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Gully erosion and environmental change: importance and research needs

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Abstract

Assessing the impacts of climatic and, in particular, land use changes on rates of soil erosion by water is the objective of many national and international research projects. However, over the last decades, most research dealing with soil erosion by water has concentrated on sheet (interrill) and rill erosion processes operating at the (runoff) plot scale. Relatively few studies have been conducted on gully erosion operating at larger spatial scales.

Recent studies indicate that (1) gully erosion represents an important sediment source in a range of environments and (2) gullies are effective links for transferring runoff and sediment from uplands to valley bottoms and permanent channels where they aggravate off site effects of water erosion. In other words, once gullies develop, they increase the connectivity in the landscape. Many cases of damage (sediment and chemical) to watercourses and properties by runoff from agricultural land relate to (ephemeral) gullying. Consequently, there is a need for monitoring, experimental and modelling studies of gully erosion as a basis for predicting the effects of environmental change (climatic and land use changes) on gully erosion rates.

In this respect, various research questions can be identified. The most important ones are:

(1) What is the contribution of gully erosion to overall soil loss and sediment production at various temporal and spatial scales and under different climatic and land use conditions?
(2) What are appropriate measuring techniques for monitoring and experimental studies of the initiation and development of various gully types at various temporal and spatial scales?
(3) Can we identify critical thresholds for the initiation, development and infilling of gullies in different environments in terms of flow hydraulics, rain, topography, soils and land use?
(4) How does gully erosion interact with hydrological processes as well as with other soil degradation processes?

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(5) What are appropriate models of gully erosion, capable of predicting (a) erosion rates at various temporal and spatial scales and (b) the impact of gully development on hydrology, sediment yield and landscape evolution?
(6) What are efficient gully prevention and gully control measures? What can be learned from failures and successes of gully erosion control programmes?

These questions need to be answered first if we want to improve our insights into the impacts of environmental change on gully erosion. This paper highlights some of these issues by reviewing recent examples taken from various environments.

Keywords: Gully erosion; Climate change; Land use change; Sediment yield; Techniques; Thresholds; Flow hydraulics; Rainfall; Topography; Soils; Infiltration; Drainage; Models; Erosion control; Connectivity

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1. Introduction

Assessing the impacts of climatic and land use changes on rates of soil erosion by water is the objective of many national and international research projects (e.g. Favis-Mortlock and Boardman, 1995; Williams et al., 1996; Poesen et al., 1996a; Van Oost et al., 2000; Nearing, 2001). However, over the last decades, most research dealing with soil erosion by water has mainly focussed on sheet (interrill) and rill erosion processes operating at the (runoff) plot scale. This is seen in (1) the numerous field studies where runoff plots have been established in order to assess soil loss rates due to sheet (interrill) and rill erosion under various climatic conditions or land use practices (e.g. Risse et al., 1993; Kosmas et al., 1997) and (2) the use of both empirical and process-based field-scale and catchment-scale soil erosion models (e.g. Jetten et al., 1999), addressing mainly sheet and rill erosion, 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 landscapes under different climatic conditions and with different land uses, one can observe the presence and dynamics of various gully types, i.e. ephemeral gullies, permanent or classical gullies and bank gullies (Figs. 1–3). Field-based evidence suggests that sheet and rill erosion as measured on runoff plots are not realistic indicators of total catchment erosion nor do they indicate satisfactorily 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 watercourses (e.g. Evans, 1993b).

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. *Permanent gullies* (e.g. Fig. 2) are often defined for agricultural land in terms of channels too deep to easily ameliorate with ordinary farm tillage equipment, typically ranging from 0.5 to as much as 25–30 m depth (Soil Science Society of America, 2001).

In the 1980s, the term *ephemeral gully erosion* was introduced to include concentrated flow erosion 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

Fig. 1. Shallow ephemeral gully (ca. 2 m wide) in cropland (cotton) near Athens, GA, USA (May 1991).

Fig. 2. Permanent gully at Thysse Kamor, Senegal (January 1996). Despite very low slope gradients (i.e. < 0.05 m m^{-1}) and the presence of sandy soils (sand content >80%), gullies tend to develop rapidly in this Sahelian environment. Most gullies have been initiated during the early 1970s due to the protracted drought. With a low vegetation cover, these sandy soils develop crusts which generate Hortonian runoff, even during low intensity rains (< 5 mm h^{-1}). During the last two decades, the rapid increase (over 2% per year) of the rural population has led to a decrease of the land left under fallow, reducing the organic matter content of the topsoil, already strongly depleted (i.e. $< 0.5\%$) and leading to high runoff production rates. Once runoff concentrates, it promotes gully erosion. Gullies often originate in tracks made by cattle or vehicles.

Fig. 3. Bank gully which developed in sunken lane bank (in the foreground) near Leefdaal, Belgium (January 1994). Note the rills (to the right of the standing person) which connect the bank gully with the upland.

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 major part of the erosional systems on cropland (Evans, 1993b). According to the Soil Science Society of America (2001), ephemeral gullies (e.g. Fig. 1) are small channels eroded by concentrated overland flow that can be easily filled by normal tillage, only to reform 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, etc.). 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 unsuited. In order to account for any type of concentrated flow channels 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. For instance, Derose et al. (1998) studied sediment production by a large gully, i.e. 500 m wide and 300 m deep. 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 to ephemeral gully erosion (Fig. 1) to classical gully erosion (Fig. 2) and to river channel erosion represents a continuum, and any classification of hydraulically related erosion forms into separate classes, such as microrills, rills, megarills, ephemeral gullies, gullies, is, to some extent, subjective (Grissinger, 1996a,b). In fact, Nachtergaele et al. (2002a) demonstrated that (ephemeral) gullies can be considered as channels characterised by a mean width (W) between that of rills and (small) rivers. For all these channels, W seems to be essentially controlled by peak flow discharge (Q) and the relation between both parameters can be expressed by the equation $W = aQ^b$, with a being a coefficient and the exponent b varying from 0.3 for rills, over 0.4 for (ephemeral) gullies to 0.5 for (small) rivers (Fig. 4). For gullies, the proposed W–Q relation only holds for concentrated flow incising relatively homogenous soil material in terms of erodibility (i.e. soil erodibility remains constant with depth). If a resistant soil horizon is present at shallow depth (e.g. frozen layer, plough pan, Bt-horizon or fragipan), W will be much larger than the value predicted with this equation. In addition, if a more erodible layer is present at shallow depth, this relation will not hold anymore (Nachtergaele et al., 2002a).

By definition, *bank gullies* (Fig. 3) develop wherever concentrated runoff crosses an earth 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

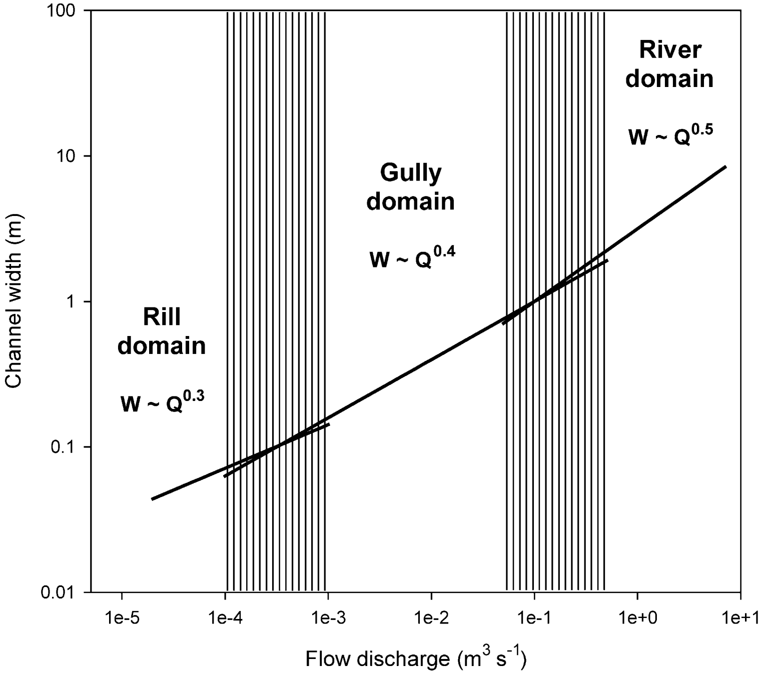

Fig. 4. Power relation between concentrated runoff discharge (Q) and mean eroded channel width (W) for various types of eroded channels. Note the change in exponent b from 0.3 for rills to 0.4 for gullies and 0.5 for small river channels. Vertical bars indicate transition zones between the established relations (after Nachtergaele et al., 2002a).

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).

So far, no systematic compilation of morphological characteristics (e.g. length, width, depth) of the different types of gullies and their controlling factors (e.g. topography, soil type, land use, hydrology) in a wide range of environments has been made. Such quantitative data would be needed so as to allow land managers to foresee the type of gullies they might expect when land use changes are taking place.

Recent field-based studies (e.g. see papers in this volume) indicate that (1) gully erosion is an important soil degradation process in a range of environments, causing considerable soil losses and producing large volumes of sediment and (2) gullies are effective links for transferring runoff and sediment from uplands to valley bottoms and permanent channels where they aggravate offsite effects of water erosion (e.g. flooding, pollution). Field observations in different environments clearly indicate that the development of (ephemeral) gullies increases the connectivity in the landscape and hence also the sediment delivery to lowlands and watercourses. Many cases of damage (sediment and chemical) to watercourses and properties by runoff from agricultural land relate to the occurrence of (ephemeral) gully erosion (e.g. Verstraeten and Poesen, 1999; Boardman, 2001). However, soil losses caused by (ephemeral) gully erosion are rarely accounted for in current soil loss assessment programmes (e.g. Liggitt and Fincham, 1989; Poesen et al., 1996a; Garen et al., 1999). Consequently, there is a need for monitoring, experimental and modelling studies of gully erosion as a basis for predicting the effects of environmental change (climatic and land use changes) on gully erosion rates. In order to better predict impacts of environmental change on gully erosion processes and rates, more research efforts are needed. For recent literature reviews on gully erosion, the reader is referred to Bocco (1991), Bull and Kirkby (1997, 2002) and Poesen et al. (2002). This paper addresses some research issues/questions which are felt to be crucial if one wants to progress with the prediction and the control of this geomorphic/soil degradation process under environmental change.

2. Contribution of gully erosion to soil loss and sediment production

What is the contribution of gully erosion to overall soil loss and sediment production at various temporal and spatial scales and under different climatic and land use conditions? The answer to this question cannot be readily given (Poesen et al., 1996b), but a compilation of data from various sources indicates that this contribution may vary considerably. Data collected in different parts of the world (Table 1) show that soil loss rates by gully erosion (SLgully) represent from minimal 10% up to 94% of total sediment yield caused by water erosion. In this section, we explore the main factors controlling SLgully and we discuss some trends. First of all, we address the effects of spatial scale (size of study area) and temporal scale (time span) considered before focussing on environmental factors.

Table 1
Contribution of (ephemeral) gully erosion to overall soil loss rates and sediment production rates by water erosion

Location	SLgully (ton ha^{-1} year^{-1})	SLgully (%)	Source
Belgium, Central	22.3	10	Govers and Poesen (1988)
France, North	n.a.	10–45	Ludwig et al. (1992)
Germany, South	n.a.	12–29	Auerswald (1998)
USA, New York	11.3	18	USDA-NRCS (1997)
USA, Wisconsin	0.5–2.0	18–36	Trimble (1999)
USA, Iowa	2–18.2	19–35	Laflen (1985)
USA, Iowa	8.7	19	Bradford and Piest (1980)
France, Normandy	n.a.	21–56	Cerdan et al. (2003)
USA, Michigan	2.7	21	USDA-NRCS (1997)
USA, Iowa	6.7	24	USDA-NRCS (1997)
USA, Louisiana	13.5	25	USDA-NRCS (1997)
Spain, North–West	1.5	26	Valcarcel et al. (2003, this volume)
USA, Kansas	17.9	27	USDA-NRCS (1997)
USA, Georgia	12	28	Thomas et al. (1986)
USA, Rhode Island	8.3	29	USDA-NRCS (1997)
USA, Mississippi	16.8	30	USDA-NRCS (1997)
USA, Maine	11.5	31	USDA-NRCS (1997)
USA, North Dakota	8.0	32	USDA-NRCS (1997)
Ethiopia, Tigray	4.7–12.1	33–55	Nyssen (2001)
USA, Wisconsin	9.4	35	USDA-NRCS (1997)
Germany, South–West	n.a.	36	Baade (1994)
Romania	n.a.	37	Nedelcu (2001)
USA, Alabama	20.8	37	USDA-NRCS (1997)
China, North	25–43	40–70	Li et al. (2000)
USA, Pennsylvania	4.0	41	USDA-NRCS (1997)
USA, Illinois	11.6	42	USDA-NRCS (1997)
USA, Maryland	9.0	43	USDA-NRCS (1997)
USA, New Jersey	11.6	44	USDA-NRCS (1997)
Belgium, Central	3.6	44	Poesen et al. (1996b)
USA, Iowa	11.9	45	Spomer and Hjelmfelt (1986)
France, North	n.a.	46–55	Auzet et al. (1995)
Portugal, Bragança	16.1	47	Vandekerckhove et al. (1998)
USA, Virginia	28.7	50	USDA-NRCS (1997)
Australia	n.a.	50	Wasson et al. (1996)
USA, Alabama	19.7–35.9	50–60	Laflen (1985)
Spain, Guadalentin	37.6	51	Poesen et al. (2002)
Kenya, Baringo	3.4	53	Oostwoud Wijdenes and Bryan (1994)
Norway, Leira basin	12.7	55	Bogen et al. (1994)
Spain, Catalunia	n.a.	58	Martinez-Casasnovas et al. (2002)
USA, Vermont	13.7	58	USDA-NRCS (1997)
Argentina, Northeast Patagonia	n.a.	58	Coronato and Del Valle (1993)
Spain	1.2	59	Oostwoud Wijdenes et al. (2000)
USA, Mississippi	7.7	60	Grissinger and Murphey (1989)
Australia, New South Wales	0.1	60	Crouch (1990)

(continued on next page)

Table 1 (*continued*)

Location	SLgully (ton ha^{-1} $year^{-1}$)	SLgully (%)	Source
Belgium, Central	n.a.	60	Quine et al. (1994)
USA, Arizona	1.3–3.9	60–81	Osborn and Simanton (1989)
USA, South California	36.8	71	Trimble (1997)
USA, Delaware	5.6	71	USDA-NRCS (1997)
USA, Washington	4.2	73	USDA-NRCS (1997)
Spain	64.9	74	Casali et al. (2000)
Niger, Ader Dutchi Massif	32	75	Heusch (1980)
Australia, Northwest	n.a.	80	Wasson et al. (2002)
Portugal, Alentejo	3.2	80	Poesen et al. (1996b)
Spain, Almeria	9.7	83	Poesen et al. (1996b)
China, Guangdong	n.a.	87	diCenzo and Luk (1997)
Lesotho	15	94	Rydgren (1990)

SLgully is soil loss rate by gully erosion, % SLgully = 100 (ratio between SLgully and total SL rates due to interrill, rill and gully erosion).

2.1. Spatial scale

Govers and Poesen (1988) measured SLgully to amount to 10% of total soil loss by water erosion processes on a hillslope in central Belgium (Table 1). This relatively low contribution of gully erosion to overall soil loss can be partly attributed to the limited size of the study area considered, i.e. 0.75 ha. An illustration of the impact of area considered on SLgully (%) can be deduced from data published by Poesen et al. (1996b) who measured the rill and gully volumes eroded on an abandoned agricultural plot in south–east Spain, 200 m wide and 500 m long, along a hillslope section at the footslopes of the Sierra de Gata. From the top of the plot down to 130 m, i.e. within an area of 2.6 ha, sheet and rill erosion dominated and produced a mean soil loss of ca. 2 tons ha^{-1} $year^{-1}$, whereas soil loss due to gully erosion remained <1 ton ha^{-1} $year^{-1}$. This resulted in a SLgully figure of less than 33%. When investigating the hillslope sections located more downslope, gully erosion became by far the dominant soil erosion process (SLgully = 85%) resulting in a mean soil loss figure of about 12 tons ha^{-1} $year^{-1}$, whereas soil loss by sheet and rill erosion remained unchanged. Thus, depending on the size of the area considered in the range between 2.6 and 10 ha, SLgully would range between 33% and 85%. In other words, this example clearly shows that SLgully highly depends on the size of the study area considered.

Sediment yield data for two river basins in the US presented by Osterkamp and Toy (1997) also clearly illustrate the importance of spatial scale when it comes to the assessment of the contribution of SLgully to sediment yield. At the runoff plot scale, interrill and rill erosion dominate and SLgully always equals 0%. However, once the study areas considered exceed a critical value ranging between 1 and 10 ha, gully erosion becomes very important and even becomes the dominant sediment-producing process.

An indication of the importance of sediment production by gullies in Mediterranean environments can also be found when comparing mean sediment deposition rates in Spanish reservoirs with sediment production rates by interrill and rill erosion measured on runoff plots (Poesen and Hooke, 1997). Mean sediment deposition rate measured over a period of 5–101 years (Avendaño Salas et al., 1997) in Spanish reservoirs with corresponding catchments ranging between 31 and 16,952 km^2 equals 4.3 tons ha^{-1} year^{-1} and can even go up to 10 tons ha^{-1} year^{-1} or more (Avendaño Salas et al., 1997; López-Bermudez, 1990; Romero Díaz et al., 1992; Sanz Montero et al., in press). These figures are significantly higher than reported short- to medium-term mean rates of interrill and rill erosion in the Mediterranean as measured on runoff plots (Castillo et al., 1997; Kosmas et al., 1997; Andreu et al., 1998; Puigdefabregas et al., 1999; Romero-Diaz et al., 1999; Cerda, 2001), i.e. less than or equal to 0.1 ton ha^{-1} year^{-1} for shrubland (matorral, $n=95$ plot–years) and olive groves ($n=3$), 0.2 ton ha^{-1} year^{-1} for wheat ($n=65$) and *Eucalyptus* plantations ($n=12$) and 1.4 tons ha^{-1} year^{-1} for vines ($n=9$) (Kosmas et al., 1997). There are various possible reasons to explain the discrepancy between the reported sediment production rates at the catchment scale and at the runoff plot scale. One of these is that at the catchment scale, sediment production processes other than interrill and rill erosion such as gully and channel erosion also operate. Moreover, most sediment produced by interrill and rill erosion in uplands is often deposited at the foot of hillslopes or in depressions within the landscape and therefore does not reach the river channel. Hence, other sediment-generating processes in catchments such as gully or channel erosion must play an important role in the production of sediments which are transported by (ephemeral) rivers and which cause reservoir infilling. This hypothesis is confirmed by observations reported by Plata Bedmar et al. (1997) who studied Cs^{137} content of sediments deposited in the Puentes reservoir (south–east Spain). These authors reported that only 40% of the sediment deposited in the Puentes reservoir between 1970 and 1994 originated in the 10-cm-thick topsoil from the catchment (which was assumed to accumulate most of the Cs^{137} fallout). Hence, 60% of the sediment accumulated in the reservoir came from subsurface soil horizons, which contained no Cs^{137}. It is most likely that gully and river channel processes could be held responsible for the erosion and transport of this sediment volume from subsurface horizons to the reservoir.

A recent survey within the catchments of 22 Spanish reservoirs clearly indicates that specific sediment yield increases when the frequency of gullies increases in the catchment (Fig. 5, Poesen et al., 2002; Verstraeten et al., in press). For catchments where no gullies were observed, mean specific sediment yield was 0.74 ton ha^{-1} year^{-1} ($n=3$). For catchments where numerous gullies could be observed, however, mean specific sediment yield was one order of magnitude larger, i.e. 9.61 tons ha^{-1} year^{-1} ($n=7$). Catchments with some gullies had an intermediate mean specific sediment yield of 2.97 tons ha^{-1} year^{-1} ($n=12$). In other words, the presence of (active) gullies in these Mediterranean catchments seems to be an important indicator for the magnitude of sediment production within these catchments.

All cited data clearly indicate that SLgully highly depends on the spatial scale considered and that for particular spatial scales, it can even become the dominant soil erosion process. Several studies have demonstrated that when scaling up area-specific soil loss rates, the latter do not remain constant or increase gradually with increasing size of the considered study area, but that area-specific soil loss rates may suddenly increase one order of magnitude once a critical area (corresponding to a topographic threshold value needed for gullies to develop) has been exceeded (e.g. Poesen et al., 1996b; Osterkamp and Toy, 1997). Thus, clearly, neglecting soil losses caused by gully erosion when

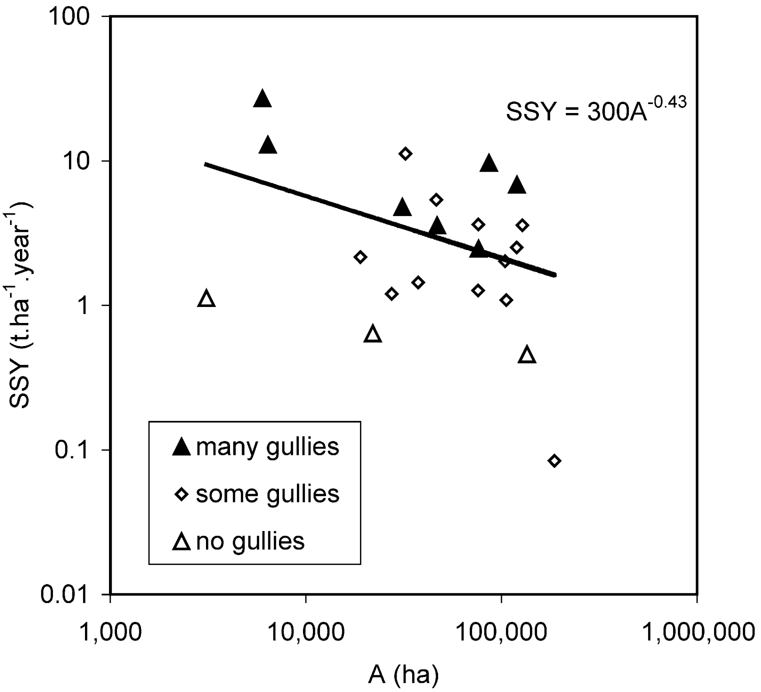

Fig. 5. Impact of the presence of active gullies in 22 selected Spanish catchments (draining to a reservoir) on area-specific sediment yield (SSY). Specific sediment yield was calculated based on published reservoir sedimentation data (Avendaño Salas et al., 1997; Sanz Montero et al., 1996). Presence of ephemeral and active permanent gullies as well as of bank gullies in an area within 5 km from the reservoir or in the vicinity of the main river channels draining to the reservoir was recorded during field surveys (after Poesen et al., 2002; Verstraeten et al., in press). *A* is catchment area.

changing spatial scale would definitely result in a significant underestimation of soil loss rates as observed in the field in a range of environments. Therefore, when scaling up sediment yield data from the plot scale to the hillslope or catchment scale, gully erosion needs to be addressed.

2.2. Temporal scale

The few available data indicate that SLgully also clearly depends on time span considered. For instance, data presented by Poesen et al. (2002) indicate that soil losses caused by ephemeral gully erosion for a relatively wet winter (1996) on the Iberian Peninsula represent 47–51% of total soil loss by water erosion, whereas at the medium time scale (i.e. 3–20 years) this figure rises to 80–83%. Data published by Trimble (1999) for Coon Creek (USA) allow the calculation of the contribution of SLgully to overall sediment production on uplands by water erosion for three successive periods, i.e. (1) 1853–1938, (2) 1938–1975 and (3) 1975–1993. The calculations yield values of 18%, 36% and 20%, respectively, of total sediment produced on uplands being caused by gully erosion. These fluctuations are attributed to changing land use during these successive periods. More research is needed to assess and elucidate changes in SLgully when considering different time periods.

2.3. Environmental controls

Apart from spatial and temporal scale differences, differences in SLgully for various measuring sites (Table 1) or different time periods can also be attributed to differences in gully types and to various environmental controls. For (small) catchments, SLgully = *f* (gully type, soil type, land use, climate, topography).

2.3.1. Gully type

Poesen et al. (1996b) found that rates of ephemeral gully erosion in central Belgium ranged between 3.0 and 6.6 tons ha^{-1} $year^{-1}$ and exceeded by one order of magnitude rates by bank gully erosion, i.e. 0.3–0.6 ton ha^{-1} $year^{-1}$.

2.3.2. Soil type

Field data collected by Evans (1993a) 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. In central Belgium, ephemeral gully volumes that eroded in truncated soil profiles (i.e. with no Bt-horizon) can be four to five times larger than volumes eroded by ephemeral gullies developing into intact soil profiles (Poesen, 1993). In addition, where large amounts of rock fragments are present at the soil surface (e.g. erosion pavements), sheet and rill erosion rates are usually relatively small compared to (ephemeral) gully erosion rates (Poesen et al., 1998).

2.3.3. Land use

For catchments with hillslopes producing small amounts of sediment by interrill and rill erosion, such as, for instance, hillslopes under grassland (Bradford and Piest, 1980), gullies contribute significantly more to overall sediment yield compared to sheet and rill erosion than if the hillslopes produced large amounts of sediment, such as hillslopes under cropland. Similar observations for bare and crop-covered catchments have been reported by Cerdan et al. (2003). Development of infrastructure, such as irrigation canals or roads in a catchments, can also induce an increase in gully erosion rate due to inappropriate drainage of surface water (e.g. Nyssen, 2001; Vanacker et al., in press). Data collected by Nyssen (2001) in the Ethiopian Highlands, for instance, indicate that SLgully evolved from 33% to 55% after the construction of a road in the study area because of more runoff concentration.

2.3.4. Climate and weather

Limited available data indicate that SLgully (%) is relatively more important in dry environments compared to wet environments (Poesen et al., 1996b; Poesen and

Hooke, 1997). Data from central Belgium indicate that the relative contribution of gully erosion to total sediment production within a given catchment decreases with increasing return period (and thus, intensity) of the rain event (Fig. 6). 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 characterised by more intense rainstorms (Vandaele and Poesen, 1995). Depending on the observation period, SLgully (%) will be partly determined by the magnitude and frequency of rain events causing gully erosion. In addition, data from Fig. 6 indicate that any change in the rainfall regime (due to a climate change) for a given area will most likely also affect SLgully (%). In areas of pronounced continentality, there may be a considerable seasonal variation in SLgully because of a dominance of gully erosion by concentrated snowmelt runoff in spring (with little or no sheet erosion because of the lack of raindrop impact forces and the small velocity of sheet flow under a snow cover) and sheet and rill erosion during thunderstorms in summer (Auerswald, personal communication).

2.3.5. Topography

Although no data are available on the relation between SLgully (%) and topography, it is clear that topographic attributes such as slope gradient and drainage area affect the

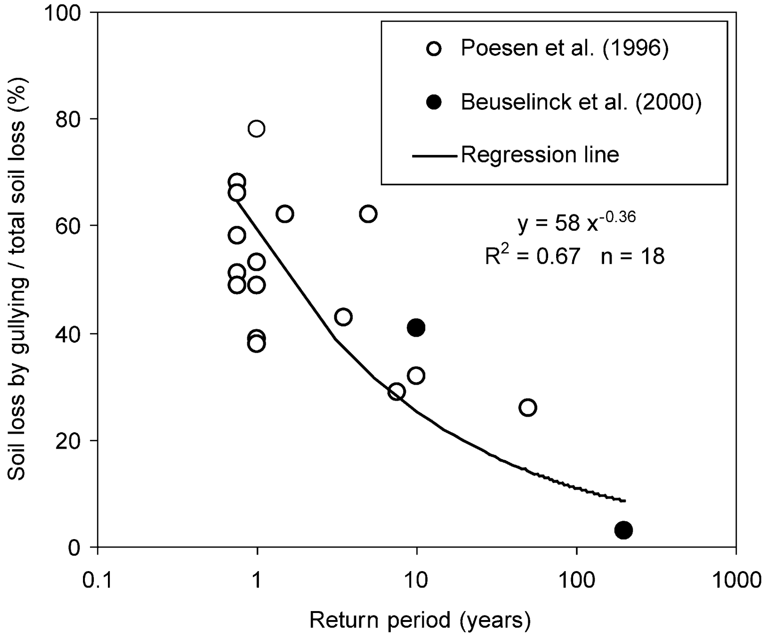

Fig. 6. Relation between return period of rain event and ratio of soil loss by gully erosion and total soil loss by water erosion in central Belgium [SLgully(%)]. Data presented in Poesen et al. (1996b) were measured by Vandaele and Poesen (1995) for a 25-ha catchment, whereas data from Beuselinck et al. (2000) were measured in a 250- and 300-ha catchment, respectively.

density of the drainage network and hence the probability of gully channel development (see Section 4.3).

This section highlighted some factors controlling SLgully. At present, however, no tool is available to predict SLgully for different spatial and temporal scales and for a range of environmental conditions. Clearly, more research is needed in this domain if we want to predict impacts of land use and climate changes on the risk for gully erosion.

3. Techniques for measuring gully erosion processes and rates

What are appropriate measuring techniques for monitoring and for experimental studies of the initiation and development of different gully types at various temporal and spatial scales? Contrary to sheet and rill erosion, where standardised procedures for assessment of erosion rates exist (e.g. runoff plot technique widely used for collecting soil loss data for assessment of erosion factors in, e.g. RUSLE), no standardised procedures are available for measuring gully erosion rates and controlling factors.

Here, we present a brief overview of recent field and laboratory-based techniques used in order to assess gully erosion rates at various time scales.

At the short-time scale ($<1-10$ years) both ground-based and airborne techniques have been used to assess eroded volumes by gullying. Measuring directly the volumes of soil eroded by ephemeral gullying has been done in a range of cropland environments (e.g. Auzet et al., 1995; Casali et al., 1999; Vandaele and Poesen, 1995; Nachtergaele et al., 2001a,b; Valcárcel et al., 2003; Øygarden, 2003). Short-term monitoring of gully head or gully wall retreat has been conducted by measuring regularly the change in distance between the edge of the gully head or wall and benchmark pins installed around the gully wall (e.g. Vandekerckhove et al., 2001b; Oostwoud Wijdenes and Bryan, 2001) or by measuring the three-dimensional morphology of the gully wall using a direct contact protractor system (e.g. Sneddon et al., 1988; Archibold et al., 1996). Several studies have applied photogrammetric techniques to sequential, large-scale aerial photographs in order to determine the volume of soil lost by concentrated flow erosion (e.g. Thomas et al., 1986; Ries and Marzolff, 2003, this volume). Ritchie et al. (1994) measured gully cross-sections using a laser altimeter mounted in an aircraft. Although several new techniques have been proposed, few of these have been tested in a wide range of environments.

At the medium-time scale (10–70 years) aerial photographs have been analysed to measure temporal changes in length, area or volume of various gully types (e.g. Burkard and Kostaschuk, 1995; Derose et al., 1998; Nachtergaele and Poesen, 1999; Daba et al., 2003; Gábris et al., 2003; Martinez-Casasnovas, 2003). Only gully systems with sufficiently large changes in morphology over time can be studied in this way. For gullies experiencing smaller changes over time, Vandekerckhove et al. (2001a) developed a framework using dendrochronological methods for estimating medium-term gully erosion rates based on the analysis of roots exposed by gully erosion, browsing scars by ungulates, exposed and dead root ends, root suckers, stems, branches or leading shoots of fallen trees and a sequence of trees within a gully.

For the long-time scale, several studies have used historical data (documents and maps), artefacts and various dating techniques to reconstruct the conditions leading to significant gully erosion in the past (e.g. Prosser and Winchester, 1996; Trimble, 1998, 1999; Bork et al., 1998; Webb and Hereford, 2001; Dotterweich et al., 2003; Gábris et al., 2003).

In order to better understand and model gully erosion processes, several field and laboratory-based experiments have been undertaken (for a recent overview of gully erosion processes, see Poesen et al., 2002; Bull and Kirkby, 2002). In the field, concentrated flow erosion has been simulated on undisturbed soil surfaces in order to detect critical flow intensity parameters leading to significant soil detachment and transport (e.g. Riley, 1992; Prosser et al., 1995; Franti et al., 1999). However, in the field, the relative importance of various subprocesses in gully development, i.e. flow detachment by flow shear stresses or by seepage forces, plunge pool erosion, headcutting, tension crack development and mass wasting on gully walls, cannot always easily be measured. Therefore, laboratory experiments with flumes ranging in length between 15 and 29 m filled with soil and using simulated concentrated flow erosion have been set up to study the mechanics of channel development (e.g. Meyer, 1989; Govers et al., 1990; Robinson and Hanson, 1996; Bennett et al., 2000). Smaller laboratory flumes have been used to investigate subprocesses of channel initiation and development under drainage and seepage conditions (e.g. van der Poel and Schwab, 1988; Zhu et al., 1995; Bryan and Rockwell, 1998; Gabbard et al., 1998; Poesen et al., 1999; Bennett and Casali, 2001; Römkens et al., 2001).

Although a significant number of studies dealing with the measurement of gully erosion rates exist, the possibilities and limitations of the various monitoring and experimental approaches used in these studies are not always clear. In addition, due to a lack of standardisation, the data on gully erosion rates obtained in various environments are not always comparable. Standardisation of the various measuring techniques will lower the uncertainties on the measurements of gully erosion rates but will still not always solve the problem of how to compare these erosion rates with those caused by other erosion processes.

4. Thresholds for gully development

Gully erosion clearly is a threshold phenomenon. This geomorphic process occurs only when a threshold in terms of flow hydraulics, rainfall, topography, pedology and land use has been exceeded. Can we identify critical thresholds for the initiation, development and infilling of gullies in different environments?

4.1. Hydraulic thresholds for gully development under various land uses

Gully channels can only develop if concentrated (overland) flow intensity during a rain event exceeds a threshold value. Horton (1945) first proposed the concept of a threshold force required for channel initiation. This force of flow is often expressed in terms of the boundary flow shear stress ($\tau_b = \rho g d s$ with ρ = density of runoff water, g = acceleration due to gravity, d = depth of flow and s = sine of the soil surface gradient). The threshold force required to cause channel incision into the soil surface in the concentrated flow zone is termed the critical flow shear stress (τ_c). A key question is: how large should τ_c be for (ephemeral)gullies to initiate?

Critical flow shear stress values for incipient motion of individual soil particles have been well studied. Entrainment of loose silt and fine to medium sand grains occurs at τ_c values of less than 1 Pa (as deduced from the Shields curve, Vanoni and Brooks, 1975, p. 99). For bare, cohesive topsoils with soil shear strength values at saturation up to 10 kPa, laboratory experiments indicate that τ_c values can go up to 4 Pa (e.g. Rauws and Govers, 1988; Brunori et al., 1989; Crouch and Novruzzi, 1989). These τ_c values are of the same order as those reported for rill incision in bare topsoils in the field under drainage conditions, i.e. 1.8–10.6 Pa depending on soil properties (texture, soil water content, content of calcium, iron, organic carbon and potassium, e.g. Gilley et al., 1993). Soil shear strength values at saturation appear to be a good indicator for τ_c (Poesen et al., 1998). Experimental data collected by Huang and Laflen (1996) indicate that critical flow conditions for rilling under seepage conditions may be significantly less than those for drainage conditions. Land management practices may affect the critical flow shear stress values for concentrated flow erosion as Franti et al. (1999) reported that τ_c values for no-till were about twice that for tilled soil. Along the same lines, Laflen and Beasly (1960)clearly demonstrated that compaction of the topsoil increased τ_c values. Living plant roots may increase critical flow conditions for rill channel development (Li, 1995; Sidorchuk and Grigorév, 1998).

In contrast with the number of publications on critical flow conditions for incipient rilling, very few studies report critical flow conditions for incipient gullying. During a rain event, many rills may develop, but only a few may grow into a gully provided that flow intensities exceed those needed for the erosion of a gully channel. For cultivated land, Nachtergaele (2001) calculated critical shear stresses during peak flow that occurred in 33 ephemeral gully channels in central Belgium and in 40 ephemeral gully channels in southern Portugal. For each study area, a frequency distribution of τ_c values was established (Fig. 7): τ_c. ranges between 3.3 and 32.2 Pa (mean = 14 Pa) for ephemeral gullies eroded in silt loam (loess-derived) topsoils in Belgium, whereas τ_c ranges between 16.8 and 74.4 Pa (mean = 44 Pa) for ephemeral gullies formed in stony sandy loams in Portugal. In general, an inverse relation between concentrated flow width and τ_c for ephemeral gully development in these study areas is observed (Poesen et al., 2002). The significant difference in τ_c between both study areas cannot be explained by differences in land use, as in both study areas ephemeral gullies developed in tilled cropland, but are attributed to different soil types. Whereas no rock fragments are present in the Belgian loess-derived soils, rock fragment content of topsoils in southern Portugal amounts to 30% by mass on average. Poesen et al. (1999) demonstrated experimentally that rock fragment content in topsoils significantly reduces the susceptibility of these soils to concentrated flow erosion. For noncultivated land in Australian valley floors, Prosser (1996) reported τ_c values for gully initiation of 21 Pa for bare clay, 70 Pa for heavily degraded aquatic plants or tussock and sedge, >105 Pa for undisturbed aquatic plants, >180 Pa for lightly degraded tussock and sedge and >240 Pa for undisturbed tussock and sedge. Grassed irrigation canals have also been found to resist flow shear stresses of up to 260 Pa before showing

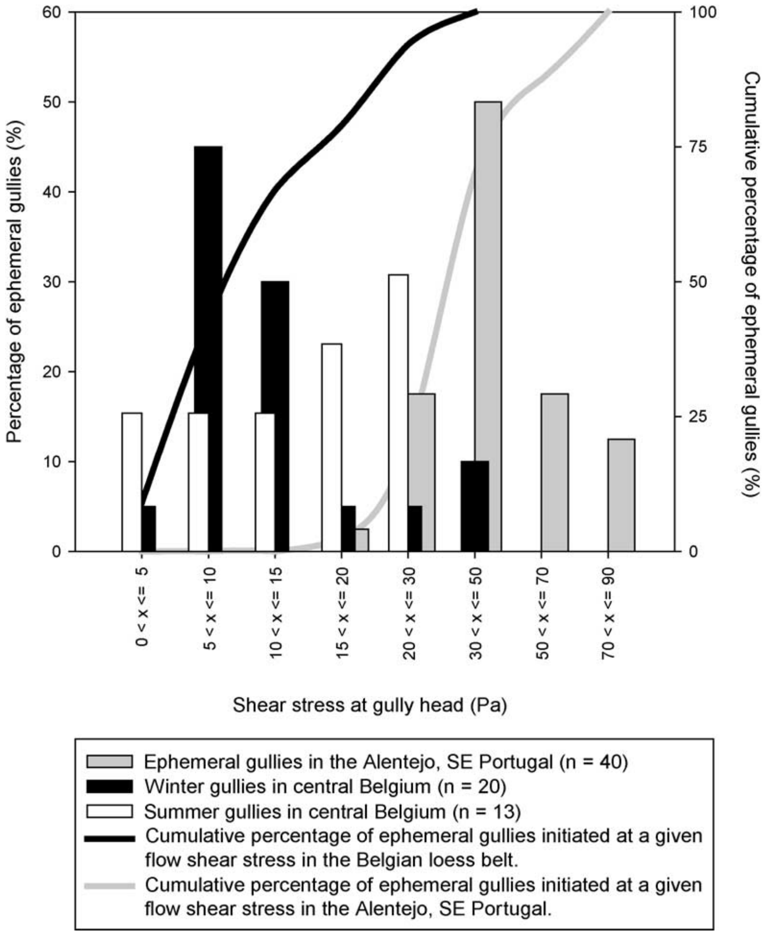

Fig. 7. Distribution of calculated peak flow shear stress values at points where ephemeral gullies start (i.e. where channel cross-section >930 cm^2) on loess-derived soils during winter and summer rains in Belgium ($n = 33$) and on stony topsoils in the Alentejo (SE Portugal; $n = 40$) (after Nachtergaele, 2001).

signs of scour (Reid, 1989; cited by Prosser, 1996). Few studies deal with the hydraulic geometry characteristics and hydraulic efficiency of various gully types (e.g. Billi and Dramis, 2003; Ionita, 2003).

This review reveals that for prediction purposes, more data are needed on critical hydraulic conditions leading to gully initiation, development and infilling in a range of environments as well as for different land management practices. Very few studies have attempted to measure critical hydraulic conditions for incipient gullying in field conditions mainly because of logistic constraints. Therefore, several studies have attempted to assess critical environmental conditions for gullying in terms of rainfall, topography, soils (or lithology) and land use as these factors control either the runoff hydraulics (e.g. rainfall, topography) or the resistance of the soil surface to incision (e.g. soils) or both (e.g. land use).

4.2. Rainfall thresholds

What are critical rainfall characteristics leading to the development of gullies in different environments?

Table 2 summarises some data on threshold rains (P) needed to initiate rills and (ephemeral) gullies. P values needed to initiate ephemeral gullies in cropland (i.e. $14.5 < P < 22$ mm) are only slightly larger compared to those needed to initiate rills (i.e. $7.6 < P < 25$ mm). Differences in threshold rains for ephemeral gully development on cropland between the various study areas, i.e. $14.5 < P < 22$ mm, are attributed to different

Table 2
Rainfall thresholds for rill and (ephemeral) gully development under field conditions; P = depth of rain event, P_d = daily rain depth, P_i = rain intensity, P_{i-30} = rain intensity calculated over 30 min

Erosion process	Rain threshold	Location	Soil/land use	Source
Rill	P_d>7.5 mm	North Norfolk, UK	loamy to sandy loam soils, cropland	Evans and Nortcliff (1978)
	P = 10 mm and P_i>1 mm h^{-1}	West Midlands, UK	sandy loam soils, cropland	Reed (1979)
	P>10 mm (summer)	East Anglia, UK	all soil types, cropland	Evans (1981)
	P_d = 10–15 mm	North Thailand	clay soils, cropland	Turkelboom (1999)
	P = 15 mm	Alsace, France	loam soils	Auzet (personal communication)
	P_d>15 mm and P_i>4 mm h^{-1}	England and Wales, UK	sand loam soils, cropland	Chambers et al. (1992)
	P = 20 mm and P_i = 3 mm h^{-1}	Bedfordshire, UK	sand loam soils, cropland	Morgan (1980)
	P_d>15–20 mm	Scotland, UK	sandy loam and loam soils, cropland	Speirs and Frost (1985)
	P>20–25 mm during winter	lowland England, UK	all soil types, cropland	Evans (1980)
	P>30 mm during 2 days	South Downs, England, UK	stony soils, cropland	Boardman (1990)
Ephemeral gully	P = 14.5 mm	Almeria, Spain	stony soils, cropland	Vandekerckhove et al. (2000)
	P_d = 18 mm (summer); P_d = 15 mm (winter)	Central Belgium	silt loams, cropland	Nachtergaele (2001)
	P = 17 mm	Navarra, Spain	loamy soils, cropland	Casali et al. (1999)
	P = 20 mm	North Thailand	clay soils, cropland	Turkelboom (1999)
	P = 22 mm and P_{i-30} = 33 mm h^{-1}	Extremadura	shallow soils, cropland	Schnabel and Gomez (1993)
Gully	P_d>80–100 mm	Bombala, SE Australia	loamy sand and sandy loam soils, forestry operations	Prosser and Soufi (1998)

states of the soil surface (roughness, degree of sealing) as affected by tillage operations and antecedent rains.

Nachtergaele (2001) analysed 38 ephemeral gully erosion events that occurred over a 15-year period in central Belgium and found critical P values of 15 mm in (late) winter ($n = 21$) and of 18 mm in (early) summer ($n = 17$) which is attributed to a difference in soil moisture content between winter and summer. Threshold rains for gully development in land under forestry operations in Australia are significantly larger ($P = 80-100$ mm) than those for ephemeral gully development on seedbeds. Sudden snowmelt on frozen/thawing soil presents a special case of a meteorologic threshold condition at higher latitudes, higher altitudes or areas with a continental climate, which can lead to the rapid development of ephemeral gullies. Øygarden (2003) documents how the combination of frozen subsoils, saturated topsoils with low strength and intense rainfall led to the development of ephemeral gullies in Norway, even in areas with gentle slope gradients. These observations point to the fact that a gradual climate change to more unstable winter conditions (i.e. freezing and thawing combined with intense rain) is likely to increase the risk of (ephemeral) gully erosion. One of the difficulties encountered when assessing critical rain depths for gully initiation is the lack of representative rain data for the sites where observations on gully erosion processes have been made (e.g. Vandekerckhove et al., 2000).

4.3. Topographic thresholds and the role of land use

Where do gullies develop in the landscape? Most soil erosion models (apart from some GIS-based models) do not predict the location of gullies. However, this is important for land managers and for predicting possible impacts of climatic or land use changes on the spatial distribution and density of gullies. The main question here is: where do gullies start and where do they end in the landscape?

4.3.1. Where do (ephemeral) gullies start?

An approach to predict locations where gully heads might develop is presented by the threshold concept, first applied to geomorphic systems by Patton and Schumm (1975). This concept is based on the assumption that in a landscape with a given climate and land use, there exists for a given slope gradient of the soil surface (S) a critical drainage area (A) necessary to produce sufficient runoff which will cause gully incision. As slope steepens, this critical drainage area decreases and vice versa. For different environmental conditions and different gully initiating processes, different thresholds apply. Threshold lines for gully development by hydraulic erosion can be represented by a power-type equation (Begin and Schumm, 1979; Vandaele et al., 1996): $S = aA^b$ with a and b coefficients depending on the environmental characteristics. Kirkby et al. (2003) shows that power law equations describing sediment transport for water erosion occurring on runoff plots are consistent with S–A relations describing the location of ephemeral and permanent gully channel head location in the landscape. The topographic threshold concept for gully initiation permits one to predict, for a given land use, the location in the landscape where gully channels may develop by providing a physical basis for the initiation of gullies. Various studies conducted in a range of different environments have established critical S–A relations for incipient permanent and ephemeral gullying (e.g. Patton and Schumm, 1975; Harvey, 1987, 1996; Montgomery and Dietrich, 1988, 1994; Moore et al., 1988; Riley and Williams, 1991; Boardman, 1992; Prosser and Abernethy, 1996; Prosser and Winchester, 1996; Vandaele et al., 1996; Vandekerckhove et al., 1998, 2000; Nachtergaele et al., 2001a,b; Nyssen et al., in press; Moeyersons, 2003; Morgan and Mngomezulu, 2003). Poesen et al. (1998) summarised and compared 10 published critical *S*–*A* data sets for ephemeral gullies and permanent gullies in different environments and found that not only the environmental characteristics, but also the methodology used to assess critical *S* and *A* also affects the reported topographic threshold for incipient gullying (Fig. 8). Fig. 8 indicates that topographic threshold conditions for gully initiation in noncultivated land plot above those needed to initiate ephemeral gullies in cropland. Other factors controlling the position of the threshold lines are climate as well as all other factors controlling the

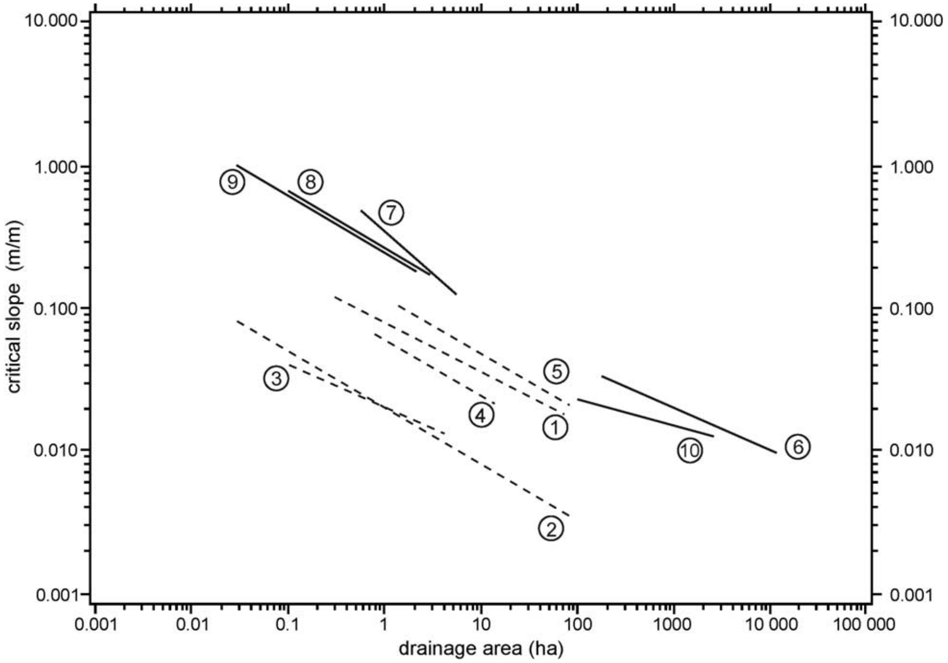

Fig. 8. Relation between critical slope of soil surface and drainage area for incipient gully development in a variety of environments (after Poesen et al., 1998). Dotted lines indicate threshold conditions for ephemeral gully development in cultivated cropland (1–5). Solid lines indicate threshold conditions for gully head development in noncultivated land (6 = sagebrush and scattered trees; 7 = open oak woodland and grasslands; 8 = coastal prairie; 9 = logged forest and 10 = swampy, reed-covered valley floors). (1) Central Belgium: field survey (Poesen, unpublished data); (2) Central Belgium: analysis of aerial photos and topographic maps (Vandaele et al., 1996); (3) Portugal: analysis of aerial photos and topographic maps (Vandaele et al., 1996); (4) France: analysis of aerial photos and topographic maps (Vandaele et al., 1996); (5) UK (South Downs): field survey (Boardman, 1992). (6) USA (Colorado): analysis of aerial photos and topographic maps (Patton and Schumm, 1975); (7) USA (Sierra Nevada): field survey (Montgomery and Dietrich, 1988); (8) USA (California): field survey (Montgomery and Dietrich, 1988); (9) USA (Oregon): field survey (Montgomery and Dietrich, 1988); (10) Australia (New South Wales): field survey (Nanson and Erskine, 1988).

mechanisms of incipient gullying, i.e. hydraulic erosion by concentrated overland flow, seepage flow and mass movement processes (Montgomery and Dietrich, 1994; Kirkby, 1994). From a comparison of six critical S–A data sets corresponding to various Mediterranean study areas in Europe and collected using the same methodology, Vandekerckhove et al. (2000) found that vegetation type and cover were far more important than climatic conditions in explaining differences in topographic thresholds for different areas. In cultivated fields, topsoil structure and soil moisture condition, as controlled by the antecedent rainfall distribution, are crucial factors affecting the S–A relationships, rather than daily rain for the gully-initiating events. For rangelands, vegetation cover and type (annuals and perennials) at the time of gully head development appears to be the most important factor differentiating between topographic thresholds. The importance of vegetation biomass in concentrated flow zones for reducing gully initiation risk in semi-arid environments was also stressed by Graf (1979) and Nogueras et al. (2000). This statement is also in line with conclusions drawn from various studies in Australia by Prosser (in press): "Natural vegetated surfaces in humid environments are highly resistant to scour by concentrated overland flow and consequently are only sensitive to gully erosion from extreme events or climate change experienced at 1000 years or longer time scales. Once vegetation cover is degraded, however, these systems become more sensitive to climate change and decadal scale changes can contribute to gully initiation. Many of these degraded hollow or valley bottoms would ultimately scour from large events, regardless of climate changing toward more intense runoff. Particularly, areas of high intensity cropland have periods of low resistance to concentrated flow erosion, which make them quite sensitive to relatively small storms and changes to the intensity of rainfall and runoff."

From these conclusions, it becomes clear that any land use change implying a vegetation biomass decrease as well as a lowering of the erosion resistance of the topsoil by tillage operations in the landscape and, more particularly, in concentrated flow zones will decrease the threshold for incipient gullying. This implies that for a given slope gradient (S), critical drainage area (A) for gully head development will decrease, and therefore gully density will increase, as pointed out by Kirkby (1988).

Several studies have been reported where the topographical threshold concept in combination with a hydraulic threshold has been applied to predict areas at risk of gullying (Dietrich et al., 1993; Prosser and Abernethy, 1996). Desmet and Govers (1997) and Desmet et al. (1999) investigated the relative importance of slope gradient (S) and drainage area (A) for the optimal prediction of the initiation and trajectory of ephemeral gullies. In the latter study, a striking discrepancy was found between the high A exponent (i.e. 0.7–1.5) required to predict optimally the trajectory of the gullies and the low A exponent (i.e. 0.2) required to identify spots in the landscape where ephemeral gullies begin.

4.3.2. Where do (ephemeral) gullies end?

Gullies usually end where the transporting capacity of the concentrated runoff drops and/or where the erosion resistance of the topsoil increases sharply. A sudden change from one land use to another might trigger sediment deposition instead of channel entrenchment (vegetation-controlled sediment deposition, e.g. Takken et al., 1999; Beuselinck et al., 2000; Steegen et al., 2000). In many field conditions, a lowering of the slope gradient with increasing drainage area causes a drop in transporting capacity and hence a decrease in gully channel depth (slope-controlled sediment deposition). In contrast with critical S–A relations established for the location of gully heads, few S–A relations have been established for the location of sites where (ephemeral) gullies end (e.g. Poesen et al., 1998; Vandekerckhove et al., 2000; Nachtergaele et al., 2001a,b). Field measurements in different cropland areas of northern Europe reveal that topographically induced sediment deposition at the downlsope end of ephemeral gullies, which developed in loamy to loamy sand soils, usually occurs in a narrow range of local slope gradient along catenas under cropland, i.e. 2–4%. However, when rock fragment content of the topsoil increases, topographically induced sediment deposition occurs on steeper slopes, i.e. up to 25–30% (Poesen et al., 2002).

From this review we conclude that detailed information on the impact of various land uses on topographic thresholds needed to initiate gullies under a range of climatic conditions is rather scarce. However, such information is crucial for predicting where in the landscape gully development might be expected under different environmental conditions.

4.4. Pedologic and lithologic controls

To what extent do soil type and lithology control gully development and gully characteristics?

4.4.1. Soil type

Many studies have investigated the susceptibility of soils (soil erodibility) to interrill and rill erosion (for a recent review, see Bryan, 2000). Comparatively few studies have investigated the susceptibility of soils to gully erosion. Soil type and, in particular, the vertical distribution of the erosion resistance of the various soil horizons largely controls the size and, more specifically, the depth and cross-sectional morphology of gullies. Ireland et al. (1939) were the first to point to the important role of the resistant Bt-horizons in controlling gully depth and gully head shape in the southeastern USA. Other studies conducted on gully development in duplex soils in Australia (e.g. Sneddon et al., 1988) and on loess-derived soils in Europe (Poesen, 1993) also came to the same conclusion. Poesen (1993) found that soil shear strength at saturation of the various loess-derived soil horizons is a good indicator of their resistance against concentrated flow erosion. For loess-derived soils, Nachtergaele and Poesen (2002) showed that (1) τ_c and channel erodibility (related to concentrated flow erosion) for a Bt-horizon was significantly larger compared to τ_c and erodibility for an Ap or a C horizon and (2) that an increasing antecedent moisture content of each horizon had a negative effect on their erodibility. In landscape positions where Bt-horizons are still present, ephemeral gully depth is limited to a maximum of 0.50 m. However, for landscape positions where no Bt-horizon is present, concentrated flow may erode ephemeral gullies several meters deep (Poesen, 1993). Erosion of Bt-horizons caused by various processes (i.e. water erosion, tillage erosion, removal of soil during root and tuber crop harvesting, land levelling), therefore, largely increases the risk for deep gully development. Other reported soil horizons resistant to gully erosion are plough pans, fragipans, petrocalcic horizons or unweathered bedrock. On the other hand, less permeable soil horizons can induce positive pore water pressures in the overlying soil layers which in turn lowers the erosion resistance of these soil horizons, particularly when seepage conditions (return flow) occur (e.g. Moore et al., 1988; Huang and Laflen, 1996). This in turn may alter the topographic threshold for gully head initiation (e.g. Montgomery and Dietrich, 1994; Vandekerckhove et al., 2000; Poesen et al., 2002).

4.4.2. Lithology

Figs. 9 and 10 illustrate two contrasting examples of how lithology (respectively, hard unweathered rock and unconsolidated loose sandy sediments) controls the size of gullies that can develop under cropland. The occurrence of landscapes heavily dissected by gullies in the Mediterranean (i.e. badlands) is strongly controlled by particular lithologic conditions, i.e. the presence of unconsolidated or poorly sorted materials such as shales, gypsiferous and salty silt marls and silt–clay deposits of Tertiary and Quaternary age (Poesen and Hooke, 1997; Gallart et al., 2002). Faulkner et al. (2003) report on the role of site geochemistry in morphological development of badlands. In contrast with sheet and rill erosion, relatively little is known about the properties of soils or parent materials and the associated processes that control the dynamics of their resistance to gully erosion.

4.5. Land use thresholds

Gully development over the last 1500 years triggered by a combination of human-induced land cover changes and extreme rainfalls have been documented for various

Fig. 9. Ephemeral gully in Vulci, central Italy (November 1987). Note the hard, unweathered bedrock at a depth of ca. 90 cm.

Fig. 10. Large (ca. 15–20 m deep and ca. 30–40 m wide) permanent gully which developed in unconsolidated Tertiary sandy sediments, Owerri, South Nigeria (April 1988). The development of such gullies leads to enhanced subsurface drainage (water table lowering) of these hillslopes.

parts of the world: e.g. arroyo development in the southwestern US caused by the introduction of cattle (which caused overgrazing) and a climatic shift (e.g. Webb and Hereford, 2001), gully initiation and development in eastern Australia since European settlement, 200 years ago (Prosser and Winchester, 1996), gully development in the UK in the 9th to the 10th century caused by a change in catchment hydrology in response to human-induced vegetation change (Harvey, 1996) or gully development in central Europe due to high land use pressure and extreme rains in the 14th century in Germany (Bork et al., 1998) or during the Little Ice Age in Slovakia (Stankoviansky, in press). In many forested areas of Europe, large gully systems can be often found (Fig. 11). What kind of environmental conditions have led to the development of these (large) gullies and what do we learn from this? Most of these gullies are the result of a land use different from the present land use (in combination with extreme rainfall?) in the past rendering these landscapes more vulnerable to gully incision. Much can be learned from detailed case studies on environmental conditions leading to this kind of land degradation (e.g. Poesen et al., 2000; Dotterweich et al., 2003; Gábris et al., 2003; Boardman et al., 2003; Strunk, 2003).

Several recent case studies have documented the significant impacts of a gradual or sudden shift in land use on the triggering of gullying or the increase in gully erosion rates. For instance, field observations in central Belgium indicate that the increase in area under maize over the last two decades has resulted in an increased ephemeral gully erosion risk (Nachtergaele, 2001). Faulkner (1995) reported on the triggering of gully erosion associated with the expansion of unterraced almond cultivation after hasty clearance of native Mediterranean matorral in southern Spain. This land use

Fig. 11. Old gully channel under forest, most probably formed under a different land use (Poesen et al., 2000; Tersaert forest, Huldenberg, Belgium, February 2000).

change also caused the development or reactivation of bank gullies along ephemeral streams in southeastern Spain (Oostwoud Wijdenes et al., 2000). Bork et al. (2001) documented the effect of agricultural intensification in the second half of the 20th century in the Upper Yangtze river basin (SW China) on rapid gully development and the subsequent gully stabilisation as a consequence of reforestation by air seeding. Several studies conducted in a range of different environments have documented the impact of road construction on the increased gully erosion risk on steep slopes (e.g. Moeyersons, 1991; Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001; Nyssen, 2001). Gully incision is significantly more likely below culverts on steep slopes with longer than average contributing ditch length (Wemple et al., 1996; Nyssen, 2001). Montgomery (1994) showed that for a given slope gradient, the drainage area required to support a gully head is smaller for road-related runoff than for undisturbed slopes. Contributing road length and the gradient of the discharge hillslope have been successfully used to separate gullied and non-gullied flow pathways within catchments (Croke and Mockler, 2001). Burkard and Kostaschuk (1997) attributed the increased growth rates of bank gullies along the shoreline of Lake Huron to increased snowfall, extreme flow events but also to the extension of municipal drains and the use of subsurface drainage. Vanacker et al. (in press) have documented the impact of collapsing irrigation canals and the mismanagement of excess irrigation water on the extension of the rill and gully network in a semi-arid region of Ecuador.

Many more detailed case studies are needed if we want full understanding of the impact of various types of land use change and its interaction with extreme weather conditions on gully development. In addition, more research is needed on the (socio-economic) drivers of land use changes causing increased or decreased gully erosion risk.

5. Interaction between gully development, hydrological and other soil degradation processes

What is the impact of gully erosion on hydrological processes such as infiltration and drainage? Once gullies develop, water infiltration rate through the gully bottom may be significantly larger compared to that of the soil surface in the intergully areas if the gully channel develops into more permeable horizons. Through the gully bed and banks, significant runoff water transmission losses can then take place, particularly in semi-arid and arid environments as shown by Esteves and Lapetite (2003) in Niger. Such water transmission losses have also been reported to occur in smaller erosion channels (i.e. rills, e.g. Poesen and Bryan, 1989; Parsons et al., 1999) as well as in larger (ephemeral) river channels (for recent review, see Beven, 2002). Recent studies (e.g. Leduc et al., 2001; Avni, in press) indicate that gully development in semi-arid areas may therefore lead to significant groundwater recharge. On the other hand, if gullies develop into hillslopes with temporary water tables, they may cause an enhanced drainage and a rapid water table lowering which results in a significant drying out of the soil profiles in the intergully areas as observed by Moeyersons (2000) in Africa. In addition, Okagbue and Uma (1987) reported that gullies located at the discharge areas of groundwater systems in southeastern Nigeria may become very active during the peak recharge times of the rainy season because high pore–water pressures reduce the effective strength of the unconsolidated materials along the seepage faces. The seepage forces caused by exit hydraulic gradients at the levels of seepage on the gully walls produce boiling conditions, piping and tunnelling that undermine the gully walls and activate their retreat (see also Fig. 10). Most erosion models are driven by hydrological models (runoff). The previous discussion clearly indicates that there are also important feedback mechanisms, i.e. gully erosion may in turn also control the intensity of some hydrological processes (water transmission losses or groundwater depletion). These interactions deserve more attention.

How does gully erosion interact with other soil degradation processes? Once gullies develop, they often trigger other soil degradation processes such as piping, soil fall or soil topple (driven by gravity) after tension crack development and undercutting. Furthermore, gully channels enhance the export of sediment produced on the intergully areas (sheet and rill erosion) by increasing the connectivity in the landscape (e.g. Stall, 1985; Poesen et al., 2002, Fig. 5), which leads to an increased risk of sediment deposition downslope. If no gully control measures are taken, gully growth rates usually decline exponentially (e.g. Graf, 1977; Rutherford et al., 1997; Nachtergaele et al., 2002b). However, in cropland areas, ephemeral gullies are usually filled in by tillage (tillage erosion and tillage deposition) within less than a year of their initiation. During subsequent storms (years), the infilled soil material 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 for concentrated flow erosion. Thus, ephemeral gully erosion and tillage erosion reinforce each other. In various parts of Europe, heavily dissected landscapes by gullying (badlands) have been levelled, thereby causing strong soil profile truncation in the intergully areas and infilling of gullies with this material (e.g. Revel and Guiresse, 1995; Poesen and Hooke, 1997; Torri, 1999). Such land levelling operations have often resulted in renewed gully incision of the levelled land as well as in shallow landsliding causing large soil losses (Clarke and Rendell, 2000). In other words, important interactions exist between concentrated flow erosion and tillage erosion (Poesen, 1993) as well as with erosion caused by land levelling.

The significant interactions between gully erosion on the one hand and hydrological (i.e. infiltration, drainage) as well as other soil degradation processes (piping, mass wasting, tillage erosion and erosion by land levelling) need to be better understood for improving predictions of hydrological processes and land degradation rates under different environmental conditions as well as for taking appropriate measures to control them.

6. Gully erosion models

What are appropriate models of gully erosion, capable of predicting (a) erosion rates at various temporal and spatial scales and (b) the impact of gully development on hydrology, sediment yield and landscape evolution?

6.1. Modelling ephemeral gullies and permanent gullies

At present, only a few models claim to be capable of predicting ephemeral gully erosion rates (Poesen et al., 1998), i.e. CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems; Knisel, 1980)–GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Knisel, 1993), EGEM (Ephemeral Gully Erosion Model; Merkel et al., 1988; Woodward, 1999) and WEPP watershed model (Water Erosion Prediction Project; Flanagan and Nearing, 1995). The channel erosion routines from both the EGEM and the WEPP watershed model are slightly modified procedures from the CREAMS channel erosion routines (Lane and Foster, 1980). In these models, concentrated flow detachment rate is proportional to the difference between (1) flow shear stress exerted on the bed material and the critical shear stress and (2) the transport capacity of the flow and the sediment load. Net detachment occurs when flow shear stress exceeds the critical shear stress of the soil or gully bed material and when sediment load is less than transport capacity. Net deposition occurs when sediment load is greater than transport capacity.

Although these models claim to have a great potential in predicting soil losses by ephemeral gully erosion, they have never been thoroughly tested for this erosion process. Recently, the suitability of EGEM for predicting ephemeral gully erosion rates in various cropland environments (Spain, Portugal and Belgium) was evaluated by Nachtergaele et al. (2001a,b). These authors found a very good relationship between predicted and measured ephemeral gully volumes. However, as ephemeral gully length is an EGEM input parameter, both predicted and measured ephemeral gully volumes have to be divided by this ephemeral gully length in order to test the predictive capability of EGEM. The resulting relationship between predicted and measured ephemeral gully cross-sections is rather weak. Therefore, Nachtergaele et al. (2001a,b) concluded that EGEM is not capable of predicting ephemeral gully erosion properly for the studied cropland environments. From their study, it becomes clear that ephemeral gully length (L) is a key parameter in determining the ephemeral gully volume, as illustrated in Table 3. Results from this table

Table 3
r^2-values for the relation between gully volume on the one hand and depth, width and length on the other for ephemeral gullies which developed in different cropland environments (based on Nachtergaele et al., 2001a,b)

Study area	Number of gullies	Depth	Width	Length
Alentejo (Portugal)	40	0.43	0.46	0.84
Guadalentin (Spain)	46	0.0002	0.52	0.79
Belgium (winter)	21	0.25	0.76	0.66
Belgium (summer)	28	0.013	0.26	0.72

indicate that if one wants to assess total eroded ephemeral gully volume, predicting gully length correctly is relatively more important than predicting width (W) or depth (D) correctly. This is attributed to the fact that the range of typical values for L is significantly larger than those of W and D, i.e. $10 < L < 1000$ m (factor 100), $0.3 < W < 6$ m (factor 20) and $0.3 < D < 3$ m (factor 10). Most models concentrate on predicting gully cross-section, while their capacity of predicting gully length is rather poor.

Besides, all (ephemeral) gully erosion models listed above lack routines to predict the location of gullies (Poesen et al., 1998). However, such information is important for land managers and for predicting the impact of environmental change on the spatial distribution and frequency of gullies. Essentially, predicting the location of (ephemeral) gullies is answering the question where do (ephemeral) gullies start and where do they end in the landscape?

6.1.1. Where do (ephemeral) gullies start?

A possible approach to predict locations in the landscape where gully heads might develop is to apply the topographic threshold concept, as explained above and illustrated in Fig. 8. For each pixel in the landscape, A and S must be calculated and using an appropriate critical S–A relation for that environment, one can then assess the risk of having a gully head developing in this pixel. Using such an approach, Prosser and Abernethy (1996) predicted the extent of a stable gully network successfully.

6.1.2. Where do (ephemeral) gullies end?

Ephemeral gullies end in a downslope direction where massive sediment deposition and fan building occurs. This is where either surface roughness increases suddenly (e.g. where a different land use begins, i.e. land use-induced sediment deposition) or where local slope gradient decreases (i.e. slope-induced sediment deposition, Beuselinck et al., 2000). Here, transport capacity of the concentrated flow will drop sharply leading to sediment deposition. As reported above (Section 4.3) very few S–A relationships for sediment deposition exist. For several European cropland conditions, Nachtergaele et al. (2001a,b) reported data sets indicating that the topographic threshold (S–A relationship) for sediment deposition at the bottom end of ephemeral gullies was smaller than the corresponding S–A relationship for incipient ephemeral gullying. The difference between the critical topographical conditions for ephemeral gully initiation and those for sedimentation are different for the studied environments and depend among others on rock fragment content of the topsoils (Vandekerckhove et al., 2000; Poesen et al., 2002). These few data sets allow one to locate the initiation point and the sediment deposition point of an ephemeral gully, based on topographic attributes (S and A) and on rock fragment content. Consequently, ephemeral gully length can be derived by routing concentrated flow from the gully head towards the fan at the gully end. For other environments, more data are needed to predict ephemeral gully length.

Desmet et al. (1999) investigated the possibility of predicting the location of ephemeral gullies using an inverse relationship between local slope gradient (S) and upslope contributing area per unit length of contour (As). Predicted locations of ephemeral gullies were confronted with the locations recorded in three intensively cultivated catchments over a 5-year observation period. The optimal relative area (As) exponent (relative to the slope exponent) ranged from 0.7 to 1.5. A striking discrepancy was found between the high relative area exponent required to predict optimally the entire trajectory of the ephemeral gullies and the low relative area exponent (0.2) required to identify the spots in the landscape where ephemeral gullies begin. This indicates that zones in the landscape where ephemeral gullies start are more controlled by slope gradient, while the presence of concavities control the trajectory of the gullies until the slope gradient is too low and sediment deposition dominates. Such an approach can be improved by incorporating the presence of linear landscape elements, soil surface state, vegetation cover and possibly rain to the input parameters. Souchère et al. (2003, this volume) present an expert-based model for predicting the location and the volumes of ephemeral gullies, whereas Kirkby et al. (2003) present power law equations describing the locations of ephemeral and permanent gully channel heads.

Over the last 15 years, several studies have developed dynamic models that predict rapid changes of gully morphology during the early stages of gully development and static models to calculate final morphometric parameters of permanent gullies in different environments (e.g. Kemp, 1987; Howard, 1997; Sidorchuk, 1999; Sidorchuk et al., 2003). Casali et al. (2003) and Torri and Borselli (2003) present process-based approaches to predict (ephemeral) gully cross-sections at various points along the gully.

A limited number of studies have focussed on predicting sediment yield from intensively gullied badland catchments, using process-based approaches which incorporate gully erosion (e.g. Bathurst et al., 1998a,b; Mathys et al., 2003). Rey (2003) pointed at the importance of vegetation cover on the gully floors, and not total vegetation cover in the catchment, when predicting sediment yield from gullied catchments.

6.2. Modelling gully headcut retreat

Once initiated, (bank) gullies essentially expand by gully headcut retreat, and to a lesser extent, by gully wall retreat. Whether a bank gully retreats by a single headcut or by multiple headcuts is controlled by factors such as topography, material type and land use, and the processes involved have been discussed above.

Oostwoud Wijdenes et al. (2000) found for a study area in Southeast Spain that land use has a significant impact on bank gully head erosion activity as indicated by features such as sharp headcut edges, presence of plunge pools, tension cracks, recent deposited sediments and flow marks. Recent land use changes involving the extension of almond cultivation appeared to intensify bank gully head activity. In addition, lithology had a clear impact on bank gully headcut activity: for the same land use type, headcuts in marls, sandy loams and loams were significantly more active compared to headcuts that developed in gravels and conglomerates. Similar observations were reported for Romania by Radoane et al. (1995). These authors reported that mean rate of gully headcutting was over 1.5 m year^{-1} for gullies developing in sandy deposits and under 1 m year^{-1} for gullies cut in marls and clays.

Several studies have attempted to quantify and predict gully headcut retreat (R) in a range of environments, including linear measurements (e.g. Thompson, 1964; Seginer, 1966; Soil Conservation Service, 1966; De Ploey, 1989; Burkard and Kostaschuk, 1995, 1997; Radoane et al., 1995; Oostwoud Wijdenes and Bryan, 2001; Vandekerckhove et al., 2001a,b, 2003, this volume), area measures (e.g. Beer and Johnson, 1963; Burkard and Kostaschuk, 1995, 1997), volumetric measures (e.g. Stocking, 1980; Sneddon et al., 1988; Vandekerckhove et al., 2001a,b, 2003, this volume) and weight measures (e.g. Piest and Spomer, 1968). According to Stocking (1980), volumetric measures are the best compromise avoiding difficult considerations of bulk density of soils no longer in situ. The resulting equations typically link R with parameters such as drainage area (A) above the gully head (an index for surface runoff volume), rainfall depth, erodibility, height of the headcut, relief energy of drainage basin and runoff response of the drainage area. Most of these equations are quite empirical and need to be established for each study area. In addition, the time span considered affects the coefficients and exponents in these equations. Vandekerckhove et al. (2003) show that when predicting R in Southeast Spain, the weight given to drainage basin area (A) increases from the short term (i.e. few years) to the long term (decades, centuries) and attribute this to several reasons. Most studies have focussed on the medium-term retreat of gullies. Little is known about the processes and factors controlling the short-term gully head erosion of gullies. Predicting long-term gully head retreat rates seems to be more simple than short-term retreat rates because of the stochastic nature of some gully wall subprocesses such as tension crack development, soil toppling and soil fall, piping and fluting (Vandekerckhove et al., 2003). Some attempts have been made to develop process-based gully headcut retreat models (e.g. Kemp, 1987; Robinson and Hanson, 1994), whereas Prasad and Römkens (2003) present a holistic and energy-based conceptual framework for modelling headcut dynamics.

Although several 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 allowing one to predict impacts of environmental change on gully erosion rates at various temporal and spatial scales, and their impacts on sediment yield, hydrological processes and landscape evolution.

7. Gully prevention and control

When should gully prevention and control measures be taken? Tolerable soil losses for water erosion are usually defined solely for sheet and rill erosion (e.g. Renard et al., 1997). What are tolerable soil losses for soil erosion by (ephemeral) gullying? Is gully erosion not tolerable at all or are small rates of gully erosion acceptable? Researchers should address this question in order to provide a scientific base for deciding under what conditions gully erosion needs to be prevented or controlled. Future definitions of tolerable soil losses at the scale of the catchment and beyond should take soil losses by (ephemeral) gully erosion into account (Nearing, personal communication).

What are efficient gully prevention and gully control measures? What can be learnt from failures and successes of gully erosion control programmes? Innovation in gully erosion control research is rather limited compared to innovation in gully erosion process research. Traditional gully control approaches in concentrated flow zones are the establishment of grassed waterways to prevent gully development (e.g. Ouvry, 1989; Baade et al., 1993) and of check dams with drop structures in gullies, dissipating flow energy so as to control their expansion (e.g. Heede and Mufich, 1974; Schouten and Rang, 1984). Grassed waterways are broad shallow channels often located within large fields, with the primary function to drain surface runoff from cropland without gullying along 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; otherwise, the tall grass would induce sediment deposition that might damage the sward, and subsequently, ephemeral gullies may develop (Fiener and Auerswald, 2002). Whereas grassed waterways are a common (ephemeral) gully erosion control practice in North America (e.g. Chow et al., 1999), this erosion control measure is rarely adopted by farmers cultivating relatively small field plots or cultivating fields in semi-arid parts of the world where it is difficult to establish and maintain a good vegetation cover.

Vegetation cover, because of its thinness, is often undervalued in terms of its control over landscape incision and evolution. Its resistance to erosion may be of the same order of magnitude as the underlying bedrock (Howard, 1997). Several studies have demonstrated the crucial role of vegetation in valley bottoms when it comes to reducing incision by concentrated flow and to triggering sediment deposition in different environments (e.g. see critical flow shear stress values [τ_c] for bare and vegetated surfaces discussed above, but also Graf, 1979; Prosser, 1996; Sidorchuk and Grigorév, 1998; Nogueras et al., 2000; Rey, 2003). Although the increased resistance to entrenchment by concentrated flow due to the presence of vegetation has been mainly attributed to the impacts of the aboveground biomass on overland flow energy dissipation through increased hydraulic resistance, few studies have also demonstrated the significant impacts of plant roots on the reinforcement of topsoils, thereby increasing cohesion (e.g. Li, 1995; Sidorchuk and Grigorév, 1998). Clearly, the impacts of various vegetation types as well as the effects of the belowground biomass on the resistance of topsoils to concentrated flow erosion remain under-researched areas.

Where possible, natural vegetation with well-developed root mats should be (re-) established in disturbed concentrated flow zones affected by gully erosion (e.g. Sidorchuk and Grigorév, 1998; Morgan and Mngomezulu, 2003). In doing so, soil loss and sediment production will be cut down and the connectivity in the landscape will be interrupted resulting in a smaller sediment delivery to valley bottoms or river channels. Very often, this approach is not feasible and solutions adapted to local agricultural practices need to be found. Several studies have come up with alternatives to grassed waterways in order to control (ephemeral) gully erosion, i.e. no tillage, topsoil compaction, double drilling and the establishment of grass and shrub hedges in concentrated flow zones.

7.1. No tillage

Fig. 12. clearly illustrates that no tillage plots (with compact and cohesive topsoils) in valley bottoms can resist the flow shear stresses exerted by concentrated flow, whereas conventional ploughing results in a loose, less cohesive and hence, more erodible material that is easily eroded by (ephemeral) gullying (Poesen, 1990).

Several studies have clearly documented the larger resistance of no-till treated topsoils to concentrated flow erosion compared to conventional ploughed topsoils (e.g. Laflen, 1985; Ouvry, 1989; Poesen and Govers, 1990; Franti et al., 1999). However, Ludwig and Boiffin (1994) found that the effects of no tillage on ephemeral gully erosion largely depended on the spatial location of the no-till treated plots within the catchment and that no-tillage was overall less effective compared to grassed waterways.

7.2. Topsoil compaction

Overall, compact (and hence, more cohesive) topsoils or soil horizons have a larger resistance to incision by concentrated flow compared to tilled ones (Fig. 12). Therefore, Ouvry (1989) compacted mechanically concentrated flow zones after seeding and found

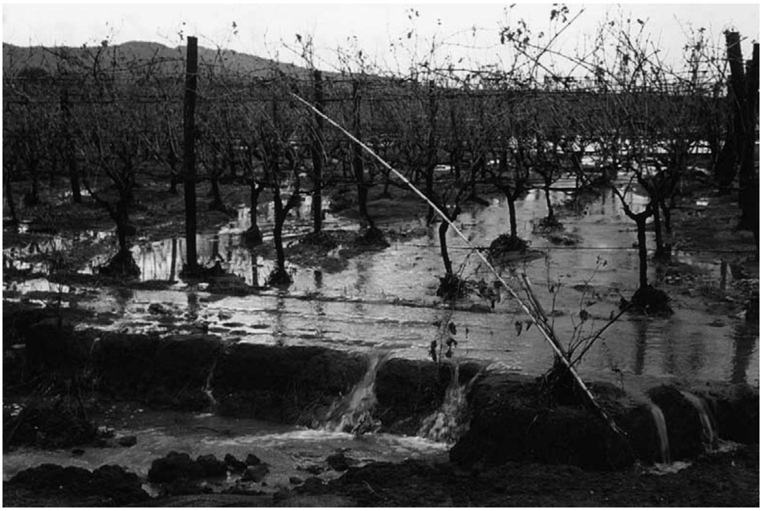

Fig. 12. Effect of no-tillage (vineyard) and of conventional tillage (foreground) on the erodibility of a volcanic ash soil in a concentrated flow zone (Montalto di Castro, Latium, Italy, November 1987). Note that the compact and cohesive topsoil in the vineyard (background) resisted almost completely detachment by concentrated runoff. On the other hand, ploughing of the topsoil (foreground) has resulted in a loose, less cohesive and hence more erodible material which has been completely washed down to the plough sole by concentrated flow. The headcut at the contact zone between the undisturbed topsoil in the vineyard and the ploughed field is ca. 30 cm high (Poesen, 1990).

that this treatment significantly reduced ephemeral gully development within drainage basin areas smaller than 50 ha. Along the same lines, Poesen (1993) concluded that knowledge of the thickness and resistance properties of compact soil sublayers is crucial (e.g. Nachtergaele and Poesen, 2002) and that any tillage operation (e.g. subsoiling) in concentrated flow zones leading to a loosening of these layers should be avoided so as to prevent deep incisions by concentrated flow.

7.3. Double drilling

More recently, Gyssels et al. (2002) observed that double drilling of wheat in concentrated flow zones reduced rill and ephemeral gully erosion rates by 50%. 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 to conventionally drilled topsoils.

7.4. Grass and shrub hedges

An alternative technique to prevent ephemeral gully development is to establish stiff grass hedges (e.g. Dabny et al., 1996; Ritchie et al., 1997). These grass hedges are narrow strips of stiff, erect, dense grass, e.g. vetiver [*Vetiveria zizanoides* (L.) Nash] and miscanthus (*Miscanthus sinensis* Andress), planted close to the contour across concentrated flow zones where they can retard and spread out surface runoff, cause deposition of eroded sediment, and hence prevent gully incision. Several studies have documented the hydraulic and erosion/sedimentation processes triggered by these stiff grass hedges as well as their effectiveness. Bi et al. (2002) report on the potential of planting seabuckthorn (*Hippophae rhamnoides* L.) in rows across concentrated flow zones, hence creating flexible dams, for controlling gully erosion in China. Along the same lines, Rey (2003) points to the crucial role of vegetation on gully beds triggering sediment deposition and therefore reducing sediment delivery from gullied catchments. However, downslope of (vegetation-induced) flow retardation zones, the concentrated runoff may cause incision because of a clear water effect as observed under various field conditions in central Belgium and in southern Germany (Auerswald, personal communication).

Where seepage (return flow) is a cause of (ephemeral) gully development, soil conservation measures that only protect the topsoil and favour infiltration will have little or no effect on concentrated flow erosion. For these areas, subsurface drainage aiming at lowering the water table could be an important erosion control measure (e.g. Uma and Onuoha, 1988; Huang and Laflen, 1996).

Despite the several case studies reported in the literature, there is still a need for more research on the effectiveness and cost-efficiency of gully prevention and control measures. Textbooks (e.g. Lal, 1992; Grissinger, 1996b) provide good principles to control gully erosion but when applying them to particular conditions, these techniques often need to be adjusted to local conditions. For instance, Poesen (1989) reported that stabilising a bank gully head in central Belgium with a rock plug did not work in loess-derived soils and an alternative technique with geomembranes had to be developed. A lot can be learned from failures when applying (established) gully erosion control techniques and these need to be documented in the literature. More quantitative data are also needed on how management practices of topsoils affect their resistance to incipient gully development. Relatively little is known about the role of various tillage practices and vegetation types on concentrated flow erosion. More particularly, we are lacking quantitative information on the impacts of the belowground biomass (roots) on reinforcement of topsoils (and their erosion resistance), which is rarely accounted for in erosion models. However, in field conditions, roots often play a crucial role in rill and gully development (e.g. Sidorchuk and Grigorév, 1998; Gyssels et al., 2002). More research is also needed on how spatial patterns of management practices affect spatial patterns of gully erosion and sediment deposition rates (e.g. Takken et al., 1999).

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