limit of gullies, no clear-cut definition exists. In other words, the boundary between a large gully and a(n) (ephemeral) river channel is very vague. Nevertheless, it must be acknowledged that the transition from rill erosion over ephemeral gully erosion and classical gully erosion to river channel erosion (Figure 2.5.1) represents a continuum, and any classification of hydraulically related erosion forms into separate classes, such as microrills, rills, megarills, ephemeral gullies and gullies, is, to some extent, subjective (Grissinger, 1996a,b). In fact, Nachtergaele *et al.* (2002a) demonstrated that the relationship between mean width of (ephemeral) gullies and concentrated flow discharge is very similar to the corresponding relation for rills and (small) rivers.

Figure 2.5.4 Bank gullies that developed in an ephemeral channel bank consisting of gravelly sandy loam. Gully headcut retreats into cropland (October 1996, Zarcilla de Ramos, Murcia, Spain)

By definition, *bank gullies*, also termed *edge-of-field gullies* in North America (Dabney *et al*., 2004) (see Figures 2.5.1 and 2.5.4), develop wherever concentrated runoff crosses an earth bank (e.g. river bank, terrace bank, sunken lane bank, lynchet or quarry bank). Given that the local slope gradient of the soil surface at the bank riser is very steep (i.e. subvertical to vertical), bank gullies can rapidly develop at or below the soil surface by hydraulic erosion, piping and eventually mass movement processes even though catchment areas are very small (Poesen and Govers, 1990). Once initiated, bank gullies retreat by headcut migration into the more gentle sloping soil surface of the bank shoulder and further into low-angled pediments, river or agricultural terraces (Poesen *et al*., 2002).

2.5.3 WHERE DO GULLIES TYPICALLY OCCUR IN EUROPE?

Gully erosion occurs throughout Europe. Typically, gullies can be found in croplands, rangelands and badlands. Figure 2.5.5 indicates on a map of western Europe (compiled by De Ploey, 1989a, based on literature and field observations) areas with arable land where rates of soil erosion by water may regularly exceed $10\,\mathrm{t\,ha^{-1}\,yr^{-1}}$. Such areas are characterised by periods during the year with low or negligible vegetation cover. If, in addition, the soils in these areas are susceptible to surface sealing, significant volumes of Hortonian runoff can be produced during rainfall, which in concentrated flow zones with slope gradients in excess of 4–5 % leads to the development of ephemeral gullies (e.g. Figure 2.5.3) and bank gullies (Figure 2.5.4).

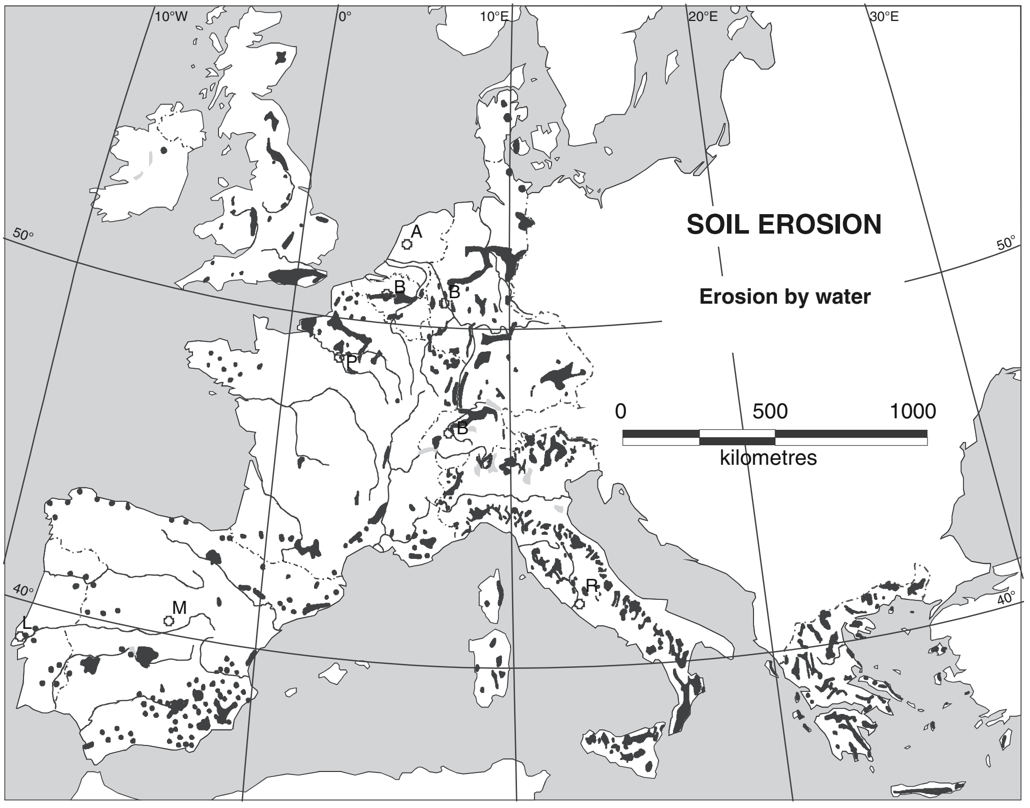

Figure 2.5.5 Map of western Europe indicating regions where soil erosion by water regularly exceeds soil loss tolerance levels. In most of these regions cropland is the dominant land use and ephemeral gully erosion frequently occurs. (From De Ploey J, *Soil Erosion Map of Europe*, 1989. Reproduced by permission of Catena-Verlag GmbH)

Active permanent gullies can be observed in a wide range of environments, from degraded rangelands (due to overgrazing or after burning schrubs), both in northern Europe (e.g. Iceland) and in Mediterranean Europe, to peatland (e.g. Wishart and Warburton, 2001).

Spectacular permanent, dense gully networks can be found in badland areas in the Mediterranean (Figure 2.5.6 and 2.5.7) but also in other severely eroded areas such as in Iceland. Badlands result from both water erosion and mass movement processes. These processes interact and their effects are therefore difficult to separate from each other, e.g. gullying by hydraulic erosion followed by gully wall collapse (mass failure) (Poesen and Hooke, 1997). Lithological conditions are important and badlands tend to develop on unconsolidated or poorly sorted materials such as shales, gypsiferous and salty-silty marls and silt-clay deposits of Tertiary and Quaternary age. Most badlands are situated on or near major mountain ranges, especially on those that are still being uplifted. Badlands evolve by surface and subsurface erosion by water, including chemical erosion (soil dispersion due to the high concentration of salts) and piping (Torri *et al*., 2000; Gallart *et al*., 2002). Characteristics of active badlands are high contemporary erosion rates, low surface permeabilities and high erodibilities. Measured erosion rates in Mediterranean badlands vary widely, ranging between 5 and 220–330 t ha^{-1} yr^{-1} (e.g. Benito *et al*., 1992; Bufalo and Nahon, 1992; Martínez-Casasnovas and Poch, 1998). This wide range is the result of differences in climatic, lithologic and topographic characteristics at the various study sites, differences in spatial and temporal scales considered, and also differences in measurement and calculation techniques used in the various studies.

Figure 2.5.6 Dense gully network in badlands that developed in marls (April 1999, Librilla, Murcia, Spain). The presence of such a gully network near a reservoir increases the runoff and sediment connectivity significantly, leading to rapid siltation of the reservoir

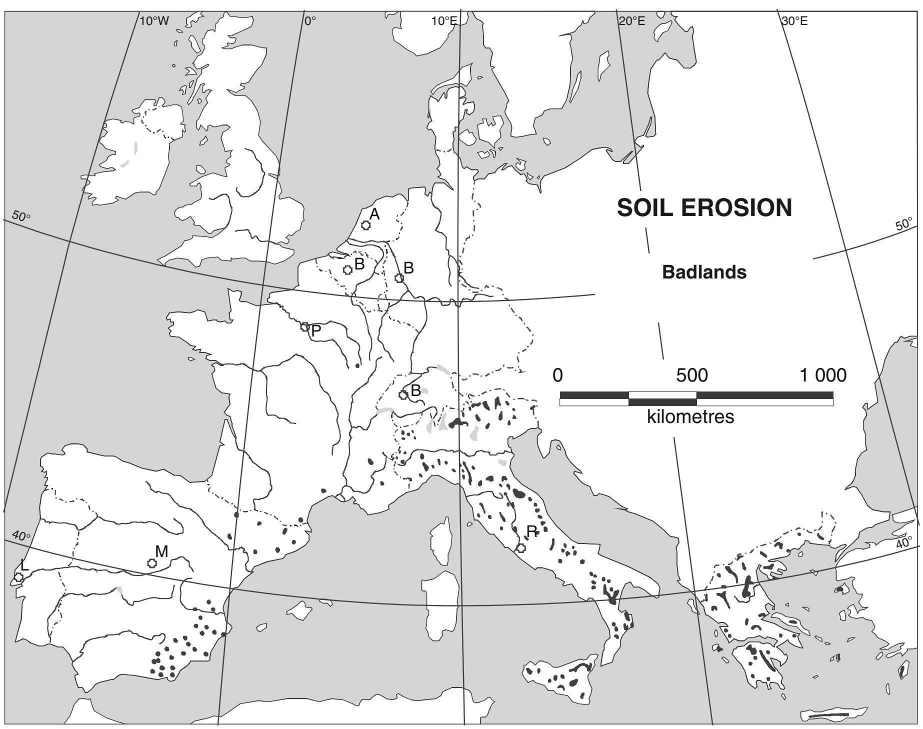

Figure 2.5.7 Map of western Europe indicating regions with dense gully networks in badlands. (From De Ploey J, *Soil Erosion Map of Europe*, 1989. Reproduced by permission of Catena-Verlag GmbH)

2.5.4 IS GULLY EROSION A RECENT PHENOMENON IN EUROPE?

There are several reports indicating that throughout Europe gully development has been locally significant over the last 3000 years. Some of these gullies are still clearly visible, for instance in forested areas of Belgium (Gullentops, 1992; Vanwalleghem *et al*., 2003, 2005c), France (Vogt, 1953), Germany (Semmel, 1995; Bork *et al*., 1998), Slovakia (Stankoviansky, 2003) and Hungary (Gábris *et al*., 2003), where the forests have preserved these geomorphic phenomena, or in stabilized badlands of the Mediterranean (e.g. Wise *et al*., 1982).

In northern Europe, for instance, recent reports indicate that gully erosion occurred as early as the late Neolithic (2857–2495 BC) in Germany (Schmidtchen and Bork, 2003), the late Bronze Age (ca 1700 BC) and the end of the Roman period in central Belgium (Vanwalleghem *et al*., 2005d), in the 9–10th centuries in the UK (Harvey, 1996), in the 14th century in Germany (Bork *et al*., 1998; Dotterweich *et al*., 2003) and Slovakia (Stankoviansky, 2003) or during the Little Ice Age in Belgium (Vanwalleghem *et al*., 2005b), Germany (Bork *et al*., 1998; Dotterweich *et al*., 2003) and in Slovakia (Stankoviansky, 2003). For Mediterranean Europe, various studies reported that gully erosion already occurred in prehistoric times (e.g. Wainwright and Thornes, 2004). For instance, Allée and Denèfle (1989) report that gullying has been initiated in the eastern French Pyrenees from ca 650 BC on. De Ploey (1992) calculated the age of badlands in the Mediterranean to range between 2700 and 40 000 years. It is very likely that throughout historical times, gully erosion was significant in the Mediterranean. For instance, Vandekerckhove *et al*. (2001) calculated the age of active bank gullies in southeast Spain and found that they initiated in a time span ranging between 350 and 1940 AD. Torri and Rodolfi (2000) report that badlands in central Italy were initiated around 1850.

In conclusion, gully erosion in Europe is not a recent phenomenon. Several studies report that gully development coincided with periods of land clearing, often in combination with very intense rains resulting in a change of catchment hydrology in response to changing environmental conditions. From a detailed study of an infilled gully under cropland in Belgium, Vanwalleghem *et al*. (2005b) concluded that over the last 350 years, at least five cut and fill cycles occurred, indicating that the landscape reacts in a very dynamic way to gully incision. Under cropland, an ephemeral gully can develop into a large permanent gully over a few months or years, but within subsequent decades, the entire gully can be almost completely filled in again if there is continuous cultivation in the catchment with runoff and sediment production. Much can be learned from detailed studies on environmental change leading to intensive gullying (Poesen *et al*., 2003).

2.5.5 HOW IMPORTANT IS GULLY EROSION IN EUROPE?

Data on gully erosion rates reported in the literature have been compiled in Table 2.5.1. In European cropland, mean rates of ephemeral gully erosion range between 1 and 40 $t\,ha^{-1}\,yr^{-1}$ depending on rainfall and site conditions (Table 2.5.1). However, the highest soil erosion rates in Europe have been recorded in active badland areas where gully erosion is the dominant erosion process. In such areas, soil losses at the catchment scale equal 57–137 $t\,ha^{-1}\,yr^{-1}$ in badlands of the Alpes de Haute Provence (France; Mathys *et al*., 2003), 123 $t\,ha^{-1}\,yr^{-1}$ in the Pinedes region (northeastern Spain; Martínez-Casasnovas *et al*., 2003), 190 $t\,ha^{-1}\,yr^{-1}$ in densely gullied badlands on black marls in southeastern France (Bufalo and Nahon, 1992) and even 302–455 $t\,ha^{-1}\,yr^{-1}$ in badlands located within the basin of the Barasonas reservoir in north-eastern Spain (Martínez-Casasnovas *et al*. 2003) (Table 2.5.1).

The contribution of gully erosion to total soil loss by water erosion in Europe is variable and ranges between 10 and 83 % (Table 2.5.1). Factors controlling this contribution are size of the study area, time-

TABLE 2.5.1 Soil loss rates due to gully erosion (SLgully) and contribution of (ephemeral) gully erosion to overall soil loss rates and to sediment production rates by water erosion: SLgully (%) = 100 × (ratio between SLgully and total SL rates due to interrill, rill and gully erosion)

Location	SLgully ($t\,ha^{-1}\,yr^{-1}$)	SLgully (%)	Source
Belgium, central	22.3	10	Govers and Poesen (1988)
Belgium	1.1–5.9	n.a.[a]	Nachtergaele and Poesen (1999)
France, north	n.a.	10–45	Ludwig *et al*. (1992)
Germany, south	n.a.	12–29	Auerswald (1998)
France, Normandy	n.a.	21–56	Cerdan *et al*. (2002)
France, south-east	190	n.a.	Bufalo and Nahon (1992)
Spain, north-west	1.5	26	Valcarcel *et al*. (2003)
Germany, south-west	n.a.	36	Baade (1994)
Romania	n.a.	37	Nedelcu (1999)
Belgium, central	3.6	44	Poesen *et al*. (1996)
France, north	n.a.	46–55	Auzet *et al*. (1995)
Italy, Sicily	5.0	n.a.	Capra and Scicolone (2002)
Portugal, Bragança	16.1	47	Vandekerckhove *et al*. (1998)
Spain, Guadalentin	37.6	51	Poesen *et al*. (2002)
Norway, Leira basin	12.7	55	Bogen *et al*. (1994)
Spain, Catalunia	n.a.	58	Martínez-Casasnovas *et al*. (2002)
Spain, Catalunia	123	n.a.	Martínez-Casasnovas *et al*. (2003)
Spain, Northeast	302–455	n.a.	Martínez-Casasnovas *et al*. (2003)
Spain, south-east	1.2	59	Oostwoud Wijdenes *et al*. (2000)
Belgium, central	n.a.	60	Quine *et al*. (1994)
Spain, north	64.9	74	Casali *et al*. (2000)
Portugal, Alentejo	3.2	80	Poesen *et al*. (1996)
Spain, Almeria	9.7	83	Poesen *et al*. (1996)

[a]Data not available.

scale considered, climate and magnitude of rain event(s), topography, soil type and land use (Poesen *et al*., 2003).

Few studies have reported rates of gully expansion in Europe. Oostwoud Wijdenes *et al*. (2000) observed that land use has a significant impact on the expansion of bank gully heads in southeastern Spain. Reported mean linear headcut retreat rates range between $0.1\,m\,yr^{-1}$ (min. = 0.01; max. = $0.62\,m\,yr^{-1}$) for active gully headcuts in southeastern Spain (Vandekerckhove *et al*., 2001) and $0.92\,m\,yr^{-1}$ (min. = 0.42; max. = $1.83\,m\,yr^{-1}$) in the Moldavian Plateau of eastern Romania (Ionita, 2000). For large gullies in the Penedes region (northeastern Spain), Martínez-Casasnovas (2003) measured an average rate of gully wall retreat of $0.2\,m\,yr^{-1}$, with maximum rates of channel expansion of $0.7–0.8\,m\,yr^{-1}$, occurring at the gully head and at meandering gully bends. Vandekerckhove *et al*. (2003) reported medium-term (40–43 years) mean volumetric headcut retreat rates of active gullies in southeastern Spain of $17.4\,m^3\,yr^{-1}$. Differences in retreat rates between gullies could be largely explained by drainage areas. Nachtergaele *et al*. (2002b) monitored the length, surface area and volume of a gully developing in a loess-derived soil (central Belgium) over a 13-year period and reported a degressive increase of gully extension over time which could be largely explained by changing topographic variables at the gully head (i.e. slope gradient and drainage area). Similar observations for gullies in Romania were reported by Radoane *et al*. (1999). Gullies not only expand by headcut retreat, but also by channel widening. Martínez-Casasnovas *et al*. (2004) assessed sidewall erosion in large gullies in northeastern Spain and reported soil losses for two successive periods of 16 and 83 $t\,ha^{-1}\,yr^{-1}$, the latter depending on the occurrence of an extreme rain event during the observation period.

From the data reported in this section, we conclude that soil loss rates caused by gully erosion are far from negligible and that they can exceed soil loss rates for other water erosion processes.

2.5.6 WHAT ARE THE MAJOR CONSEQUENCES OF GULLY EROSION IN EUROPE?

Here, we discuss briefly the major on- and off-site consequences of gully erosion.

2.5.6.1 On-site

The most obvious and important on-site consequence of gully erosion is the loss of soil, which can be of the same order of magnitude as soil losses due to sheet and rill erosion and in ca 50 % of cases even more (see Table 2.5.1). Hence, gully erosion is a significant soil degradation process.

Figure 2.5.8, which is based on experimental data collected in three European study areas, shows how gully length, gully area and gully volume evolve over time. From these graphs, it is clear that gully erosion increases over time but in a degressive manner. In other words, 50 % of total gully length, total gully area or total gully volume is created in 20 % or less of the total gully lifetime. Hence, if gullies are allowed to evolve without direct interference by human activities (e.g. infilling, land levelling, ploughing), gully erosion rates (caused by headcut and bank retreat) usually slow over time. However, in cropland, ephemeral gullies are typically filled in by tillage (soil translocation by tillage leading to tillage erosion and tillage deposition; see Chapter 2.9) within less than 1 year after their development. During subsequent storms, the infilled loose soil is usually eroded again by concentrated flow, thereby increasing the plan-form concavity of the site. The newly created plan-form concavity increases the probability of erosive concentrated flow (Poesen *et al*., 2003). Hence ephemeral gully erosion and tillage erosion reinforce each other.

In various parts of Europe, landscapes heavily dissected by gullying (badlands) have been levelled (e.g. Norway, Mediterranean countries), thereby causing strong soil profile truncation in the intergully areas and infilling of gullies with the translocated soil material (e.g. Poesen and Hooke, 1997; see Chapter 2.12). Such land levelling operations have often resulted in renewed gully incision of the levelled land and also in shallow landsliding, causing very large soil loss rates. In other words, important interactions exist between gully erosion on the one hand and tillage and land levelling operations on the other (Poesen *et al*., 2003).

The gully channels that develop change the local topography drastically and cause a decrease in several soil functions (e.g. bearing function, archive function, plant-growth function). Furthermore, these channels render trafficability very difficult or almost impossible.

Once gully channels have developed, the water infiltration rate through the gully bottom may be significantly larger than that of the soil surface in the intergully areas if the gully channel develops into more permeable soil horizons (Poesen *et al*., 2003). As such, gully channels may contribute to runoff water transmission losses. Where gully channels are used as garbage dumps, as is often the case, this may lead to significant groundwater contamination. However, if gullies develop into hillslopes with temporary water tables, gully channel development may cause enhanced drainage of the hillslope and a rapid water-table lowering, which leads to a drying out of the soil profiles in the intergully areas (Poesen *et al*., 2003). As a consequence, in dry Mediterranean areas crop production in the intergully area may be adversely affected by gullying.

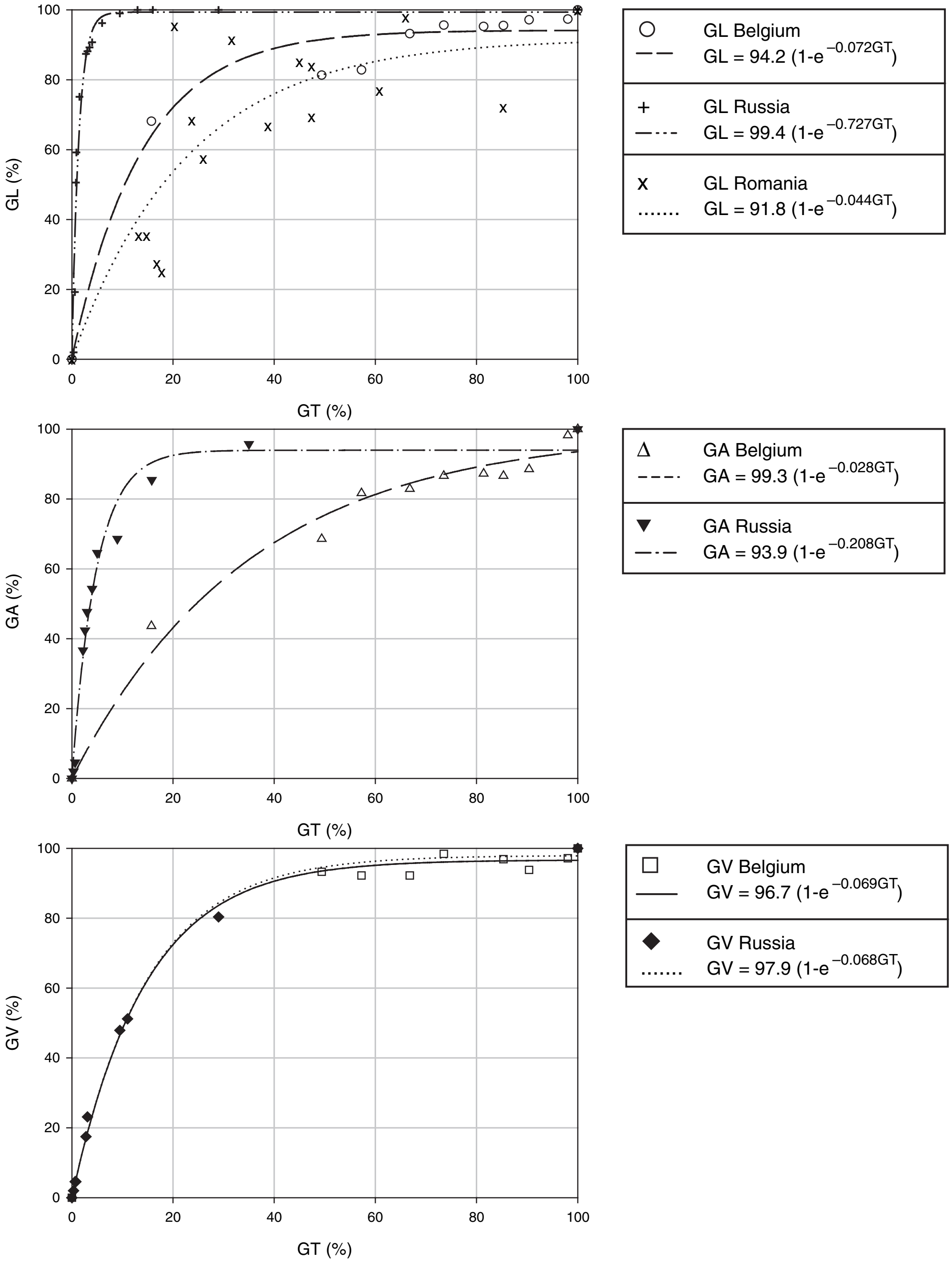

Figure 2.5.8 Evolution of gully length (GL, %), gully surface area (GA, %) and gully volume (GV, %) during gully lifetime (GT, %) for different study areas (partly based on Vanwalleghem *et al.*, 2005c). All parameters are given as percentages, relative to the last measured parameter value. Data for Belgium are given by Nachtergaele *et al.* (2002b) and Vanwalleghem *et al.* (2005b) and are based on field measurement of the evolution of a permanent gully in loess. Gully lifetime (GT) = 14.8 years. Data for Russia are given by Kosov *et al.* (1978) and are based on laboratory experiments of gully formation in sand. The data points are extrapolated from a graph. Gully lifetime (GT) is unknown. Data for Romania are given by Surdeanu *et al.* (2003) and are based on a map survey of gully evolution in marly clay rocks. The data points are extracted from a scatter plot. Gully lifetime (GT) = 325 years

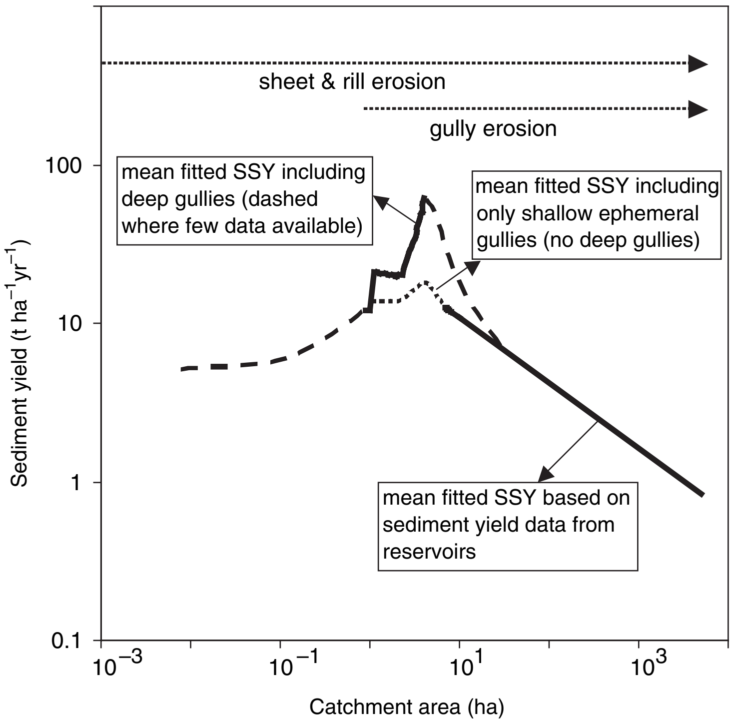

Figure 2.5.9 Relationship between catchment area and area-specific sediment yield (SSY) for cropland in the loess belt. Trends in SSY are fitted through soil loss data collected using runoff plots, volumetric measurements of shallow and deep ephemeral gullies and sediment deposition volumes in flood retention ponds, all located in central Belgium. (Reprinted from Vanwalleghem T *et al.*, Characteristics, controlling factors and importance of deep gullies under cropland on loess-derived soils, *Geomorphology*, **69**: 76–91, 2005, with permission from Elsevier)

2.5.6.2 Off-site

Gully erosion represents a very significant sediment source. This is well illustrated in Figures 2.5.9 and 2.5.10. Sediment yield (SSY) clearly depends on the size of the catchment for which the data have been collected. In the Belgian loess belt, for instance, the mean SSY for areas less than 1 ha is usually less than 10 t ha^{-1} yr^{-1} (Figure 2.5.9). For areas between 1 and 10 ha, however, SSY increases to 20 t ha^{-1} yr^{-1} if shallow ephemeral gullies develop, and may rise to 60 t ha^{-1} yr^{-1} if deep (>0.8 m) gully channels develop (Vanwalleghem *et al.*, 2005a). For catchments larger than 10 ha, SSY decreases because of an increased probability of sediment deposition taking place. A similar trend, although with a peak SSY occurring between 10 and 1000 ha, has been reported for Spain (de Vente and Poesen, 2005; Figure 2.5.10). In both case-study areas, the development of gullies in areas larger than 1 ha may be held responsible for the rapid increase in sediment yield with increasing drainage area.

Not only do expanding gullies produce large volumes of sediment, but gullies also form effective links in the landscape, transferring both runoff and sediment (produced in the intergully areas) from uplands to valley bottoms. In other words, gullies increase the connectivity for sediment in the landscape (Poesen *et al.*, 2003). As a consequence, gully erosion contributes significantly to reservoir siltation, as illustrated by Figures 2.5.6 and 2.5.11 (see also Chapter 2.20), and muddy floods (see Chapter 2.19). Active gullies are thus important indicators for high sediment production rates within catchments (Poesen *et al.*, 2003; Verstraeten *et al.*, 2003; de Vente *et al.*, 2005).

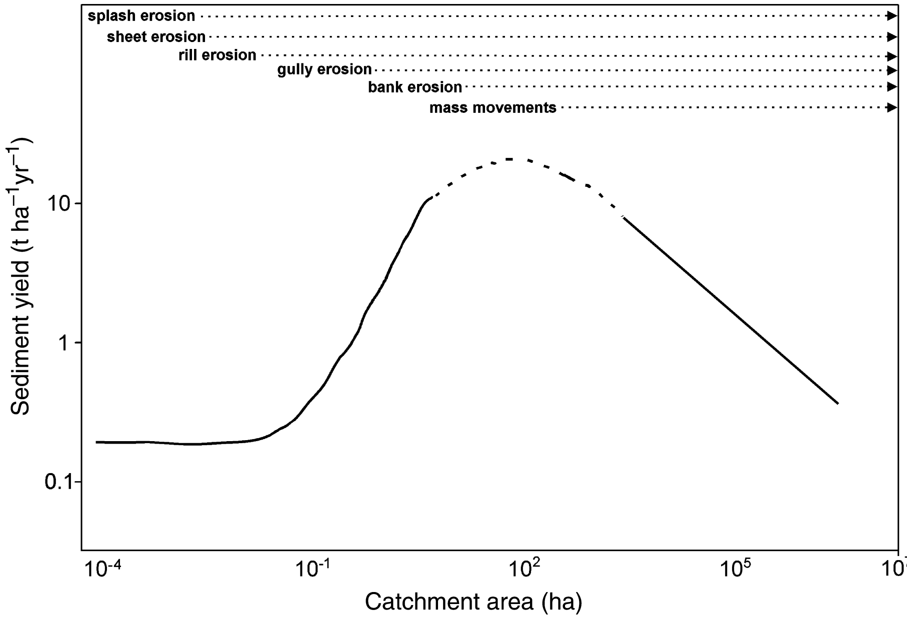

Figure 2.5.10 Relationship between catchment area and area-specific sediment yield (SSY) for Spain. Trends in SSY are fitted through soil loss data collected using runoff plots, volumetric measurements of gullies and sediment deposition volumes in reservoirs, all located in Spain. Dominant soil erosion process for each spatial scale is indicated as well. (Reprinted from de Vente J and Poesen J, Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models, *Earth Science Reviews*, **71**: 91–125, 2005, with permission from Elsevier)

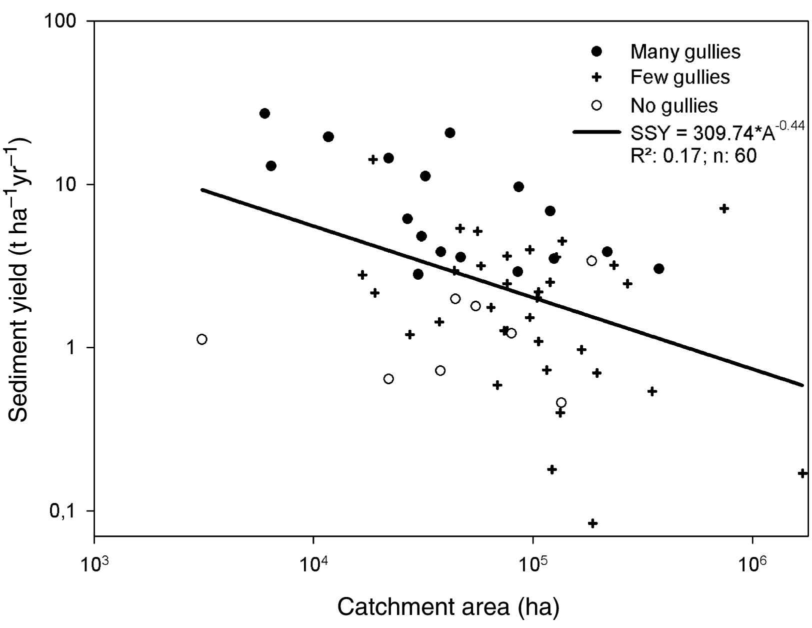

Figure 2.5.11 Relationship between catchment area, area-specific sediment yield (based on reservoir sedimentation data reported by Avendaño Salas *et al.*, 1997) and the presence of gullies. (Reprinted from de Vente J *et al.*, The application of semi-quantitative methods and reservoir sedimentation rates for the prediction of basin sediment yield in Spain, *Journal of Hydrology*, **305**: 63–86, 2005, with permission from Elsevier)

2.5.7 WHAT ARE MAJOR TRIGGERING AND CONTROLLING FACTORS FOR GULLY EROSION?

The probability of gullies developing during concentrated overland flow increases if several conditions are met. First, during a rain event, concentrated flow intensity (usually expressed by boundary flow shear stress $\tau_b = \rho g d s$, where ρ = density of runoff water, g = acceleration due to gravity, d = depth of flow and s = sine of the soil surface gradient) must exceed a critical value (in this case the critical flow shear stress, τ_c), so that a channel exceeding the critical cross-section (i.e. 929 cm^2) can be cut in the topsoil. Reported τ_c values for incipient gully channel development on cropland typically range between 5 and 90 Pa but can be as high as 240–260 Pa for well-established pasture (Poesen *et al.*, 2003). Second, a large channel erodibility (*Kc*) value of the soil in which a gully might develop increases the probability of gully incision during a rain storm.

Various factors affect both τ_b and *Kc*. Rain depth and intensity, topography [slope gradient (*S*), drainage area (*A*), plan concavity], soil type and land use affect τ_b whereas soil type and landuse affect *Kc*. Critical rain event depths for the initiation of ephemeral gullies in European cropland range between 15 and 22 mm (Poesen *et al.*, 2003). On cropland with poor vegetation cover, and hence a significant Hortonian runoff production, ephemeral gullies usually start to develop in concentrated flow zones when local slope gradients exceed 3–4 %. Critical *S*–*A* relations for gully initiation and for sediment deposition (at the bottom end of gully channels) in a range of European environments have been reported by Vandaele *et al.* (1996), Vandekerckhove *et al.* (2000), Nachtergaele *et al.* (2001a,b) and Poesen *et al.* (2003). Soils prone to (ephemeral) gully development in Europe are soils that developed on loess, sandy loams, marls and volcanic ashes. In addition to soil type, the vertical distribution of erosion resistance of the various soil horizons largely controls the depth, the cross-sectional morphology and hence the total eroded soil volume by gullies. For instance, the presence of a well-developed Bt horizon in loess-derived soils drastically reduces gully depth in the loess belt. Where the Bt horizon has been eroded, deeper gullies can develop (Poesen, 1993; Nachtergaele and Poesen, 2002, Vanwalleghem *et al.*, 2005a). In Mediterranean environments, the presence of very stony soils with hard unweathered bedrock at shallow depth in the soil profile (Leptosols) limits the development of deep gullies. Land use significantly affects gully erosion rates. On poorly vegetated areas (cropland, degraded rangeland), large volumes of Hortonian runoff are usually produced, resulting in large shear stresses in concentrated flow zones. If, in addition, the land is tilled, channel erodibility (*Kc*) is fairly high as illustrated in Figure 2.5.12b (after Knapen *et al.*, submitted). If the land is left untilled, the mean *Kc* is on average a factor 10 smaller, resulting in a much smaller probability of gully development. Tillage results in a loosening of the topsoil and therefore in a reduction in soil cohesion and a drastic increase in channel erodibility. In general, the transformation of natural vegetated slopes to tilled cropland or very degraded rangeland causes a significant lowering of the topographic threshold for gully development (Poesen *et al.*, 2003). This scenario explains in many cases the presence of old gullies on slopes which were formerly cultivated but are nowadays covered by natural vegetation. Along the same lines, Oostwoud Wijdenes *et al.* (2000) reported that the shift from matorral to cropland (i.e. wheat and intensively cultivated almond groves) in Spain resulted in a drastic reactivation of bank gullies. Not only the aboveground biomass but also the roots play an important role in increasing the soils'resistance to concentrated flow erosion (Gyssels *et al.*, 2005).

2.5.8 DO WE HAVE RELIABLE GULLY EROSION MODELS IN EUROPE?

In contrast to sheet and rill erosion models, few models have the potential to predict gully erosion rates. One of these is the EGEM (Ephemeral Gully Erosion Model; Merkel *et al.*, 1988; Woodward, 1999), developed in the USA. This model was tested for its suitability to predict ephemeral gully erosion rates in various European cropland environments (i.e. Belgium, Portugal, Spain and Italy) (Nachtergaele *et al.*, 2001a,b; Capra *et al.*, 2005).

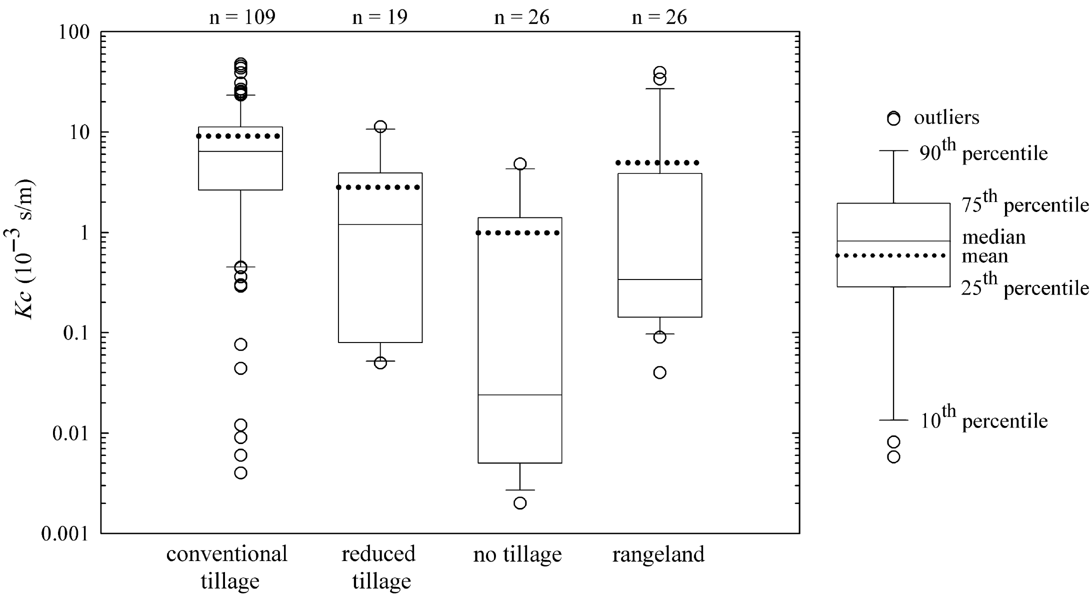

Figure 2.5.12 Channel erodibility (*Kc*) measured during concentrated flow erosion experiments on soils having different textures under different land use or tillage treatments. Published experimental data come from all over the world; *n* is total number of tested soils in each land use class. (After Knapen *et al.*, submitted)

From these studies, it can be concluded that EGEM is not capable of predicting ephemeral gully erosion properly in the studied cropland environments. These studies also point to the fact that the ephemeral gully length (*L*) is a key parameter in determining ephemeral gully volume (Poesen *et al.*, 2003): *L* explains in all studies more than 64 % of the variance in ephemeral gully volume.

However, few erosion models have the capacity to predict the exact location of gully initiation points, points where gullies end (i.e. where sediment deposition occurs) and therefore gully lengths. Desmet *et al.* (1999) investigated the possibility of predicting the location of ephemeral gully channels in the loess belt using an inverse relationship between local slope gradient (*S*) and upslope contributing area per unit length of contour (*As*). Along the same lines, Jetten *et al.* (in press) used empirical equations predicting topographic thresholds for gully trajectories in terms of *S* and *As* in order to select critical areas in the landscape where ephemeral gully incision might take place. For such areas, then, the event-based spatially distributed LISEM model was used to predict eroded gully channel dimensions. Kirkby *et al.* (2003) presented power law equations describing the locations of ephemeral and permanent gully channel heads. Souchère *et al.* (2003) combined an expert-based approach and field data to predict the location and volume of ephemeral gullies within the main runoff collector network of agricultural catchments in France. Casali *et al.* (2003) and Torri and Borselli (2003) developed gully cross-section models to predict changes in gully channel width and depth during concentrated flow events in Spain and Italy. However, these models still need calibration.

Once initiated, bank gullies essentially expand by gully headcut retreat and, to a lesser extent by gully wall retreat. Whether a headcut retreats as a single headcut or by multiple headcuts is controlled by factors such as topography, soil type and land use. Several studies have attempted to predict gully headcut retreat in a range of European environments. De Ploey (1989b) developed a process-based headcut retreat model. Radoane *et al.* (1995) reported several regression models linking gully headcut retreat rates in Romania to lithology, drainage basin area, gully length, relief energy of the basin and drainage basin inclination.

Vandekerckhove *et al*. (2001, 2003) proposed several empirical equations allowing one to predict short- and medium-term retreat rates of active gully headcuts in Spain. Although few attempts have been made to develop models for predicting either gully subprocesses or gully erosion in a range of environments, there are still no reliable (validated) models available that allow one to predict impacts of environmental change on gully erosion rates at various temporal or spatial scales in Europe, nor the impacts of gully erosion on sediment yield, hydrological processes and landscape evolution. This lack of knowledge explains why gully erosion is not included in most soil erosion assessments in Europe.

2.5.9 HOW CAN GULLY EROSION BE PREVENTED OR CONTROLLED?

In order to prevent (ephemeral) gullies from developing in cropland, all possible measures leading to an increase in rain infiltration, to a reduction in Hortonian overland flow discharge and hence also to a reduction of flow shear stress (τ_b) need to be applied. At the same time, all measures leading to an increase in erosion resistance of the concentrated flow zone will also reduce the risk of gully development.

Where possible, natural vegetation with well-developed root mats should be established in concentrated flow zones with a high risk of gullying. As a consequence, soil loss and sediment production will be reduced and the connectivity for sediment in the landscape will be interrupted, resulting in a smaller sediment delivery to valley bottoms or river channels (Poesen *et al*., 2003). Often, this approach is not feasible because of interference with other land use and therefore solutions adapted to local agricultural practices need to be found.

One of these solutions is the establishment of grassed waterways (e.g. Ouvry, 1989; Baade *et al*., 1993; Fiener and Auerswald, 2003). Grassed waterways are broad, shallow channels often located within large fields, with the primary function to drain surface runoff from cropland without gullying in the thalweg. To serve this function as effectively as possible, selected fast-growing grasses are sown in the waterway and, once established, the grass is frequently mowed to reduce hydraulic roughness. Whereas grassed waterways are a common (ephemeral) gully erosion control practice in North America, this measure is rarely adopted by farmers cultivating relatively small field plots in Europe. Several studies have come up with alternatives to control ephemeral gully erosion, i.e. conservation tillage, topsoil compaction and double drilling.

Figure 4.5.12 clearly illustrates that conservation tillage practices such as reduced tillage or no tillage lower the channel erodibilty (*Kc*) significantly. Whereas conventional tillage (i.e. mouldboard ploughing) results in a loose, less cohesive and hence more erodible plough layer that is easily eroded by concentrated flow, the application of no tillage in the concentrated flow zones will increase the topsoil resistance, as observed in France, Belgium and Italy (e.g. Ouvry, 1989; Poesen and Govers, 1990; Ludwig and Boiffin, 1994; Poesen *et al*., 2003). However, Ludwig and Boiffin (1994) reported that the effects of no tillage on ephemeral gully erosion rates in France largely depend on the spatial location of the no-till treated plots within the catchment and that no tillage was overall less effective than grassed waterways.

As compact and hence more cohesive topsoils or soil horizons have a larger resistance to incision by erosive concentrated flow compared with tilled ones (e.g. Figure 2.5.12), Ouvry (1989) compacted mechanically concentrated flow zones after drilling in France. He observed that this treatment significantly reduced ephemeral gully development within drainage basin areas smaller than 50 ha. Poesen (1993) and Nachtergaele and Poesen (2002) reported that information on the thickness and resistance properties of compact soil horizons (e.g. Bt horizon) is crucial for selecting appropriate soil conservation measures in concentrated flow zones and that any tillage operation (such as subsoiling) resulting in a loosening of compact horizons should be avoided to prevent deep incisons by concentrated flow erosion.

Gyssels *et al*. (2002, personal communication) observed that double drilling of wheat only in concentrated flow zones reduced ephemeral gully erosion rates on average by 25 %, but the reduction could be as high as

50 % in some cases. The effect of double drilling on channel development was particularly clear in the early growth stages of the wheat seedlings because of larger root densities and therefore larger cohesion of the topsoils compared with conventionally drilled topsoils (Gyssels *et al*., 2005).

Once formed, gullies in Europe are usually controlled by check dams. Although check dams in gullies are widespread in Mediterranean Europe, little information is available on their effectiveness and efficiency. For instance, check dams in gullies induce sediment deposition upstream and therefore cause more runoff water with a reduced sediment load to flow downstream of the dam. In many cases, this causes a clear water effect, sometimes resulting in significant channel incision (Boix Fayos *et al*., 2005; Castillo *et al*., 2005). An alternative approach is to establish vegetation barriers on the gully bottom, as documented by Rey (2004).

Despite the several case studies reported in the literature, there is still a need for more information on the effectiveness and cost-efficiency of gully prevention and control measures. Handbooks usually provide the principles on how to control gully erosion, but when applying them in a given environment these techniques often need to be adjusted to local conditions. For instance, Poesen (1989) reported that stabilising a gully headcut in central Belgium with a rock plug did not work in loess-derived soils because of their very high erodibility. In such cases, the use of geomembranes was an effective and efficient alternative.

2.5.10 CONCLUSIONS AND RESEARCH NEEDS

Over the last decade, gully erosion research has contributed significantly to a better understanding of spatial and temporal patterns of gully erosion rates and of controlling factors in Europe. However, several aspects of gully erosion still remain under-researched (Poesen *et al*., 2003):

- Conditions for the initiation, development and infilling of gully channels under a range of environmental conditions;
- Rates and factors controlling gully subprocesses, such as tension crack development, piping, plunge-pool erosion, fluting, bifurcation, mass wasting processes on gully walls and their interactions (e.g. hydraulic erosion and mass wasting processes);
- Models predicting the location of gully channels in the landscape and gully expansion or contraction at different temporal scales;
- Appropriate and standardised monitoring techniques enabling the study of gully development with a higher precision than that obtained by current techniques;
- Detailed monitoring, experimental and modelling work to increase the capacity to predict impacts of environmental changes on gully erosion rates;
- Interaction between gully development, hydrological and other soil degradation processes;
- Innovation in gully erosion control techniques, which is rather limited compared with innovation in gully erosion process research. What can be learned from failures and successes of gully erosion control techniques? What are effective and efficient gully prevention and gully control measures?

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