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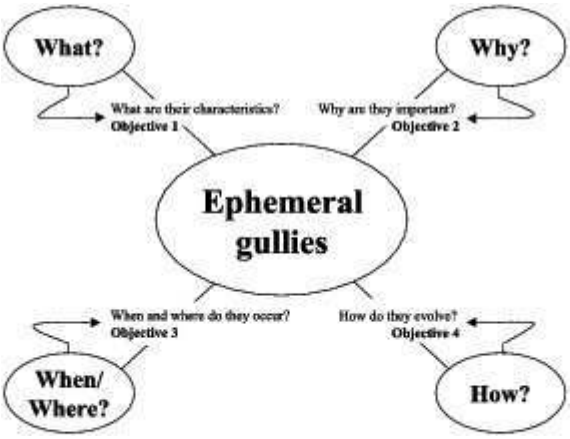
1 Water erosion can be defined as the detachment and transport of soil material at rates in excess of soil formation (Kirkby, 1980; Barrow, 1991). Besides the contributions of many individual researchers, the current soil erosion research has been largely influenced by the U.S. National Resources Conservation Service (NRCS; formerly called Soil Conservation Service SCS). The major achievement of the NRCS in predicting erosion rates, is the development and extension of the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978). The USLE is an empirical erosion model that quantifies soil erosion as the product of six factors representing rainfall and runoff erosiveness, soil erodibility, slope length, slope steepness, cover-management practices and support conservation practices. The appropriate (input) value of each of the factors of the USLE

has to be derived from an evaluation unit called the standard plot. A standard plot is 22.13 meter long, has a uniform lengthwise slope of 9%, is tilled up and down slope and has been under continuous fallow for the last two years (Mitchell and Bubenzer, 1980). Inherent to the size of the standard plot, USLE only predicts soil loss from interrill and rill erosion (Wischmeier and Smith, 1978). Therefore, when considering water erosion due to surface water in zero-order catchments, it is clear that USLE and all USLE-based studies, omit one major type of water erosion, namely (ephemeral) gully erosion. Therefore, the objective of this study is to address four basic questions related to ephemeral gully erosion (Fig. 1).

Figure 1. Schematic summary of the objectives of this study.



- WHAT are the ephemeral gully characteristics? Special attention will be paid to the spatial and temporal variability within three different study areas.
- WHY is ephemeral gully erosion an important water erosion process? Emphasis is put on extending the existing research in both space and time.
- WHEN/WHERE will ephemeral gullies occur? Existing ephemeral gully prediction tools will be tested and if required these tools will be optimized/replaced following a dual strategy: (1) empirical modelling with a focus on end-users outside the scientific world and (2) process-based modelling as required by researchers.
- HOW do ephemeral gullies evolve over time? The medium to long-term evolution of an (ephemeral) gully will be studied.

Definitions

2 Problems related to the definition of ephemeral gullies are two-fold. (1) Traditionally ephemeral gullies have been defined in the way they differ from rills and (classical) gullies. Such ‘negative’ definition is rather vague and open to discussion since it states what an ephemeral gully is not instead of expressing the essential nature of this erosion feature. (2) As it is often the case with newly defined concepts, many synonyms or nearly-synonyms have been used to describe this erosion feature. In what follows, it is attempted to define ephemeral gully erosion and its related erosion features in such a way that it is at least clear what within this study is understood by the term ephemeral gully erosion.

3 Rill erosion is defined as erosion in numerous small channels that are uniformly distributed across the slope and that can be obliterated by tillage (Hutchinson and Pritchard, 1976). According to the Soil Science Society of America rill erosion is

characterized by numerous and randomly occurring small channels of only several centimetres in depth. Rills form on sloping fields, mainly on cultivated soils. Rills can follow tillage marks, or they may develop much like a drainage network of rivers in a large basin (Foster, 1986).

4 (Classical) gully erosion is defined as erosion in channels that are too deep to cross with farm equipment (Hutchinson and Pritchard, 1976). According to the USDA Soil Conservation Service (1966), classical gullies are channels formed by concentrated flow of water removing topsoil as well as parent material. (Classical) gullies are of a size too large to be obliterated by normal tillage operations.

5 Bank gully erosion occurs where a concentrated flow zone, a rill or an ephemeral gully crosses and erodes an earth bank, e.g. a terrace, a river bank (Poesen, 1993; Poesen and Hooke, 1997). Bank gullies may develop upslope by head-cut migration.

6 Ephemeral gully erosion was first comprehensively discussed by Foster (1986). The topography of most fields causes runoff to collect and concentrate in a few major natural waterways before leaving the fields. Erosion occurring in these channels is what is known as ephemeral gully erosion (Foster, 1986). The 'ephemeral' nature of this erosion feature results from the fact that ephemeral gullies are ploughed in and tilled across annually (or more frequent), therefore restoring the original hollow, but leaving a potential zone for subsequent ephemeral gully erosion. Poesen (1993) added to the view of Foster (1986) that ephemeral gullies may also form where overland flow concentrates along (or in) linear landscape elements (e.g. drill lines, plough furrows, parcel borders, access roads). Synonyms used to describe (erosion due to) ephemeral gullies are: concentrated flow erosion (Foster, 1986; Auzet *et al.*, 1995), talweg erosion (Papy and Souchère, 1993), thalweg gullies (De Ploey, 1990), megarills (Foster, 1986), rills in valley floors (Evans and Cook, 1987), valley-bottom rills (Boardman, 1992).

7 With respect to the differences between rill, ephemeral gully and (classical) gully erosion, it is clear that ephemeral gullies and classical gullies can be discerned based on their persistence. In contrast to the permanency of classical gullies, ephemeral gullies are short-lived. Once formed, a classical gully evolves by erosion of the gully floor, head-cut migration and erosion of the gully walls, which implies a combination of processes (e.g. water erosion, mass movement) Ephemeral gullies form, are disguised and potentially form again on the same spot, so that their evolution requires mainly a repetition of the incision process, while the relative importance of head-cut migration and erosion of the gully walls is less significant. With respect to the differences between rills and ephemeral gullies Foster (1986) gives two firm arguments. (1) Flow in rills is usually classified as a part of overland flow that is assumed to occur uniformly across a slope even though it is concentrated in rills. In contrast, flow in ephemeral gullies is clearly channelized. Also, erosion due to rills will affect the entire slope, while erosion due to ephemeral gullies is much more confined. (2) Subsequent ephemeral gullies will occur in the same spot, while the position of rills is variable from time to time since it is strongly influenced by micro-topography (e.g. tillage marks). In addition to the arguments of Foster (1986), it can be remarked that rills and gullies also differ in the way they contribute to the drainage pattern of a watershed. While rills are usually limited by field borders, ephemeral gullies often extend over multiple fields. In terms of erosion this implies that rills normally only redistribute soil within one field, whereas ephemeral gullies transport soil material to completely different parts of the watershed. The difference between rills and ephemeral gullies with respect to the way they affect a watershed's hydrology, is also clearly

illustrated by Steegen *et al.* (2000). They showed that there exists a positive relation between ephemeral gully development in a given watershed and measured suspended sediment concentrations at the outlet of that watershed for comparable rainfall events. In other words, ephemeral gullies do not only act as sediment sources, but once established they also function as efficient sediment transport ways. Despite the aforementioned arguments, there still exists a small overlap between rills and ephemeral gullies. For example, when a slope shows several clear rills, that concentrate gradually downslope and finally form a clear ephemeral gully, it is not clear where the critical point between rill and ephemeral gully should be placed? It is clear that there exists a transition zone between rills and ephemeral gullies. While an overlap between the two cognate concepts does not impede the existence of each individual concept, problems may arise when assessing rills/ephemeral gullies in the field. In order to have an objective measure to distinguish rills from gullies in such dubious cases, Poesen (1993) proposed a critical cross-section of 929 cm^2 or one square foot, a criterion first used by Hauge (1977). Within this study this criterion was used to ensure that the data sets assessed in all study areas and by all persons involved are fully comparable.

Ephemeral gully characteristics

8 Spatial differences in ephemeral gully characteristics for three study areas, i.e. the Guadalentin (SE Spain), the Alentejo (SE Portugal) and the Belgian loess belt, have been discussed based on a set of topographical and morphological indices. Temporal differences, on the other hand, could only be studied for the Belgian loess belt, since for this study area only field surveys had been conducted at multiple occasions.

9 Topographical ephemeral gully indices considered were: runoff contributing area (RCA), average soil surface slope of the RCA (SRCA), soil surface slope at the gully head (SGH), soil surface slope at the gully end (SGE) and average soil surface slope along the gully profile (SGP) (Table 1). All topographical indices were found to be significantly different ($P = 0.05$) between the respective study areas. Average relief intensity for the landscape positions where ephemeral gullies occurred (SGH, SRCA and SGP), decreased from the Guadalentin over the Alentejo to the Belgian loess belt and, in accordance with the valley slope instability concept (Begin and Schumm, 1979), RCA showed the opposite trend. Observed spatial differences in topographical indices were not uniquely related to topography. Differences in SGE, for example, were attributed to a combination of parameters such as topography, rock fragment content of the topsoil and concentrated flow discharge. With respect to temporal differences in topographical indices observed for the Belgian loess belt, a distinction between ephemeral gullies that formed at the end of winter – early spring (winter gullies) and ephemeral gullies that formed during summer (summer gullies) has to made. Differences in rainfall, soil moisture content, land cover and soil surface state indicated that, compared to winter gullies, summer gullies develop on average on steeper slopes with smaller corresponding RCA. Furthermore, also SGE is steeper for summer gullies, which was attributed to the fact that summer gullies typically initiate on freshly cultivated fields, while at the time of winter gully development soils are sealed. A more aggregated soil will thus be eroded by summer gullies, which in the case of topographically-controlled sediment deposition, results in coarser sediment deposits on correspondingly steeper slopes.

Table 1. Top Topographical indices for ephemeral gullies developed in three study areas.

	Guadalentin (n = 46)		Alentejo (n = 40)		Belgian loess belt (n = 42)	
	Mean	St dev.	Mean	St. dev.	Mean	St. dev.
RCA (m²)	408	1287	2935	2606	14234	21981
SRCA (%)	26.0	9.5	14.5	3.5	5.5	2.5
SGH (%)	29.0	10.5	15.0	5.5	8.0	3.5
SGE (%)	21.0	7.0	4.0	2.5	2.5	1.5
SGP (%)	30.0	10.5	10.0	4.5	6.0	2.5

	Winter (n = 28)		Summer (n = 14)	
	Mean	St dev.	Mean	St. dev.
RCA (m²)	18531	25868	5641	3839
SRCA (%)	5.5	2.5	6.5	3.0
SGH (%)	7.5	3.5	9.0	3.0
SGE (%)	2.0	1.0	3.5	1.5
SGP (%)	5.5	3.0	7.0	1.5

Bottom Topographical indices for ephemeral gullies in the Belgian loess belt, split up according to gully formation period. RCA = runoff contributing area, SRCA = average slope of the RCA, SGH = soil surface slope at the gully head, SGE = soil surface slope at the gully end and SGP = average slope of soil surface along gully profile. Accuracy of slope measurements is 0.5%.

Morphological ephemeral gully indices considered were: ephemeral gully length (GL), ephemeral gully width (GW), ephemeral gully depth (GD), the width-depth ratio of ephemeral gullies (WDR), and ephemeral gully volume (GV). In the case of morphological indices, all, except GD, were significantly different (P = 0.05) from study area to study area (Table 2). Ephemeral gullies in the Guadalentin were on average very short and often vertically limited by the presence of bedrock at shallow depth. In the Alentejo bedrock also limited the development of deep gullies, but compared to the Guadalentin, ephemeral gullies were on average four times longer in the Alentejo. Temporal differences as observed in the Belgian study area, were particularly clear with respect to the cross-sectional shape (GW, GD and WDR; Table 2.4). Winter gullies are on average 0.49 m wide and 0.27 m deep, while summer gullies tend to be very shallow (0.09 m) and wide (2.85 m).

Table 2. Top Morphological indices for ephemeral gullies developed in three study areas.

	Guadalentin (n = 46)		Alentejo (n = 40)		Belgian loess belt (n = 58)	
	Mean	St dev.	Mean	St. dev.	Mean	St. dev.
GL (m)	22	18	86	78	191	252
GW (m)	0.62	0.28	0.89	0.34	1.63	1.38
GD (m)	0.21	0.06	0.18	0.06	0.19	0.13
WDR	3.5	3.0	5.0	1.7	22.0	29.1
GV (m^3)	3.1	4.3	18.8	26.9	31.0	30.4

	Winter (n = 32)		Summer (n = 26)	
	Mean	St dev.	Mean	St. dev.
GL (m)	246	325	124	73
GW (m)	0.49	0.15	2.85	1.02
GD (m)	0.27	0.11	0.09	0.06
WDR	1.9	0.5	43.6	29.3
GV (m^3)	32.6	34.9	29.1	24.3

Bottom Morphological indices for ephemeral gullies in the Belgian loess belt, split up according to gully formation period. GL = ephemeral gully length, GW = ephemeral gully width, GD = ephemeral gully depth, WDR = width-depth ratio of ephemeral gully and GV = ephemeral gully volume.

11 In general, the characterization of ephemeral gullies, both in terms of their topographical position and their morphology (1) stressed the significant (P = 0.05) spatial variability in topographical position and morphology of the ephemeral gullies in the considered study areas and (2) revealed, for the Belgian study area, the topographical and morphological differences between ephemeral gullies that formed at the end of winter – early spring and ephemeral gullies that formed during summer. Therefore, a differentiation between summer and winter gullies in the Belgian loess belt throughout this study, is justified.

Importance of ephemeral gully erosion

12 Most existing studies on the (relative) importance of ephemeral gully erosion are based on field surveys. Due to the fact that (1) field surveys are time-consuming and (2) ephemeral gullies are temporal phenomena, this type of study is limited in time and space. In order to overcome these limitations, the potential of high-altitude (stereo) aerial photographs for the assessment of ephemeral gully erosion rates has been investigated.

13 On May 28, 1995 an intensive rainfall event (30 mm h-1 during 30 min, return period = 3 years) occurred in central Belgium. Ephemeral gullies that formed within an area of 218 ha (study area 1) were mapped and measured both in the field and from high-altitude aerial photos. Comparison of the results obtained by each of both surveying techniques showed that each method individually detected only 70-75% of the total ephemeral gully length. In other words, both during a field survey and during an aerial photo analysis, 25-30% of the total ephemeral gully length was not observed. Ephemeral gullies that were not detected during the aerial photo analysis, were either too small to be observed from an aerial photo, or located in linear landscape features, for which it is nearly impossible

to distinguish gullied from ungullied sites based on aerial photos. By assuming that the ephemeral gullies that are invisible on aerial photographs, constitute a fixed fraction of total ephemeral gully length, a correction factor (Caerial photo = 1.44) was proposed. This correction factor allows the results of an ephemeral gully erosion survey based on high-altitude (stereo) aerial photos to be adjusted for the undetected gullies.

14 In a next step, a sequential series of six high-altitude stereo aerial photographs (HASAP) taken between 1947 and 1996, were analysed in order to determine ephemeral gully erosion rates in three selected Belgian study areas (study area 2, 3 and 4). Selection criteria were chosen so that these three areas were similar to study area 1 and representative for the cultivated areas in central Belgium where intense soil erosion by water occurs. Total length of the ephemeral gullies was measured from the aerial photos and using a mean gully cross-section of 0.26 m^2 (determined in study area 1) ephemeral gully volumes could be calculated. Average eroded volumes were: 1.89 m^3 ha-1 (6 months)-1 for study area 1; 0.86 m^3 ha-1 (6 months)-1 for study area 2; 1.44 m^3 ha-1 (6 months)-1 for study area 3 and 2.37 m^3 ha-1 (6 months)-1 for study area 4 (Table 3). To take into account the ephemeral gullies that are invisible on the HASAP, mean ephemeral gully volumes have to be increased by 44%, according to the correction factor (Caerial photo) that was established for study area 1. From the sequential series of HASAP no significant change (increase) in ephemeral gully erosion rate could be observed over the last 50 years. Yet, on the spatial level, clear differences in ephemeral gully erosion rates were observed for the three study areas. This spatial variability could be explained by differences in soil type and topography between the study areas.

Table 3. Ephemeral gully erosion data for study area 2, 3 and 4, extracted from high-altitude stereo aerial photographs.

Year	Number of gullies	Total gully length (m)	Gully density (m ha^{-1})	Estimate of ephemeral gully erosion volum (m^3 ha^{-1} in 6 months) Mean	Lower	Upper	Corrected
Study area 2 (861 ha)							
1952	17	3100	3.6	0.95	0.63	1.26	1.37
1959	28	3200	3.7	0.98	0.65	1.30	1.41
1973	16	1800	2.1	0.55	0.37	0.73	0.79
1985	38	3400	3.9	1.04	0.70	1.39	1.50
1988	25	2000	2.3	0.61	0.41	0.82	0.88
1996	31	3400	3.9	1.04	0.70	1.39	1.50
mean	26	2800	3.3	0.86	0.57	1.14	1.24
Study area 3 (1095 ha)							
1947	47	5600	5.1	1.35	0.90	1.79	1.94
1952	17	2800	2.6	0.67	0.45	0.90	0.97
1969	33	4700	4.3	1.13	0.76	1.51	1.63
1980	32	6300	5.8	1.52	1.01	2.02	2.18
1985	68	9800	8.9	2.36	1.58	3.14	3.40
1990	31	6700	6.1	1.61	1.08	2.15	2.32
mean	38	6000	5.5	1.44	0.96	1.92	2.07
Study area 4 (889 ha)							
1947	66	11800	13.3	3.50	2.34	4.66	5.04
1957	34	6600	7.4	1.96	1.31	2.61	2.82
1975	41	6100	6.9	1.81	1.21	2.41	2.60
1983	21	7200	8.1	2.13	1.43	2.84	3.07
1989	17	5700	6.4	1.69	1.13	2.25	2.43
1996	43	10500	11.8	3.11	2.08	4.14	4.48
mean	37	8000	9.0	2.37	1.58	3.16	3.41

The mean gully cross section used for calculating gully volumes is 0.26 m^2. For the lower and the upper estimate of gully volumes a gully cross section of 0.18 m^2 and 0.35 m^2 is used respectively (i.e. the mean cross-section – or + the standard deviation). Corrected values are mean values multiplied by the correction factor Caerial photo = 1.44.

15 In general, this study showed that ephemeral gully erosion surveys based on aerial photo data have a great potential. This statement is supported by the fact that, overall, ephemeral gully erosion volumes assessed from HASAP corresponded very well with reported volumes that were obtained through field surveys. Moreover, HASAP enables us to extrapolate ephemeral gully erosion surveys in space and/or time.

Ephemeral gully erosion prediction

16 Three erosion models explicitly incorporate routines to account for ephemeral gully erosion, i.e. CREAMS, WEPP and EGEM. All three based their ephemeral gully erosion routine on the same theoretical framework developed by Foster and Lane (1980, 1983). This theory has been considered a significant step forward with respect to physically-based modelling of ephemeral gully erosion (Watson *et al.*, 1986). Nevertheless, the model is based on several assumptions and at the same time it requires a significant number of input data (Watson *et al.*, 1986). Since the Foster and Lane (1980, 1983) model has never been tested in the field, the first step in evaluating the existing ephemeral gully prediction technology consisted of a field validation. Within this study EGEM was chosen to perform this field validation, because of the fact within CREAMS and WEPP the ephemeral gully erosion routine forms only a secondary part of an integrated erosion model, while EGEM is entirely focused on predicting ephemeral gully erosion.

17 EGEM was tested for three different environments. In a first phase two Mediterranean study areas were selected. Detailed measurements of 46 ephemeral gullies were made in intensively cultivated land in the Guadalentin (SE Spain) and another 40 ephemeral gullies were measured in both intensively cultivated land and in recently abandoned land in the Alentejo (SE Portugal). When predicted and measured ephemeral cross-sections are plotted against each other, the resulting relationship is rather weak (R2 = 0.27) and therefore it was concluded that EGEM, and the underlying theory of Foster and Lane (1980, 1983), is not capable of predicting ephemeral gully erosion for the given Mediterranean areas. The third study area is located in the Belgian loess belt. Here, a data set containing 58 ephemeral gullies has been collected from March 1997 to March 1999. Of the observed ephemeral gullies, 32 developed at the end of winter or early spring (winter gullies) and 26 ephemeral gullies developed during summer (summer gullies). Also for the Belgian loess belt, analysis showed that EGEM is not capable of predicting ephemeral gully cross-sections well.

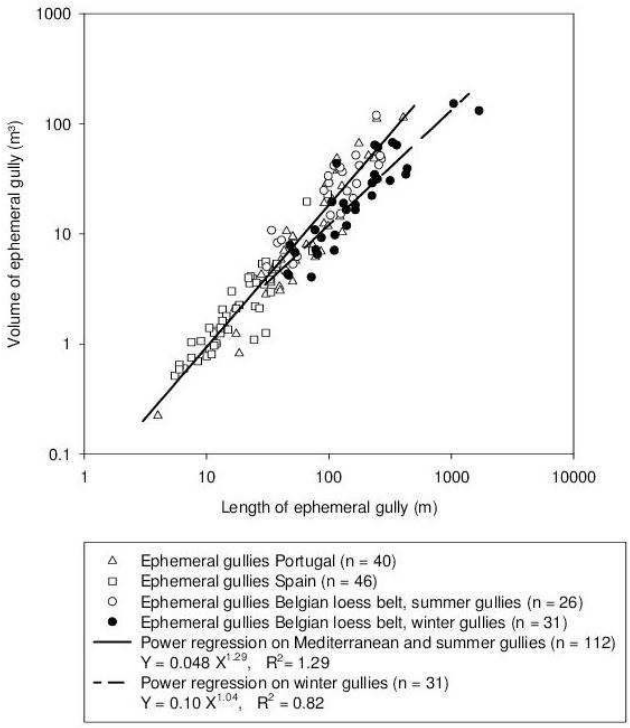
18 While for all three study areas the conditions for input parameter assessment were ideal, parameters such as channel erodibility, critical flow shear stress and local rainfall depth, showed great uncertainty. Rather than revealing EGEM's inability of predicting ephemeral gully erosion, the analyses stressed the problematic nature of physically-based models in that they often require a large number of input parameters that are not available or can hardly be obtained. In order to improve this situation, a dual strategy was followed within this study. A first option is that of developing empirical relations that can replace the complex physically-based procedures. A second option, which consists of improving the existing physically-based erosion models, needs to be further explored.

Towards simple ephemeral gully erosion models

19 Within this study a simple and straightforward alternative for the prediction of ephemeral gully volumes is proposed. From the knowledge of ephemeral gully length (GL) alone, over 90% of the observed variation in ephemeral gully volume (GV) can be explained for ephemeral gullies in the Mediterranean study areas as well as for summer gullies in the Belgian loess belt (Fig. 2). Winter gullies in the Belgian loess belt had on average smaller cross-sections, which was attributed to lower rainfall intensities at that time of the year. Consequently a different GV-GL relation was established for winter gullies (Fig. 2). The principal consequence of these GV-GL relations, is the fact that predicting ephemeral gully erosion volumes requires an accurate prediction of GL, rather than a (process-oriented) model to predict average ephemeral gully channel cross-section. Procedures to predict ephemeral gully length based on simple topographical thresholds for ephemeral gully initiation and ending have been reported in literature. Vandaele *et al.* (1996) and Vandekerckhove *et al.* (1998) discussed how points of incipient ephemeral gully erosion can be represented by a critical S-A relationship. For the Mediterranean study areas, the same S-A-logic as used to predict the gully initiation point can be used to predict points where ephemeral gullies end by topographical controlled sediment deposition. Yet, for the Belgian loess belt a simple slope threshold (S = 0.04 m m-1), irrespective of the corresponding drainage area (A), proved to be more appropriate for the prediction of sediment deposition points (Poesen *et al.*, 1998; Beuselinck *et al.*, 2000; Nachtergaele *et al.*, 2001). Given the ephemeral gully initiation point and the

sediment deposition point, GL can be derived by routing the water from the first point to the latter (Desmet and Govers, 1996; Desmet *et al.*, 1999; Takken *et al.*, 2001).

Figure 2. Potential performance of an empirical regression model relating ephemeral gully length and ephemeral gully volume for two Mediterranean areas and summer gullies from the Belgian loess belt. Winter gullies from the Belgian loess belt require a different regression equation.



While topographical thresholds for ephemeral gully erosion can be used to predict the potential location of ephemeral gullies, the actual development of an ephemeral gully on these locations, depends on many other factors than topography. Rainfall, for example, is a prerequisite with respect to the initiation of ephemeral gullies. Temporal variations in rainfall depth and/or intensity are one reason why ephemeral gullies do not occur in the same place every year. Within this study attempts were made to establish a rainfall threshold for ephemeral gully erosion on loess-derived soils in the Belgian loess belt. While it is recognized that rainfall intensity can play an important role in the development of ephemeral gullies, only daily rainfall depth has been considered for the definition of a rainfall threshold, since for most areas this is the best available rainfall information. Yet, through the establishment of a different threshold for summer (high-intensity rainfall of short duration) and winter (low-intensity rainfall of long duration), rainfall intensity was indirectly incorporated. In total 38 erosion events were documented (21 in winter and 17 in summer). For each event the causative rainfall depth, i.e. daily rainfall depth that caused ephemeral gully erosion, and the intensity of ephemeral gully erosion (subdivided in three classes) was determined. In the case of summer gullies, erosion intensity was positively correlated with causative rainfall depth. For winter gullies no such correlation could be observed, which implies that other factors (e.g. vegetation cover, soil surface state, antecedent rainfall) determine the intensity of ephemeral gully erosion at this time of the year. With respect to the establishment of a daily rainfall threshold for ephemeral gully initiation, the smallest causative rainfall depth for each of three ephemeral gully intensity categories were averaged. For summer gullies, this resulted in a daily rainfall threshold value of 18 mm was found, while for winter gullies 15 mm appeared to be a threshold value, but only after cumulative rainfall depth exceeded 150 mm. Since a daily rainfall depth of 15-18 mm has a return period << 1year, it had to be concluded that daily rainfall is no absolute criterion for the initiation of ephemeral gullies. A daily rainfall threshold is especially useful in excluding daily rainfall depths, smaller than the threshold value, from potential triggers of ephemeral gully erosion.

Towards process-based ephemeral gully erosion models

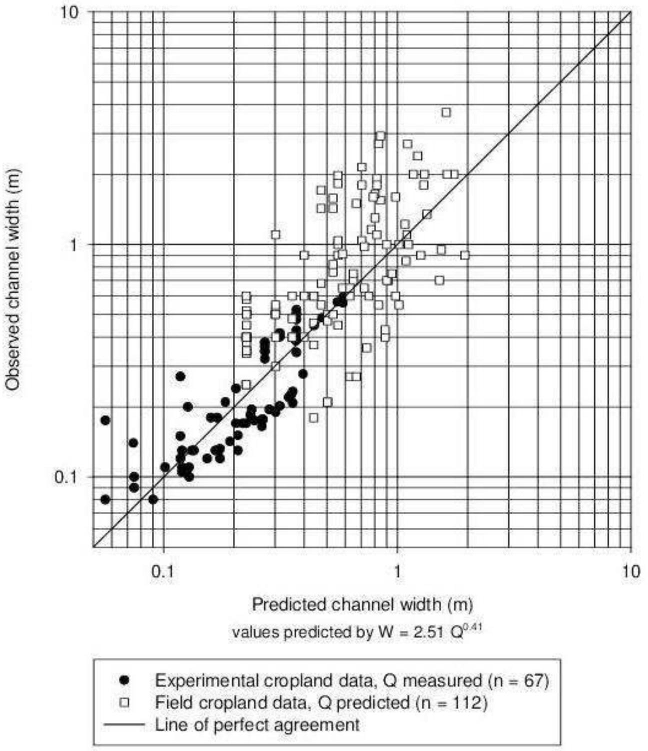
21 The development of a (good) physically-based ephemeral gully erosion model certainly is a step-by-step process. Within this study two steps are taken: (1) linking the hydrology component to the erosion component through the establishment of a flow width – flow discharge relation and (2) establishing a dynamic approach of the soil erodibility concept within ephemeral gully erosion models, as an alternative to constant soil erodibility parameters that are related to steady soil characteristics.

22 A crucial problem related to the development of an ephemeral gully erosion model is linking the hydrology routine with the erosion routine. Hydrology routines can provide the user of the erosion model with (peak) flow discharges (Q(p)), but erosion routines need a flow intensity parameter (e.g. flow shear stress or stream power) to determine flow detachment rate and flow transport capacity. In order to calculate flow intensity for concentrated flow channels, the channel geometry, and especially the channel width, has to be known.

23 Channel width prediction equations of the form W = a Qb have been reported for rills and rivers (e.g. Gilley *et al.*, 1990; Govers, 1992; Ming, 1983), but not for ephemeral gullies that developed in cultivated fields. Therefore, six experimental data sets were used to establish a channel width (W, m) – flow discharge (Q, m^3 s-1) relation for ephemeral gullies formed on cropland. The resulting regression equation (W = 2.51 Q0.412; R^2 = 0.72; n = 67) predicts observed channel width reasonably well. Due to logistic limitations related to the respective experimental set-ups, only relatively small runoff discharges (Q < 0.02 m^3 s-1) were covered. Using field data, where measured ephemeral gully channel width was attributed to a calculated peak runoff discharge on sealed cropland, the application field of the regression equation could be extended towards larger discharges (5 10-4 m^3 s-1< Q < 0.1 m^3 s-1; Fig. 3). Therefore, this equation is recommended for predicting concentrated flow width in ephemeral gully channels, when modelling ephemeral gully erosion. Yet, the proposed W-Q equation for ephemeral gullies is only valid for (sealed) cropland with no significant change in erosion resistance with soil depth. Two examples illustrate the limitations of the W-Q approach. In a first example a frozen subsoil hinders vertical erosion from a given depth on. The second example relates to a typical summer situation where the soil moisture profile of an agricultural field makes the top 0.02 m five times more erodible than the underlying soil material (Govers *et al.*, 1990). For both cases, observed W values are larger than those predicted by the established channel width equation for concentrated flow on cropland. For the frozen

soils the equation W = 3.17 Q0.368 ($R^2 = 0.78$; n = 617) was established using data collected by Sidorchuk (1999), while for the summer soils no equation could be established.

Figure 3. Predicited channel width versus observed channel width.

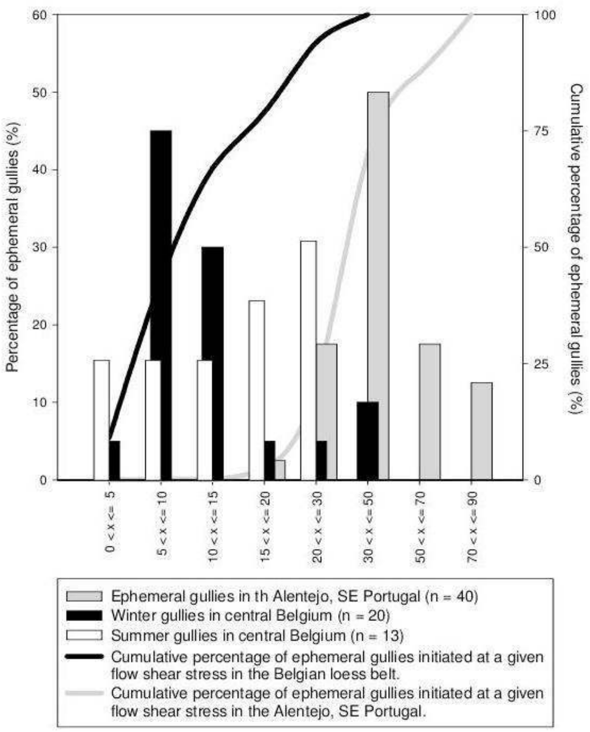


Experimental cropland data are derived from laboratory experiments (with measured Q-values) and were used to establish the predicition equation. Field cropland data were derived from field observations (with estimated Q-values) and were used to extend the applications field of the established prediction equation.

24 Using a W-Q relation, flow intensity (e.g. shear stress) can be calculated at any point in the landscape. The consequent problem is to define at which critical flow shear stress (tc) ephemeral gullies will form. Within this study, flow shear stress at the ephemeral gully head was calculated for 40 ephemeral gullies formed in SE Portugal (Alentejo) and for 33 ephemeral gullies formed in central Belgium (Belgian loess belt) (Fig. 4). The calculated shear stress values were considered to be a good estimator of tc for ephemeral gully initiation in the respective study areas. Generally, it was clear that average tc for ephemeral gully initiation in the Belgian loess belt (14 Pa) differed significantly ($P < 0.01$) from average tc for the Alentejo (44 Pa). In agreement with Poesen *et al.* (1999), who found a negative exponential relation between rock fragment cover and sediment concentration in concentrated flow, this difference in tc between the Alentejo and the Belgian loess belt was mainly attributed to the presence of rock fragments in the topsoil of the Alentejo study area. For winter and summer gullies no significant difference in average tc-values was found. Yet, from Fig. 4 it is clear that tc-values for winter and summer gullies are not equally distributed over the considered shear stress classes. While 75% of the winter gullies initiated at a tc-value between 5 and 15 Pa, summer gullies initiated at tc-values between 3 and 30 Pa. This may be explained as if summer gullies can initiate at low shear stress values (3-4 Pa), but due to high(er) rainfall intensities in summer, large discharges and consequently large shear stress values do occur as well. From a theoretical point of

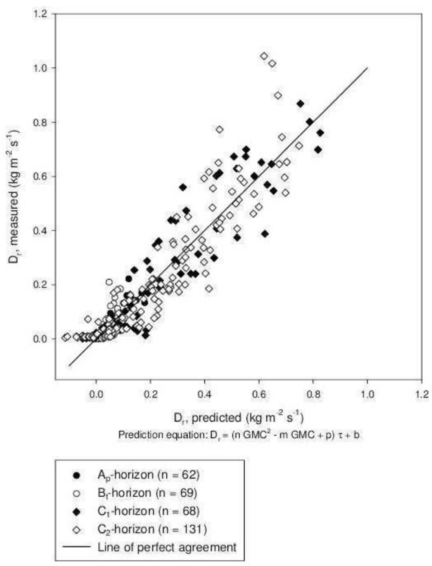
view this logic could be countered by stating that in the case of large discharges/shear stresses the ephemeral gully initiation point should migrate upslope till the point where the combination of drainage area, concentrated flow discharge, flow width and local slope yield a shear stress value equal to tc. In actual field situations, however, shear stress does not change gradually along the slope profile: (i) For a given topography, a minimum area is required to enable surface runoff to concentrate, and in the case of high-intensity summer rains in the Belgian loess belt, this minimum area may yield shear stresses (largely) exceeding tc. (ii) Concentration of surface runoff is controlled by topography and oriented as well as higher order roughness (Takken, 2000). Flow concentration due to macro-scale roughness (e.g. tillage marks, roads, field borders) occurs stepwise, so that two concentrated flows having t-values lower than tc, may concentrate and result in a flow with shear stress (largely) exceeding tc.

Figure 4. Distribution of peak flow shear stresses at ephemeral gully heads (i.e. channel cross-section > 930 cm²) observed in the Belgian loesbelt (n = 33) and in the Alentejo, SE Portugal (n = 40).



The second step to improve current physically-based ephemeral gully erosion models, consisted of the establishment of a tool to describe spatial and temporal variations in soil erodibility. In order to do so, a series of concentrated flow detachment experiments have been conducted. Four different soil horizons, typical for loess-derived soils in Belgium, have been sampled seven times during one year. In doing so, a representative range of initial soil moisture contents was obtained for each of the studied horizons. Undisturbed soil samples were subjected to five different combinations of slope gradient and concentrated flow discharge. Results showed that for a given soil horizon, variations in soil detachment rate could be very well related to temporal variations in initial soil moisture content: $Dr = [n\ GMC^2 - m\ GMC + p]\ t + b$, where Dr = soil detachment rate, GMC = initial gravimetric soil moisture content and n, m, p and b are constants for a given soil horizon (Fig.5). For a given initial soil moisture content the ploughed topsoil horizon (Ap) and the underlying clay enriched horizon (Bt), were at least five times less erodible than the decalcified loess horizon (C1) or the calcareous loess horizon (C2) (Fig. 6). Combining knowledge on the spatial distribution of soil profiles and the temporal distribution of initial soil moisture content enables to define both temporal and spatial variations in soil detachment rates. Ephemeral gully erosion modelling should incorporate these variations in soil detachment rates, with the level of incorporation depending on the type of erosion model that is applied. When an empirical erosion model is used, a (relative) ranking in detachability between two time periods (winter and summer) and two groups of soil horizons (Ap-Bt and C1-C2) may be sufficient (Fig. 6). Yet, to fully incorporate the results obtained in this study, a multi-layered physically-based erosion model is needed to describe soil profiles and the related distribution of soil moisture content within the study area. Results presented in Fig. 5 will then allow to predict spatial and temporal variations in soil detachability throughout the study area. Finally it is stressed that with respect to soil profile evolution and consequent erosion risks, it is important to integrate the effect of both water and tillage erosion.

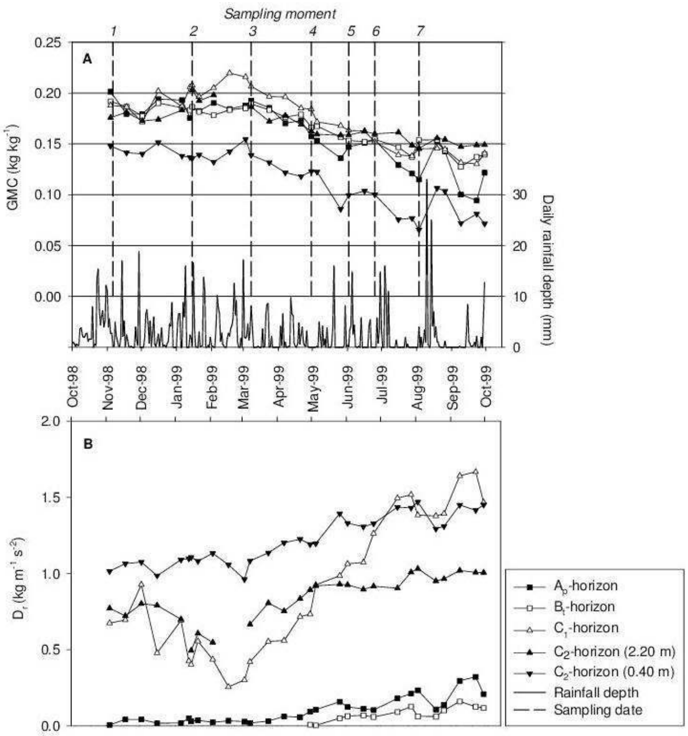
Figure 5. Predicted versus measured detachment rates (Dr) for four different soil horizons.



Soil horizon	Regression coefficients				R^2	GMC (kg kg^{-1})	
	n	m	p	b		β	ω
A_p	1.496	0.737	0.09	-0.016	0.83	0.067	0.211
B_t	-1.422	-0.025	0.036	~0	0.47	0.112	0.191
C_1	4.495	3.154	0.515	-0.135	0.86	0.121	0.221
C_2	-2.857	-0.056	0.18	-0.243	0.83	0.027	0.21

REGRESSION COEFFICIENTS (N, M, B AND P) WERE DERIVED THROUGH A NON-LINEAR REGRESSION ANALYSIS. B AND W ARE RESPECTIVELY THE LOWER AND UPPER LIMIT OF THE INITIAL GRAVIMETRIC SOIL MOISTURE CONTENT (GMC).

Figure 6. (A) Evolution of soil moisture content (GMC) of four soil horizons typical for the Belgian loess belt during one year (Nov-98 – Oct-99).
(B) Evolution of detachment rate (Dr) of four soil horizons typical for the Belgian loess belt during one year (Nov-98 – Oct-99)



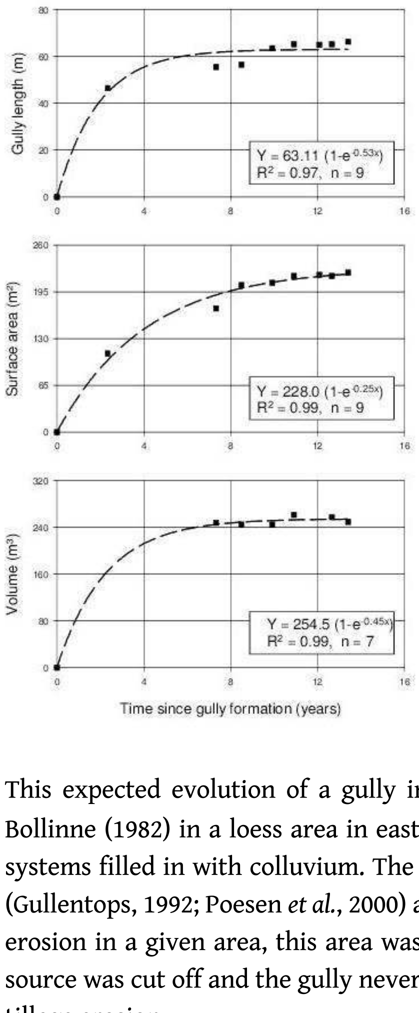
Every symbol represents a soil moisture measurement (n = 2). The line for the C2-horizon (2.20 m) is interrupted twice, since at two moments in time ground water level did not allow soil moisture measurements.The C2-horizon was sampled at two different depths.
A solid line represents daily rainfall depths. The dotted vertical lines indicate 7 moments when undisturbed soil samples were taken for flume experiments.
Dr-values were calculated using the equation and regression coefficients presented in Fig. 5. Shear stress value used to calculate Dr is 10 Pa.

The medium to long term evolution of an (ephemeral) gully

26 Field surveys in the Belgian loess belt revealed that in many forested areas large, permanent gully systems, most of which are currently inactive, can be found (Gullentops, 1992; Poesen *et al.*, 2000). In cultivated areas virtually all large gully systems are currently filled in with colluvium and therefore only observed in cross-sectional soil profiles (Bollinne, 1982). Little is known about the spatial distribution, initiation and evolution of these large, permanent gully systems on loess-derived soils. Here, we studied during 13 years the evolution of a gully that was initiated on a cultivated, loess-derived soil south-west of Leuven (Belgium) in May-June 1986. The rainfall event that created this (ephemeral) gully has a return period between less then 1 year and 25 years, depending on the assumptions made for defining rain intensity. The estimated return period indicates that the initiation of large (permanent) gullies, as observed in forested areas and through cross-sectional profiles in cultivated fields in the Belgian loess belt, does not require an extreme rainfall event.

27 Between June 1986 and December 1999, eight field surveys were conducted to measure gully dimensions. During two surveys, topographic indices (e.g. slope, drainage area) were measured as well. It appeared that length, surface area and volume of the studied gully increase with time following a negative exponential relation (Fig. 7). This is in perfect agreement with observations reported for gullies in other environments (Australia and USA). Whereas Graf (1977) only refers to a decrease in drainage area with increasing channel length to explain a degressive increase of gully extension, this study shows that the product of drainage area with slope (S*A) is a better measure to describe the changes in gully dimensions over time. Yet, gully length and gully surface area are asymptotically evolving towards a final value, but gully volume is expected to decrease from a given moment in time (Fig. 7). Sediment deposition, induced by a progressive development of vegetation (first annuals, then bushes and small trees) will fill in the gully to such an extent that the farmer can drive across it. From this moment on the combined effect of tillage erosion and water erosion in the gully's drainage area, will lead towards a rapid infilling of the gully.

Figure 7. The evolution of gully length, gully surface area and gully volume, as a function of time (years) since gully initiation.

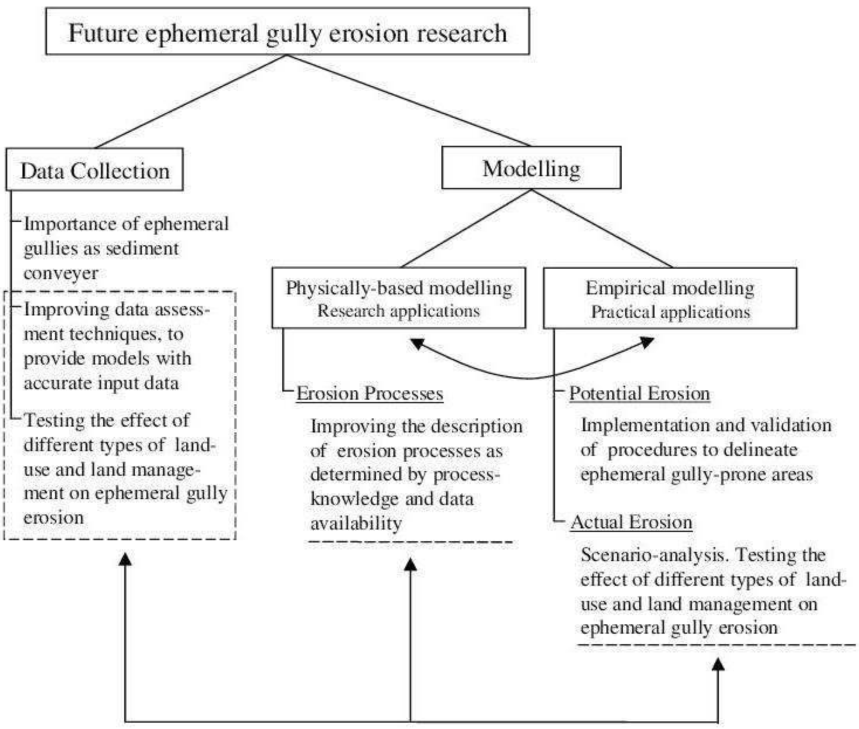


28 This expected evolution of a gully in cultivated fields fits in with the observations of Bollinne (1982) in a loess area in eastern Belgium, who found many traces of large gully systems filled in with colluvium. The permanent gullies that were observed under forest (Gullentops, 1992; Poesen *et al.*, 2000) are then attributed to the fact that after severe gully erosion in a given area, this area was reforested or abandoned. Therefore, the sediment source was cut off and the gully never filled in by sediment deposition caused by water or tillage erosion.

Recommendations for future ephemeral gully erosion research

29 Major fields of future ephemeral gully research are depicted in Fig. 8. With respect to data collection, an important topic concerns the role that ephemeral gullies (might) play in conveying runoff water and eroded soil material towards the catchment outlet into permanent drainage ways. Steegen *et al.* (2000) showed that there exists a positive relation between ephemeral gully development in a given watershed and measured suspended sediment concentrations at the outlet of that watershed. A comprehensive quantification of this relation between ephemeral gullies and the sediment delivery ratio at the catchment scale, could put an extra dimension to the ephemeral gully erosion research. Being responsible for about 50% of the total sediment production within agricultural drainage basins in central Belgium, ephemeral gullies have certainly a significant on-site effect. But when the presence of ephemeral gullies results in a higher sediment delivery ratio, this means that also > 50% of the off-site effects of soil erosion at the catchment-scale are caused by ephemeral gullies. In other words, if ephemeral gullies, occupying << 1% of the total agricultural land, can be effectively prevented, the erosion problems, both on- and off-site, will be reduced with c. 50%.

Figure 8. Schematic summary of possible future ephemeral gully erosion research (see: Recommendations for future ephemeral gully erosion research).



30 Major challenges with respect to ephemeral gully erosion modelling have to be divided between empirical and physically-based modelling (Fig. 8). The implementation of a physically-based ephemeral gully erosion model is beyond current possibilities. Restraints are both related to process description and data availability. Meanwhile, there

exists a true a need amongst people in the field (e.g. land managers, land conservationists) to model the potential location of ephemeral gullies, the on-site and off-site impact of ephemeral gullies and potential ways to prevent this erosion process. This discrepancy between possibilities and needs forms the starting-point of future research on ephemeral gully erosion modelling.

31 Empirical modelling should focus on end-users dealing with land management and land conservation. For this group of stakeholders, the main interest lies in (1) the prediction of zones in the landscape with high erosion risk and (2) the estimation of actual erosion and/or the evaluation of scenarios to prevent erosion in these high-erosion-risk zones (scenario-analysis). Concerning the first issue, this study proposes an approach to delineate ephemeral gully-prone areas (Potential erosion; Fig. 8). The major restriction to an actual implementation of this procedure is the availability of accurate digital elevation models (DEM) covering large areas. Yet, a fast adoption of revolutionary altimetric observation techniques (e.g. laser scanning) is taking place. For Flanders, plans are being made to establish, based on this laser scanning technique, a DEM with a 1 x 1 m resolution and an accuracy of < 0.10 m (Van Rompaey, pers. comm.). Similar plans exist or have already been carried out for other European countries (e.g. the Netherlands, United Kingdom). The second issue forms the logical follow-up on the first one. Once the ephemeral gully-prone areas are identified, the land manager or land conservationist needs adequate measures to prevent ephemeral gully erosion from actually taking place. Existing measures, such as grassed waterways or set-aside, are quite drastic and experience learned that farmers are not very keen on implementing them without further incentives. Therefore, the effect of a wider range of land use and land management practices on ephemeral gully erosion is a really important research topic (Actual erosion; Fig. 8), that has to be addressed through both field work and model simulations. With respect to this, it is noteworthy that the Flemish government (AMINAL – afdeling Water) has set up a project in collaboration with the universities of Leuven (K.U. Leuven) and Gent (U. Gent), that aims at reducing sediment export to water courses, using (agricultural) practices that reconcile the interests and desires of land managers/ conservationists with those of the farmers.

32 Physically-based erosion modelling should focus on research oriented end-users. This type of modelling aims at improving our understanding of current and historical erosion processes as well as to identify important gaps in our present knowledge. The major challenge for physically-based erosion modelling is to reconcile process-knowledge and data availability (Fig. 8). A (physically-based) model requiring input data that cannot be assessed with sufficient accuracy, is bound to remain a desktop exercise. Progress related to physically-based erosion modelling, therefore, depends on improvements on process-knowledge on the one hand and data availability and data assessment techniques on the other. W-Q relations, for example, are an improvement of existing physically-based erosion models that require channel width as an input parameter. Yet, with respect to the current process knowledge, the prediction of W from Q alone is certainly a simplification. Future improvements of channel width prediction, therefore, will especially depend on the availability of accurate input data for other controlling parameters (e.g. surface slope, soil roughness, critical flow shear stress). The study on the erodibility of different soil horizons stresses the need for a multi-layered modelling approach and can therefore be seen as an extension of the existing modelling knowledge. Future research with respect to soil erodibility should focus on other soil types. Also the spatial distribution of different

soils and soil horizons has to be investigated, since this kind of information is required to actually implement the obtained knowledge on soil erodibility in a physically-based erosion model. Finally, both the W-Q relations and the study on soil erodibility, reflect the situation for freshly cultivated soils with no or very little vegetation. An important challenge for future research, therefore, lies in incorporating the effect of different types of land use and vegetation cover on the erodibility and resulting channel width for a given soil.

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APPENDIXES

Results presented in this paper are a summary of the PhD thesis by J. Nachtergaele. This paper aims at providing an overview of the ephemeral gully erosion research that has been conducted at the Laboratory for Experimental Geomorphology during the last six years. Additional and more detailed information on the respective topics discussed here, can be found in:

NACHTERGAELE J. & POESEN J. (1999), «Assessment of soil losses by ephemeral gully erosion using high-altitude (stereo) aerial photographs», *Earth Surface Processes and Landforms, 24,* pp. 693-706.

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ABSTRACTS

Ephemeral gully erosion is a significant water erosion process, accounting for c. 50% of the total sediment production in agricultural catchments in the Belgian loess belt. Yet, during the last decades most soil erosion research has mainly focused on standard runoff plots. As a consequence, interrill and rill erosion were intensively studied, while little attention was paid to soil erosion processes operating at larger spatial units such as for instance ephemeral gullying. This study, therefore, aimed at:
1) describing spatial and temporal variations in ephemeral gully characteristics, in three contrasting environments;
2) extending the existing studies on the importance of ephemeral gully erosion in space and time by using high-altitude stereo aerial photos (HASAP) to assess ephemeral gully volumes;
3) improving ephemeral gully prediction, through the development of both empirical relationships to directly predict ephemeral gully volumes and process-oriented relationships to be built in physically-based erosion models;
4) evaluating the medium to long-term evolution of an (ephemeral) gully.

Erosie als gevolg van tijdelijke ravijnen is verantwoordelijk voor circa 50% van de totale sedimentproductie door afstromend water in landbouwgebieden van de Belgische leemstreek. Doordat het erosieonderzoek traditioneel sterk gericht is op gestandaardiseerde proefpercelen, werden processen als intergeulen geulerosie intensief bestudeerd. Watererosieprocessen die op een grotere ruimtelijke schaal optreden, zoals bvb. tijdelijke ravijnen, kregen tot nog toe slechts weinig aandacht. Daarom beoogt deze studie:
1) de ruimtelijke en temporele variaties in karakteristieken van tijdelijke ravijnen te beschrijven voor drie contrasterende gebieden;
2) bestaande studies inzake het belang van tijdelijke ravijnen uit te breiden in ruimte en tijd door gebruik te maken van standaard luchtfoto's;
3) de methoden voor het voorspellen van bodemerosie als gevolg van tijdelijke ravijnen te verbeteren via enerzijds het opstellen van empirische relaties om ravijnvolumes te voorspellen en anderzijds het ontwikkelen van procesvergelijkingen die kunnen worden ingebouwd in fysisch-gebaseerde erosiemodellen;
4) de evolutie van (tijdelijke) ravijnen op middellange tot lange termijn te onderzoeken.

INDEX

Trefwoorden tijdelijke ravijnerosie, Belgische leemstreek, Mediterrane gebieden, standaard luchtfoto's, empirische modellen, fysisch-gebaseerde modellen, middellange- tot langetermijnevolutie
Keywords: ephemeral gully erosion, Belgian loess belt, Mediterranean areas, high-altitude stereo aerial photos, empirical models, physically-based models, medium to long-term evolution

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