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Rill Erosion as a Function of the Characteristics of Cultivated Catchments in the North of France

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Summary

This study analyses variations in rill erosion as a function of the morphological, pedological and land use characteristics of cultivated catchments. 20 elementary catchments in Northern France, from 3.7 to 100 ha, were studied during the winter of 1988/89. The between-catchment differences in total and talweg rill volumes (m^3) and rates (m^3/ha) were very large, and could not be explained by the variations in rainfall. The size of runoff contributing area, defined by combining soil susceptibility to crusting and certain land use characteristics, was found to be the main factor accounting for variations in erosion. Other factors, such as the soil sand content, talweg incisable length, catchment compacity index and proportion of upslope contributing areas were also correlated with total and talweg rill volumes, but slope characteristics were not. Cropping systems greatly affected the catchment susceptibility to rill erosion through their influence on runoff generation, runoff concentration and soil susceptibility to scouring.

Résumé

Cette étude analyse les relations entre les variations de l'érosion en rigoles et les caractéristiques morphologiques, pédologiques et agraires de bassins versants cultivés. 20 bassins versants élémentaires, dont les superficies sont comprises entre 3.7 et 100 hectares, ont été sélectionnés dans le Nord de la France et étudiés pendant l'hiver 1988/89.

L'importance des rigoles, exprimée en volumes (m^3) ou en taux spécifique (m^3/ha), était très variable d'un bassin à l'autre: ces différences ne peuvent cependant pas être expliquées par des variations des pluies. Les résultats ont montré que le principal facteur explicatif de la variabilité de l'érosion était l'extension des surfaces qui contribuent au ruissellement, définies en combinant leur sensibilité à la battance et certaines caractéristiques d'occupation du sol.

L'importance des rigoles est également influencée par les variables suivantes: la teneur en sable, la longueur incisable des talwegs, un indice de compacité du bassin versant (Gravelius) et la proportion des surfaces contribuant au ruissellement, localisées à proximité de la ligne de partage des eaux. Par contre, elle n'apparaît pas corrélée aux caractéristiques de pente.

Ainsi, du fait de leur influence sur la genèse, la collecte et la concentration du ruissellement et sur la susceptibilité

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du sol à l'arrachement, les systèmes de culture ont un effet très important sur l'érosion en rigoles.

1 Introduction

In northwestern Europe, rill erosion appears to be an important component of total soil erosion (Morgan 1977, Torri et al. 1987, Govers 1987a, Govers & Poesen 1988). These findings are based not only on a comparison of soil losses originating from rill or inter-rill, respectively, but also on off-site effects which are the most salient feature of erosion damage in this context. Since rill erosion is the most effective process for transfering sediment over long distances, muddy floods and soil deposits on roads or urbanized areas are always associated with the development of an ephemeral network of rills and gullies in cultivated areas located upslope (Monner & Boiffin 1986, Boardman 1990, Papy & Douyer 1991). The features of these erosions vary widely in their pattern, location and size. Identifying the determinants of this variability could provide useful indications for both risk assessment and in designing protection measures.

Two groups of factors are involved in the processes of rill initiation and development:

- those controlling the hydraulics of overland flow: rainfall intensity, soil infiltrability, size of contributing areas and land slope characteristics (Dunne 1978, Foster et al. 1985, Thorne & Zevenbergen 1990);
- those related to the susceptibility of the soil to scouring and to subsequent mass movement on side walls.

This susceptibility depends mainly on soil cohesion, which is dictated by the soil texture, the structural state and the water content (Govers 1987b, Poesen 1989, Poesen & Govers 1990).

Most theoretical and experimental approaches to the study of rill erosion have been conducted in simplified conditions under which some factors could be emphasized and other neglected. Studies conducted on laboratory flumes and experimental plots have identified certain topographical conditions controlling the initiation of rills (De Ploey 1983, Foster et al. 1984, Rauws 1987, Rauws & Govers 1988, Torri et al. 1987, Bryan & Poesen 1989). But these conditions are inadequate for describing the changes which occur when runoff flows into concentrated channels. Also, as indicated by other researchers (Govers 1987b, Govers et al. 1990), the influence of dynamic factors, such as soil moisture and soil structure, remains poorly understood.

Consequently, understanding and predicting rill erosion becomes very difficult for rather large spatial units, especially cultivated areas. Under these conditions, non-uniform shapes lead to runoff concentration (Thorne & Zevenbergen 1990), and farming operations induce wide spatial and temporal variations in topsoil structure (Boiffin & Monnier 1986, Boiffin & Papy 1988, Boiffin et al. 1988, Imeson & Kwaad 1990, Foster 1990). We have therefore adopted an empirical approach in order to identify the main factors controlling the variability of rill erosion in the field.

Total rill erosion is the sum of rill erosion occurring both in concentration lines and on areas without concentration features. In the latter case, rills usually exhibit a more or less regular, parallel pattern with interrills less than 1 to 20 m wide. Rills developed on concentration lines are usually more widely spaced and are not parallel, but they can become very deep and wide; they are then called "ephemeral gullies" (Foster et al. 1985, Poesen & Govers 1990). Concentration lines are sometimes agricultural features such as headlands or dead furrows, but more often they are determined by the natural shape of the land. The highest concentrations in runoff are attained in dry valley floors, where the runoff occurring from hillslope converges along talweg lines. Less marked concentration lines, whose contributing areas have less determined and more variable limits, can also be found on hillslopes. Then concentrated flow erosion is not confined to talwegs, but talwegs should be necessary included in the scope of the research to obtain a complete and integrated view of rill erosion (Auzet et al. 1990, De Ploey 1990). These considerations indicate that the catchment scale is the most relevant for studying total rill erosion.

We have attempted to relate the rill erosion variability to the characteristics of a sample group of "elementary catchments", which are first order catchments defined by the dry valley network (and not by the stream network). Those characteristics liable to influence runoff production, flow concentration and/or sediment detachment and transfer, were selected. They were assessed from combinations of morphological, pedological and land use informations.

2 Material and methods

2.1 Spatial and temporal context of the study

The survey was conducted on small catchments, at the level of the lowest complexity: such catchments were delimited as including only one segment of valley floor, with no permanent channel and comprising only agricultural land. The minimum length of the main concentration line was taken as 250 m on a 1/25000 topographic map. The divide of such units appear to be stable throughout the year in areas of smooth slopes such as Northern France.

The downslope limits of the elementary units were defined as lying at the confluence with another unchanneled valley floor, or at the junction of the valley bottom and either a permanent channel or any major area likely to disturb the concentration and to spread the flow.

A total of 20 elementary catchments in 7 regions of Northern France were selected (fig. 1). This selection was designed to obtain a wide range of catchment characteristics.

Erosion usually occurs on agricultural land during two main periods when climatic conditions and farming operations may interact: one at the end of the autumn and during the winter, the other during the spring (Boiffin et al. 1988, Ouvry 1989, Govers, in press, Papy & Douyer 1991).

We initiated a systematic survey of the characteristics liable to influence surface flow and sediment transfer, and erosion features and their locations during the winter of 1988/89.

2.2 Catchment characterization

Data on topography, soil texture and land use were collected from measurements on topographic maps combined with field checks and measurements. These data were used to obtain the variables listed in tab. 1.

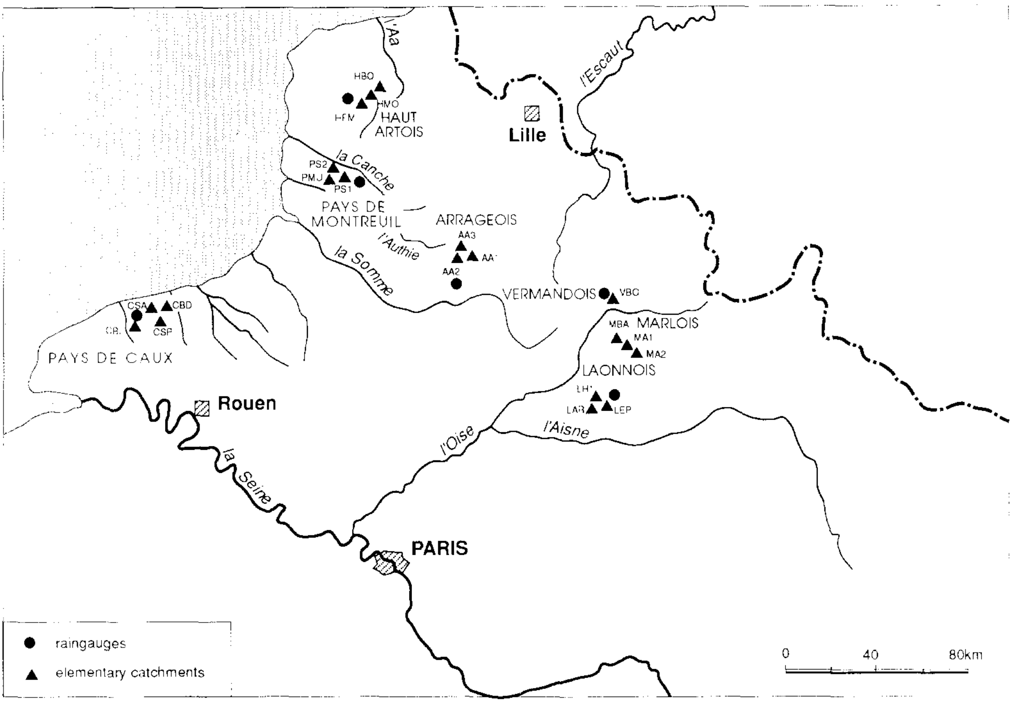

Fig. 1: *Location of catchments and raingauges.*

name	unit	definition
AT	ha	total catchment area
Ltw	m	talweg length
Ltwc	m	talweg length, corrected for the land use
K	-	Gravelius compacity index
Dcl	m/ha	density of morphological concentration lines, talweg excluded
Stw	%	mean slope gradient along the talweg
Sg	%	mean slope gradient of the total catchment
Smx	%	maximum slope gradient in the catchment
Ps5	%	% of the catchment area with a slope gradient >5%
Ps10	%	% of the catchment area with a slope gradient >10%
AC	ha	area prone to crusting
PC	%	% of the catchment area prone to crusting
Asa	ha	area with a sandy soil surface: >35% sand
Psa	%	Asa / AT
AR	ha	potential runoff contributing area
PR	%	AR / AT
ARtw	ha	potential area contributing to runoff supply to the talweg
PRtw	%	ARtw / AT
ARu	ha	potential runoff contributing area close to the divide with a slope gradient <2%
PRu	%	ARu / AT
ARuh	ha	part of ARu located upslope of the origin of the talweg
PRuh	%	ARuh / AT

Tab. 1: *List of variables characterizing the studied catchments.*

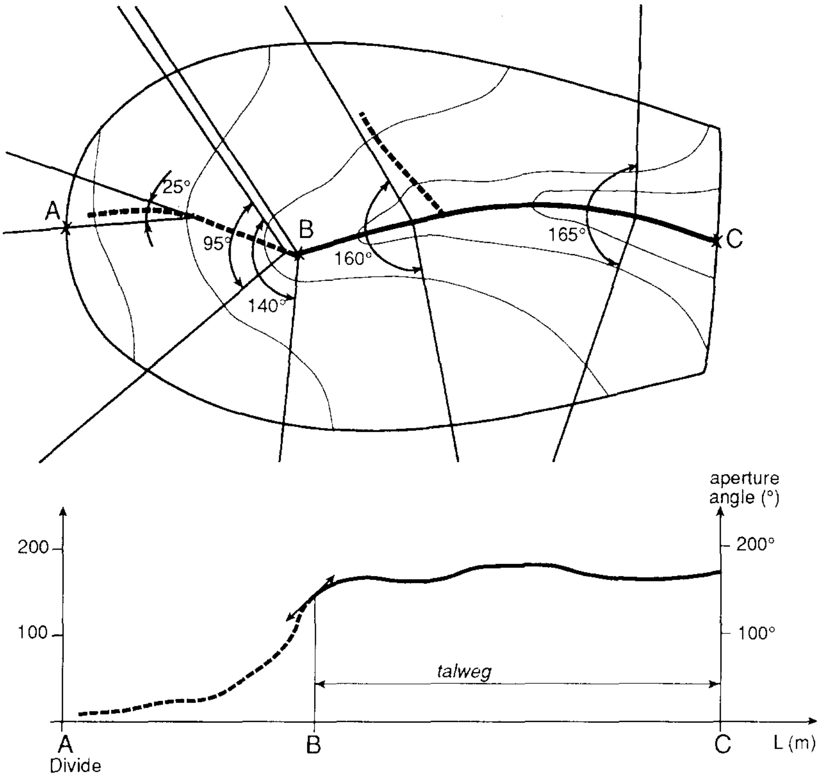

Fig. 2: *Identification of the upslope origin of the talweg.*
Dotted lines indicate concentration lines prolonging or intersecting the talweg, but not included in it

2.2.1 Morphological data and variables

The divide was located on a 1/5000 map (enlargement of the 1/25000 topographic map) and verified in the field by Abney level measurements. Slope maps for each catchment were produced from the contour lines of the topographic maps and checked by Abney-level measurements, with particular attention to changes in slope gradient.

The following morphometric variables were established by this procedure: the total catchment area AT (ha); the Gravelius compactness coefficient K (adimensional), which equals the ratio of the perimeter of the catchment to the perimeter of a circle having the same area; the proportion of the catchment area with a slope gradient >5%, Ps5 (%); the proportion of the catchment area with a slope gradient >10%, Ps10 (%); the mean slope gradient of the catchment, Sg (%) and the maximum slope gradient, Smax (%).

We also mapped each line of flow concentration on slopes and in the valley floor. The main concentration line, located in the valley floor, was denoted the talweg. Slope gradient was measured at 20 m intervals along this line.

The upslope origin of the talweg was

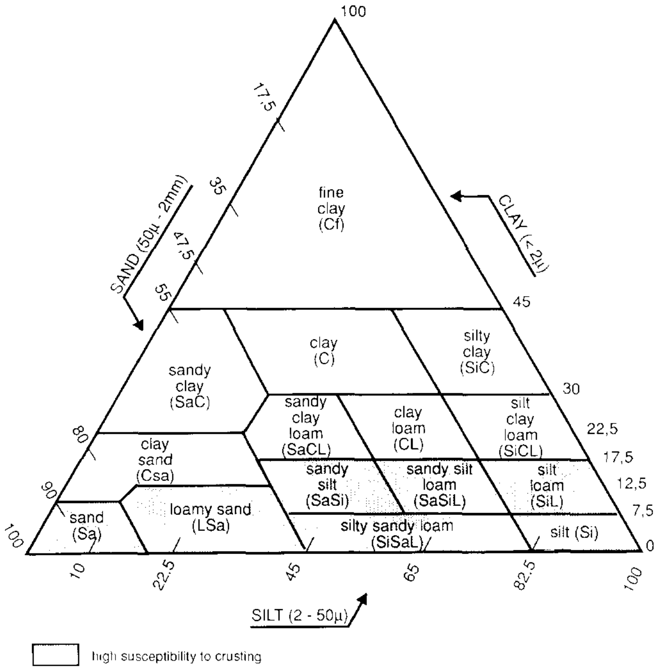

Fig. 3: *Diagram of texture classes.*

defined from the variations of the aperture angle formed by the two perpendiculars to the contourline on both sides of the talweg (fig. 2). Downslope to upslope along the talweg, this angle was initially open (120° to 200°) and then decreased suddenly: the point where this change occured is considered to be the beginning of the talweg. This point actually corresponded to the first important convergence and hence, to a critical point for flow concentration.

This procedure produced the following variables: the talweg length, Ltw (m); the density of the morphological concentration lines (talweg excluded), Dcl (m/ha); the slope of the talweg, Stw (%).

2.2.2 Soil data and variables

Topsoil textures were determined by manual testing, with 4–5 samples per ha and more frequent sampling to locate the limits. The results of tactile tests were checked by granulometric analyses (120 samples). Maps of topsoil texture were established at a scale of 1/5000. The texture classes refer to the diagram in fig. 3 (Jamagne 1967, Baize 1988).

Soils classed as sand, loamy sand, sandy silt, sandy silt loam, silty sandy loam, silt loam and silt were considered to be prone to crusting (Poesen & Savat 1981, Boiffin 1984, Römkens et al. 1987, Le Bissonnais 1988).

These data allowed us to estimate the area in each catchment which was prone to crusting, expressed in ha (AC) or as a percentage of the total catchment area (PC).

The area of land with a sandy topsoil

texture (texture classes: sand, loamy sand, sandy silt, sandy silt loam and silty sandy loam), was also estimated (in ha, Asa or %, Psa), as a sandy soil is supposed to be highly susceptible to scouring.

2.2.3 Land-use data and variables

The field limits were precisely mapped on a scale of 1/5000. Other linear features such as tracks, roads, dead furrows and headlands were also mapped.

Three types of arable land were identified:

(i) winter crop plots, for which the likelihood of runoff during the winter depends on the structural state of the soil surface and hence, on the susceptibility of the soil to crusting (Boiffin et al. 1988, Imeson & Kwaad 1990);

(ii) land left bare and untilled during the winter season, on which the soil surface is compacted by many wheel tracks and has a high runoff potential. This situation corresponded mainly to sequences between two spring sown crops (e.g. sugar beet-peas or flax-sugar beet);

(iii) tilled surfaces prepared for spring sown crops following winter cereals. These areas should not contribute to runoff because of high depressional storage induced by the surface roughness following tillage (mouldboard ploughing or stubble ploughing) (Onstad 1984).

Pastures and woods were also mapped.

2.2.4 Composite criteria

2.2.4.1 Estimation of potential runoff contributing area The aptitude of each land unit in the catchment to produce runoff during winter was evaluated by combining the susceptibility to crusting and the type of land use (tab. 2) on a map (fig. 4). This procedure was used to distinguish 2 types of land; one with low runoff potential (0) and the other with high runoff potential (1).

This was used to evaluate a potential runoff contributing area for each catchment, expressed in ha (variable AR) or as a percentage of the total catchment area (variable PR).

The runoff supply to the talweg was strongly influenced by the direction of field operations and wheeltracks in some cases. These modifications of the runoff route were taken into account by defining a new variable — area contributing to runoff supply to the talweg, expressed in ha (ARtw) or as a percentage of the catchment area (PRtw).

2.2.4.2 Location of the runoff contributing areas in the catchment Fairly flat areas located close to the divide were not expected to have the same effect as areas located close to the talweg and/or on steeper slopes. The variables ARu (ha) and PRu (%) were used to distinguish the upslope area with a slope gradient <2% and prone to runoff within the contributing areas. We also identified the part of this area which was located upslope of the origin of the talweg using the variables ARuh (ha) and PRuh (%).

2.2.4.3 Talweg susceptibility to incision The incision risk in valley floors was assumed to be much lower in the presence of permanent grassland. In this situa-

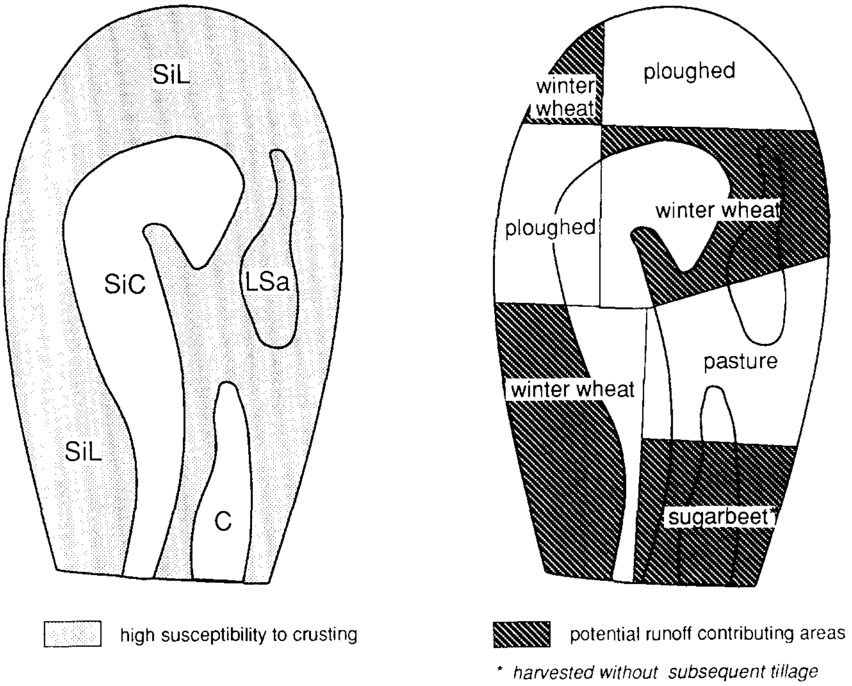

Fig. 4: *Identification of areas prone to crusting and potential runoff contribution areas.*

Land use	susceptibility to crusting(*) low	high
winter crops	0	1
no-tilled intercrops	1	1
tilled intercrops	0	0
pasture or woods	0	0

0: low aptitude to produce runoff
1: high aptitude to produce runoff
(*) see texture triangle fig. 3

Tab. 2: *Conventional scoring of the land aptitude to produce runoff during winter, as a function of land use and soil susceptibility to crusting.*

	AT	Ltw	Ltwc	K	Dcl	Stw	Sg	Smx	Ps5	Ps10	PC	Psa	PR	PRtw	PRu	PRuh
mean	34.0	496	467	1.2	36.8	3.5	4.1	22.1	34.3	9.4	53.3	13.3	36.2	34.1	11.6	5.8
max	100.0	1890	1690	1.6	88.2	8.5	7.9	66.7	71.6	50.7	100.0	100.0	78.0	78.0	55.4	35.8
min	3.7	50	50	1.0	3.3	1.5	1.9	6.3	0.3	0.0	8.0	0.0	2.7	2.7	0.0	0.0
STD	24.3	392	339	0.1	20.4	1.8	1.7	17.1	18.8	13.1	33.1	32.2	24.1	23.8	15.6	9.3
c. var.	0.7	0.8	0.7	0.1	0.6	0.5	0.4	0.8	0.5	1.4	0.6	2.4	0.7	0.7	1.4	1.6

Tab. 3: *Statistical parameters describing the distribution of catchment characteristics: mean, maximum and minimum values; standard deviation (STD); coefficient of variation (c. var.).*

	AT	AC	PC	AR	PR	ARtw	PRtw	ARu	PRu	ARuh	PRuh	Psa	Ltw	Ltwc	K	Dcl	Stw	Sg	Smx	Ps5	Ps10
AT	1																				
AC	**0.92**	1																			
PC	**0.60**	**0.80**	1																		
AR	**0.87**	**0.96**	**0.83**	1																	
PR	**0.03**	**0.66**	**0.87**	**0.80**	1																
ARtw	**0.86**	**0.96**	**0.82**	**0.98**	**0.75**	1															
PRtw	**0.49**	**0.67**	**0.86**	**0.78**	**0.92**	**0.81**	1														
ARu	**0.77**	**0.90**	**0.82**	**0.96**	**0.81**	**0.94**	**0.80**	1													
PRu	**0.52**	**0.66**	**0.79**	**0.79**	**0.87**	**0.76**	**0.81**	**0.90**	1												
ARuh	**0.71**	**0.85**	**0.69**	**0.79**	**0.60**	**0.79**	**0.80**	**0.79**	**0.69**	1											
PRuh	**0.46**	**0.60**	**0.71**	**0.64**	**0.72**	**0.63**	**0.71**	**0.73**	**0.85**	**0.86**	1										
Psa	0.31	-0.23	-0.03	0.19	0.10	-0.27	-0.06	-0.19	-0.12	-0.19	-0.18	1									
Ltw	**0.50**	-0.33	0.21	0.41	0.24	0.40	0.24	0.38	0.31	-0.02	0.00	-0.28	1								
Ltwc	**0.44**	-0.25	0.17	0.31	0.22	0.30	0.21	0.32	0.35	0.02	0.14	-0.31	**0.94**	1							
K	0.25	-0.22	0.25	0.26	0.18	0.29	0.22	0.32	0.33	0.03	0.14	-0.33	**0.80**	**0.80**	1						
Dcl	-0.32	-0.27	-0.17	0.29	-0.23	-0.33	-0.31	-0.33	-0.34	-0.21	-0.26	0.28	**-0.44**	**-0.47**	**-0.41**	1					
Stw	**-0.49**	**-0.40**	-0.16	**-0.43**	-0.20	**-0.41**	-0.17	-0.36	-0.19	-0.22	-0.07	**0.39**	-0.30	-0.21	-0.02	-0.20	1				
Sg	**-0.49**	**-0.44**	-0.25	**-0.41**	-0.09	**-0.38**	-0.05	-0.37	-0.22	-0.28	-0.14	**0.62**	-0.38	-0.33	-0.33	-0.12	**0.69**	1			
Smx	-0.19	-0.30	-0.28	-0.32	-0.22	-0.28	-0.16	-0.36	-0.31	-0.27	-0.25	**0.5**	-0.03	0.0	-0.12	-0.09	**0.62**	**0.80**	1		
Ps5	**-0.66**	**-0.73**	**-0.69**	**-0.71**	**-0.55**	**-0.71**	**-0.55**	**-0.72**	**-0.65**	**-0.64**	**-0.60**	**0.51**	-0.34	-0.35	-0.35	0.31	**0.49**	**0.78**	**0.75**	1	
Ps10	-0.27	**-0.38**	**-0.41**	**-0.38**	-0.33	-0.35	-0.27	**-0.41**	**-0.38**	-0.33	-0.35	**0.46**	-0.06	-0.06	-0.2	-0.03	**0.39**	**0.60**	**0.82**	0.73	1

(in bold characters P <0.05)

Tab. 4: *Correlation coefficients (R) between catchment characteristics.*

	Land use classes winter crops	 tilled intercrops	 non-tilled intercrops	 woodland grassland
mean*	57.9	25.2	6.5	10.4
max*	99.3	71.0	36.8	44.1
min*	14.5	0.0	0.0	0.0
STD*	21.3	19.0	10.1	12.0
c. var.	0.4	0.8	1.5	1.2

Tab. 5: *Variability of land-use characteristics within the catchment sample (winter 1988/89 (* % of total catchment area)).*

tion the variable Ltwc (m) corresponds to the total length of the talweg (Ltw) minus the length covered by permanent grass.

2.3 Variability of the catchment characteristics (tab. 3)

The average total catchment area (variable AT) was 34 ha (3.7 ha for MA2 — 100 ha for CBL). Only 1/3 of the total area had slopes steeper than 5%. The topography of plateau borders dissected to a variable extent by a large dry valley network comprised mostly smooth slopes (2–5%) and fairly flat areas (0–2%).

Apart from the Laonnois, with a sandy, clayey Tertiary substrate, the dominant superficial formations originate from Quaternary loamy deposits on chalk. As a result, most of the topsoil textures are silt and loam, which are highly susceptible to structural degradation. Those texture classes prone to crusting — silt loam to sand (fig. 3) — accounted for more than 50% of the total catchment area (variable PC). Clay with flints originating from Tertiary alteration of the top of the chalk occurs in Haut-Artois, Pays-de-Montreuil and Pays-de-Caux and shows on the steepest slopes. The thickness of this clay is fairly variable.

Morphological and textural characteristics are correlated (tab. 4):

- the importance of steeper slopes is negatively correlated with total catchment area (AT), with the area of soils prone to crusting (AC and PC) and with the potential runoff-contributing area (AR, ARtw, ARu, Pru, Aruh and Pruh).

- the area covered by soil prone to crusting (PC and AC) is positively correlated with the total catchment area (AT).

Those correlations are produced by the geomorphology of the Northern Paris Basin. Catchments located on less dissected plateaus (i.e. Pays-de-Caux) have larger areas, gentler slopes and more widespread, thick loess cover.

Most of the land in all the catchments were arable land with open fields, grassland and woodland accounting for an average of only 10% of the total area. Nevertheless, there was some variability in land use between catchments: winter crops covered 14 to 99% of the total catchment area, tilled intercrops 0 to 70% (tab. 5).

2.4 Climatic conditions

Daily data were available from the meteorological network raingauges, located up to 20 km from the catchments (fig. 1). The cumulated rainfalls from 1/10/88 (beginning of the sowing period) to 6/04/89 (end of measurement) were lower in Laonnois, Marlois, Vermandois and Arrageois (428–439 mm), than in Pays-de-Caux, Haut-Artois and Pays-de-Montreuil (491–516 mm) (tab. 6). This variability is in accordance with the usual gradient depending on the distance from the sea. However, the distributions of the rainy periods along the time axis were very similar for all the regions (fig. 5).

Since no automatic raingauge recorder was available at the time of the study, no information was obtained about peak intensities. As spatial variations in rainfall intensities might have been responsible for some part of the between-catchment erosion variability, this could be a source of bias or unexplained variations in the results. However, we assumed that the peak intensities followed the same pattern of between-regions variations as the maximum daily rainfall.

2.5 Erosion measurements

Each rill was mapped. Rill incision was evaluated by measuring rill volume. The width and depth were measured every 10–30 m along the rill, and at specific points where the section changed significantly. Erosion was measured as late as possible, in the 2 weeks from March 23 to April 6, before spring tillage, which could erase some rills.

The global volumes of the incisions (variables Vec in m^3 and Rec in m^3/ha) and the volume of the incision on the talweg (variables Vtw in m^3 and Rtw in m^3/ha) were calculated for each catchment.

3 Results and discussion

3.1 Variability of rill volumes

Total eroded volumes (Vec) were 0–250 m^3 (fig. 6) and the rates (Rec, 0–7 m^3/ha) (fig. 7). No rill erosion was observed in 4 catchments. The lowest values were found in Arrageois and Marlois, and the highest in Laonnois and Pays-de-Caux. However, in these latter regions, the variations between catchments in the same region were almost as great as the overall variation. The average contribution of talweg erosion was 45%, and varied from 0 to 100% of total eroded volume. A high value of total erosion was sometimes associated with a high percentage of talweg erosion, as in Pays-de-Caux and Haut-Artois, but in Laonnois rill erosion was entirely on hillslopes. As shown in tab. 7, rills observed in the talweg had generally greater cross-section areas than those observed on hillslopes. But some wide and deep gullies were also found on concentration lines on hillslopes.

The between-regions variations in total erosion volumes or rates did not correlate with rainfall (tab. 6), since low rainfalls were recorded in Laonnois (a region with very strong erosion) and high rainfalls in Haut-Artois (a region with low to medium erosion). Furthermore, the great variability of erosion volumes and rates between catchment of the same region could not be explained by variations in local rainfall, which is rather limited in winter. This suggests that catchment characteristics are responsible for more of the variations in erosion than is rainfall.

	Site					
Rainfall characteristics*	Laon (Laonnois & Marlois)	Bohain (Vermandois)	Albert (Arrageois)	Lottinghem (Haut-Artois)	Marconnelle (Pays-de-Montreuil)	Blosseville (Pays-de-Caux)
total (mm)	438.8	436.1	428.5	516.3	514.4	491.1
max. in 1 day	29.7	37.2	25.4	27.7	25.0	35.5
nb. days >1 mm	62	65	60	71	69	67
*(1/10/88–6/04/89)						

Tab. 6: *Rainfall characteristics during the study period.*

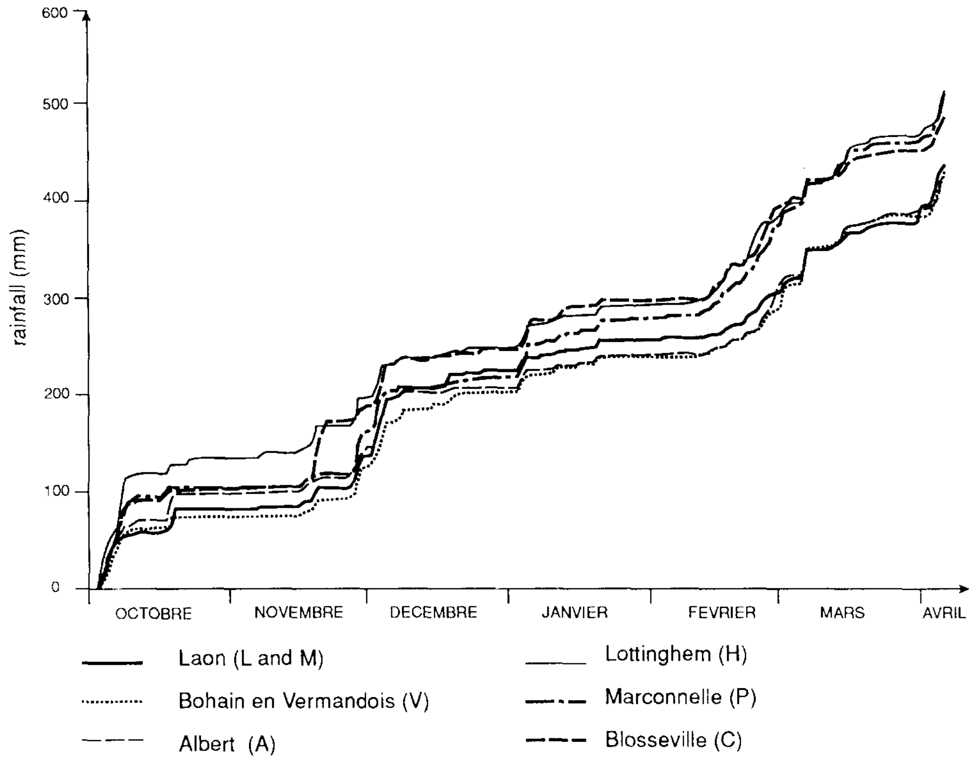

Fig. 5: *Cumulated rainfall during the study period.*

Location	width			depth		
	min.	mean	max.	min.	mean	max.
talweg	0.15	0.58	2.50	0.02	0.16	0.80
hillslopes	0.02	0.29	2.50	0.01	0.12	0.60

Tab. 7: *Width and depth of rills (m) according to their location in the catchment.*

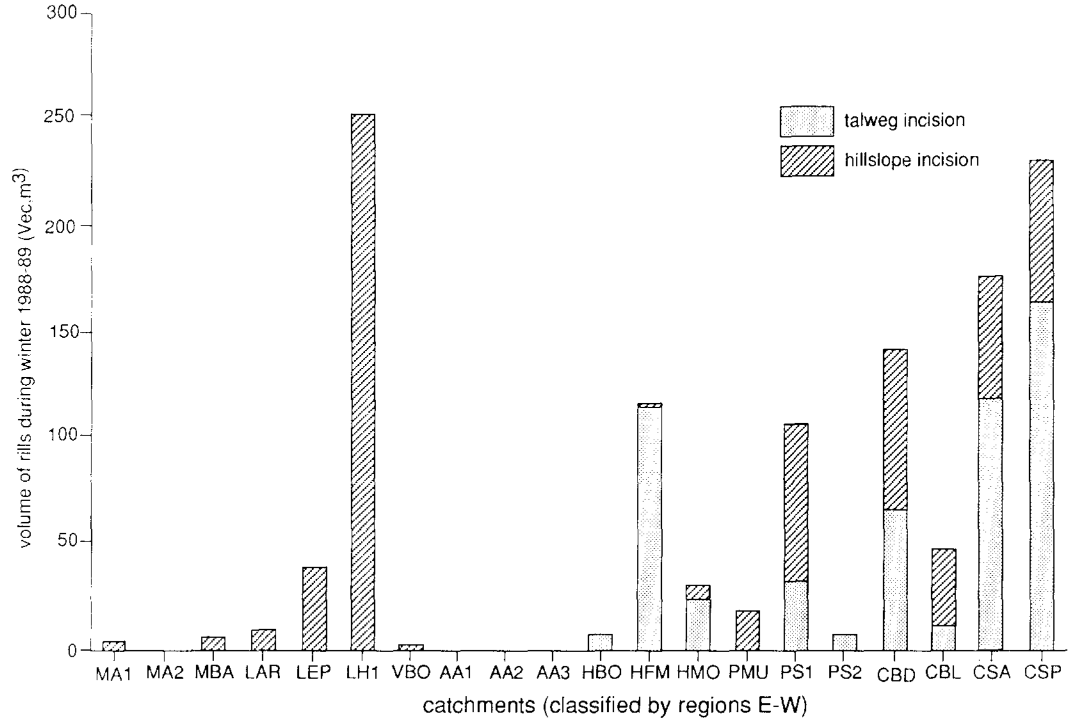

Fig. 6: *Distribution of total and talweg rill volumes (Vec, Vtw).*

3.2 Influence of runoff contributing-area size

Our basic assumption was that the size of contributing areas was the primary determinant of rill erosion variability, as it would control the runoff discharge along concentration lines. As explained in 2.2.4., AR (ha) and PR (% of the catchment area) were considered to be estimators of the absolute and relative sizes of the areas contributing to winter runoff in the whole concentration network. They were assumed to be more relevant than either the total catchment area (AT) or the area occupied by soils prone to crusting (AC, ha or PC %), since they take into account the influences of both agricultural management and soil properties on the land's propensity to runoff. The best estimators of contributing areas for the talweg were assumed to be ARtw (ha) and PRtw (%), since they take into account the actual connections between the contributing plots and the talweg line.

Linear regressions were calculated between the explained variables expressing total erosion (Vec and Rec) or talweg erosion (Vtw and Rtw) and estimators of the size of contributing areas. All determination coefficients R^2 (tab. 8) were significantly different from 0, but the highest values of R^2 were obtained with the expected best estimators. These results support the assumptions made for grading the aptitude of land surface to produce runoff. Fig. 8

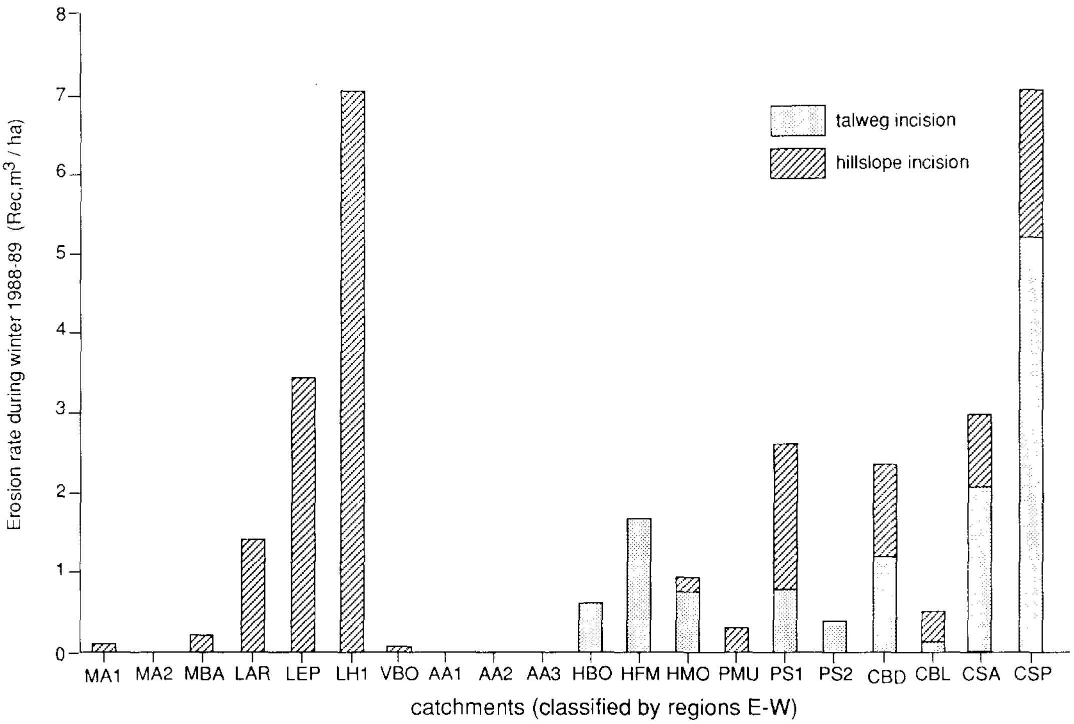

Fig. 7: *Distribution of total and talweg erosion rates (Rec, Rtw).*

	independent variable			
dependent variable	catchment area AT(ha)	prone to crusting areas AC(ha) or PC(%)	potential runoff contributing areas AR(ha) or PR(%)	pot. runoff contributing areas for the talweg ARtw(ha) or PRtw(%)
Vec(m^3)	16.1	22.9	43.1	
Rec(m^3/ha)		24.5	53.6	
Vtw(m^3)	16.7	21.9	34.1	37.3
Rtw(m^3/ha)		27.5	35.8	42.9

Tab. 8: *Correlations between erosion data and estimators of runoff contributing areas (coefficients of determination $R^2 \times 100$).*

and 9 illustrate the way in which taking into account agricultural management improves the explanation of erosion rate (Rec) variability. Fig. 8 shows that catchments CBL, PS2 and PMU, which had very high proportions of soils prone to crusting, also had very low rates of rill erosion. This is partly explained by the fact that summer or autumn tillage roughened the soil surface of large parts of these areas, giving it a certain porosity and increasing storage capacity. The points representing the catchment in fig. 9 have x-axis values

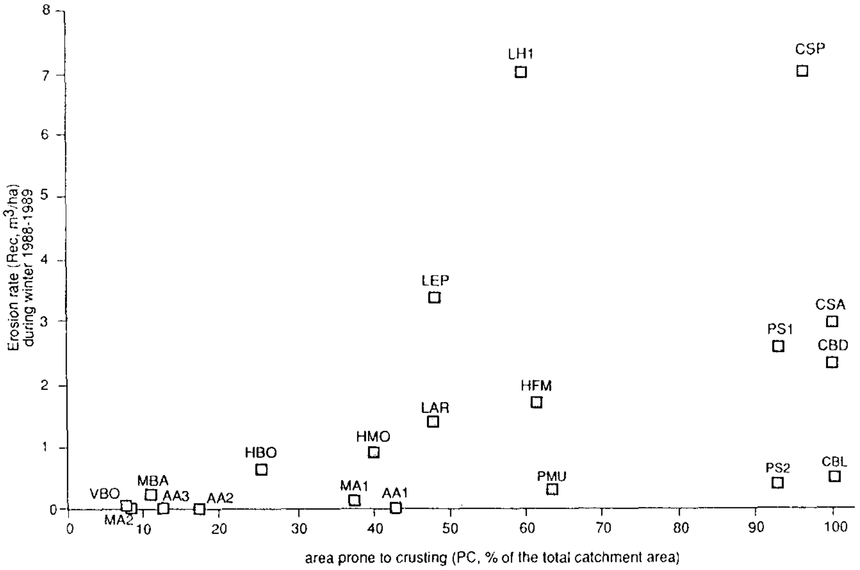

Fig. 8: ***Relationship between erosion rate (Rec) and area prone to crusting (PC).***

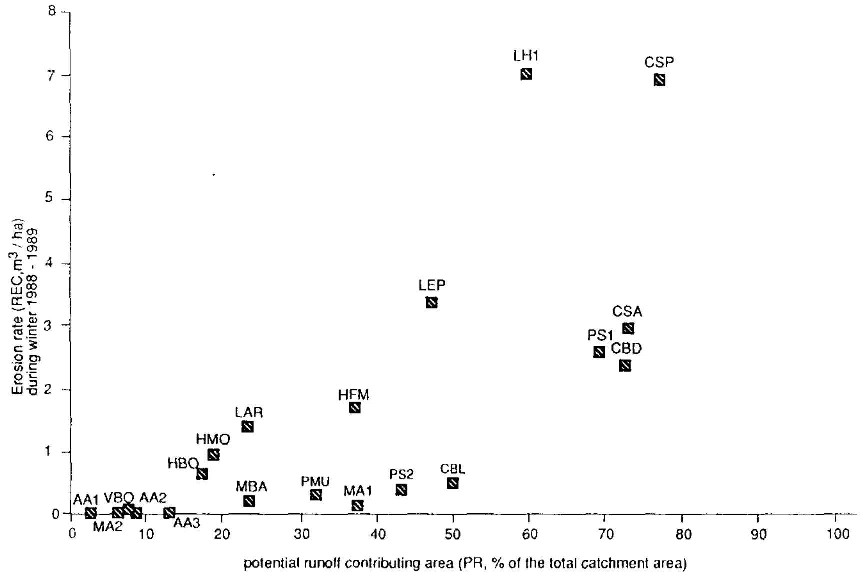

Fig. 9: ***Relationship between erosion rate (Rec) and potential runoff contributing area (PR).***

which are relatively much lower than on fig. 8.

The distribution of experimental results (fig. 9) was not in good agreement with rainfall variations. Thus rainfall erosivity was not assumed to account for a major part of the residual variance, while soil erodibility and catchment morphology were thought to have greater effects.

3.3 Detection of additional factors: multivariate analysis

Multiple stepwise regression was used to test the influence of the variables listed in tab. 1. The variables selected at each step are indicated in tab. 9.

Estimators of contributing area were introduced at the first step for total catchment erosion and talweg erosion, confirming the preeminence of this factor. Subsequent steps showed some differences between total catchment and talweg erosion. For total erosion, the absolute or relative extent of sandy soils were the second factor to be introduced, while certain factors related to catchment shape appeared more important for talweg erosion: erodible length of the talweg (Ltwc) for erosion volume and Gravelius compactness coefficient (K) for erosion rates. For total catchment erosion, the erodible length of the talweg (Ltwc) was introduced at the third step. Slope distribution characteristics were not included in any of the final regressions.

According to classical erodibility nomograph (Wischmeier & Smith 1971, Römkens et al. 1987), sandy soils have a lower erodibility than silty or silty-loamy. But experimental results sometimes conflicted with this trend, indicating a positive influence of sand content on global erodibility (Verhaegen 1984, Schwertman 1986). Moreover, a general relationship between soil composition and soil erodibility should not be applied to the specific subprocesses involved in soil detachment by the running flow (Römkens et al. 1987). Several surveys and experimental studies suggest that the sand content aggravates rill development (Evans & Northcliff 1978, Govers 1987a, Govers, in press). Soils with high sand contents were particularly wide-spread in Laonnois catchments and were associated with severe erosion on hillslopes, including a variety of rill-patterns. Large, deep gullies, with evidence of intense mass movements on sidewalls and regressive headcuts, were observed in concentration lines. Branched patterns with multiple dendritic and shallow rills were also observed when concentration channels were not marked. Low cohesion inducing high susceptibility to detachment and to mass movement may be a cause of this high erodibility (Poesen 1989, Poesen & Govers 1990).

The absence of any correlation between talweg erosion and the extent of sandy soils in the catchment can be partly explained by a systematic bias in the topographic distribution of topsoil textures. The valley bottoms of all catchments were mostly occupied by loamy or silty colluvial soils. Thus talweg erodibility could not be correlated with the texture criteria used for the whole catchment.

As indicated by the significant influence of Ltwc and K, elongated catchments with long talweg showed more erosion than compact ones with shorter talwegs. This may be because the head of the rill incising the talweg was located upstream of the conventional tal-

dependent variable	step 1	step 2	step 3	step 4
Vec (m^3)	AR^{***}	Asa^{***}	$Ltwc^{**}$	Sg^{ns}
Rec (m^3/ha)	PR^{***}	Psa^{***}	K^{NS}	
Vtw (m^3)	$ARtw^{***}$	$Ltwc^{***}$	Stw^{NS}	
Rtw (m^3/ha)	$PRtw^{***}$	K^{**}	Stw^{NS}	

$(^{***})P<0.01$; $^{**}P<0.05$; $^{NS}P>0.10$

Tab. 9: *Independent variables introduced at each step of the multiple stepwise regression.*

weg origin, or not far downstream in most cases. This indicates that runoff discharges generated at the head of the catchment, or even in a part of it, were sufficient to produce critical shear velocities and initiate rill without any contribution from lateral hillslopes. Talweg length became a limiting factor for erosion in these cases. This interpretation is supported by observations made on CSP talweg. Tillage operations during late autumn resulted in the concentrated flow in the talweg being diverted from its previous course to a new parallel line. A new rill was formed along this line with approximately the same length and cross section area as on the first one, suggesting that the talweg incisable length was the limiting factor for eroded volumes.

The fact that slope characteristics were not significant explaining variables appears to conflict with the standard concepts developed in USLE and with a recent survey of rill erosion (Govers, in press). However, the erosion systems studied were significantly different. The dominant pattern in the present study was concentrated flow erosion, either in the talweg or on hillslopes. Flow velocities of channelled runoff could have been controlled by contributing areas and rainfall intensities rather than by slope gradients or slope lengths. The effect of slope characteristics could also have been masked by other factors influencing soil erodibility. Steep slopes in the catchments studied and throughout the whole Paris Basin, are very often associated with either tertiary sands (case of Laonnois) or with relatively clayey textures, due to showing of Bt horizons or alteration clays on hillslope surfaces. Further studies on another catchment sample should be carried out to dissociate topsoil textures and slope distributions.

3.4 Form of the adjustments. Residual variability.

The same independent variables were used to compare the linear regression model with another model in which the estimators of runoff contributing areas were factorized, and other independent variables combined in a linear expression (tab. 10). This multiplicative form was considered to be physically more relevant, since it implies no erosion when the contributing area is zero, i.e. no possible runoff in the case of Hortonian pattern. Tab. 9 shows that the experimental results fit the multiplicative models at least as well as they do the linear ones. Simple correlations between residuals, given by the multiplicative models, and different variables were calcu-

dependent variable	additive form	R2	multiplicative form	R2
Vec (m^3)	Vec = -34.7 + 2.90 AR + 7.04 Asa + 0.0769 Ltwc	73.8	Vec = (1.47 + 0.120 Psa + 0.0263 Ltwc) AR	76.8
Rec (m^3/ha)	Rec = -0.922 + 0,0612 PR + 0.0217 Psa	64.5	Rec = (0.0417 + 0.000597 Psa) PR	64.8
Vtw (m^3)	Vtw = -27.7 + 1.36 ARtw + 0.0769 Ltwc	63.8	Vtw = (-0.0726 + 0.00352 Ltwc) ARtw	72.2
Rtw (m^3/ha)	Rtw = -4.95 + 0.0274 PRtw + 3.95 K	58.5	Rtw = (-0.129 + 0.125 K) PRtw	66.5

Tab. 10: *Comparison of the additive and multiplicative models.*

variables	Vec-m	Rec-m	Vtw-m	Rtw-m
AR	0.06	0.12	0.01	-0.07
ARtw	0.04	0.02	0.03	-0.06
PR	-0.39	0.32	0.33	0.17
PRtw	-0.35	0.14	0.36	0-19
Ltwc	0.01	0.38	0.05	-0.03
K	0.07	0.31	0.07	-0.13
Psa	-0.12	-0.02	-0.04	-0.02
Stw	0.11	0.04	0.20	0.20
Sg	0.02	-0.13	0.11	0.15
Smx	-0.26	-0.23	-0.21	-0.11
Ps5	-0.23	-0.29	-0.22	-0.17
Ps10	-0.23	-0.27	-0.19	-0.17
Dcl	-0.14	-0.21	-0.19	-0.17
Pru	0.61	0.60	0.54	0.41
Pruh	0.64	0.55	0.64	0.58

Tab. 11: *Correlation coefficients (R) between different variables and the residuals given by the multiplicative model (observed data - adjusted).*

lated (tab. 11). As expected, correlations with all predictive variables previously tested were low. One possible explanation of residual variance was assumed to be the error made by considering the whole contributing areas as homogeneous. For instance, the proportion of excess surface water converted to concentrated runoff might be expected to be lower for areas close to the divide with a slope gradient less than 2% for contributing areas on steeper slopes and closer to the talweg. The correlations of residuals with Pru and Pruh (definition in tab. 1) were calculated to test this assumption. The results indicated a significant increase in erosion when Pru and Pruh increased. This conflicts with our first hypothesis.

As both total and talweg rill volumes were mainly correlated with their length component (R: 0.92 in both cases), this unexpected result can be attributed to a limiting effect of runoff route on rill length. Since potential rill length is greater when runoff starts close to the divide, a given contributing area will generate more erosion if it is located in the upslope part of the catchment, and this effect is assumed to dominate the decrease of its contribution to concentrated flow caused by a lower slope and by a longer distance to the main channels. Despite their high correlation with residuals, Pru and Pruh were not included in the final equation, because there remained some doubt as to how to define the downslope limits of those upslope areas. The isocline 2% (used for Pru and Pruh) cannot be considered as a physically relevant limit. In some cases, very low values of Pru and Pruh were associated with specific landscape features, such as a path or a road crossing the catchment head which might reduce the contribution of the upslope area to downslope runoff. Further studies are needed to develop adequate variables expressing the influence of the relative positions of contributing areas along the runoff collecting network.

4 Conclusion

The empirical approach reported here was designed to identify the main variables underlying differences in rill erosion variability from one catchment to another. The relative spatial homogeneity of rainfall during winter 88/89 allowed us to distinguish the influence of 3 synthetic factors characterizing the susceptibility of a catchment to rill erosion:

1. The size of runoff contributing areas. This factor is assumed to control the total flow discharge under a given rainfall. It depends on the surface structural state of each field, or part of a field, within the catchment. This surface state, which depends on both farm operations and soil susceptibility to crusting, controls soil infiltrability and depressional storage, and hence the propensity of the land to runoff.
2. The potential incisable length. This length results from the spatial distribution of runoff contributing areas along the concentration network. When contributing areas become much larger than the critical sizes needed for rill initiation, the length of a given rill can be limited by the distance from the channel head to its outlet, rather than by the size of its contributing area.
3. The soil erodibility. This factor influences rill erosion in 2 ways:
    - (i) high soil erodibility induces low critical shear velocity and, hence, low minimum size of contributing area for initiation a rill under a given rainfall;
    - (ii) once a rill course is established, low sidewall cohesion can facilitate mass movements, increasing the cross-sectional area of the rill. The results of this study indicate that the sand content is a positive component of soil susceptibility to rill erosion.

Cropping systems have a great influence on all of these 3 factors, since they induce enormous variations of soil properties, both in time and space. Their effect must be taken into account by using adequate procedures for observation and characterization. These procedures are based on

- (i) identifying the main types of surface structure;
- (ii) relating them to specific groups of farm operations and to given land-use features;
- (iii) mapping field boundaries in order to delimit runoff emission areas and highly or poorly incisable zones;

(iiii) mapping all linear features resulting from agricultural management that can influence the runoff route and the concentration network.

The statistical relationships established in this study should not yet be considered as general or predictive. The restricted number of catchments studied and the systematic bias induced by the geomorphology of the studied area made it impossible to avoid some correlation between catchment characteristics (e.g. slope gradients, soil textures and catchment sizes). Moreover, the observations were made during a winter in which there were no extreme climatic events. Erosion caused by much heavier rainstorms could vary differently from those described in this study, especially if the relative importance of concentrated flow erosion becomes lower than it was here, compared to rill-interrill erosion on hillslopes. Further steps must be taken to validate the selection of variables, and to define the conditions for confirming this selection. However, since most of the correlations found in this study can be supported by plausible physical interpretation, they should provide a solid foundation for further studies on the erosion process at the catchment scale.

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