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Modelling ephemeral gully erosion in small cultivated catchments

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Abstract

This paper describes a new erosion model to predict the location and volume of ephemeral gullies within the main runoff collector network of agricultural catchments. This model, using an expert-based approach, combines field experiment results and knowledge about erosion processes and agricultural practices. It takes into account slope gradient, parameters reducing runoff flow velocity or increasing soil resistance (land use, plant cover percentage, roughness and soil surface crusting stage), the hydrological structure of catchments and the runoff volume. The model is used to calculate the soil sensitivity to ephemeral gully erosion at any point in four small cultivated catchments.

Results show that it is possible to predict gully erosion from simple information that can easily be recorded by farmers. However, our model tends to overestimate the erosion level in some cases. Furthermore, the quality of the results varies strongly according to the catchment and to the rainfall event used. To increase the quality of the results, it will be necessary to improve our knowledge database from experimental results and to use a calibration procedure.

Keywords: Horton overland flow; Ephemeral gully erosion; GIS-based model; Agricultural catchment

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1. Introduction

Erosion research distinguishes between erosion due to Horton overland flow and erosion linked to subsurface flow. Several authors showed that ephemeral gullies could be initiated by convergence of subsurface flow leading to saturation excess overland flow and

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saturation return flow (Dietrich and Dunne, 1993; Bull and Kirkby, 1997). On the agricultural plateaux of the European lœss belt, several studies also showed that erosion occurs despite the gentle topography because of poor infiltration and inadequate storage of surface water due to the sealing of cultivated field surfaces. The lowering of the soil infiltration capacity gives rise to Horton overland flow which is the prime cause of both interrill and gully erosion on crop land (Govers et al., 1990; Auzet et al., 1993; Boardman and Favis-Mortlock, 1998).

Most studies about soil erosion by water focus on sheet and rill erosion processes, i.e. the detachment and transport of sediment at the plot and field scales. More attention is now given to ephemeral gully erosion due to concentrated overland flow at the catchment basin scale. Recent studies showed that this form of erosion described among others by Foster (1986) represents often, besides sheet and rill erosion, another important sediment source (Thorne et al., 1986; Ludwig et al., 1995; Poesen et al., 1996; Nachtergaele and Poesen, 1999). In addition, ephemeral gullies are also effective links between agricultural and urban areas. They are responsible for rapid discharge of sediment produced by sheet or rill erosion and thus contribute to increase the sediment delivery ratio and off-site damages. To design adequate protective measures, it is essential to develop models which are able to predict location, length and cross-sectional area of ephemeral gullies.

There have been many attempts to develop models of ephemeral gully erosion. Although all have similar aims, the approaches have differed, reflecting the levels of understanding of the processes and approaches to approximating them. There is a tendency of models to increase in complexity as scientific understanding increases. This influences the needs for data and computing power. Input data, for example, are not always readily available. For this reason, simpler erosion models are needed (Moore et al., 1988; Thorne and Zevenbergen, 1990), and the use of GIS provides good support for this modelling (Ludwig et al., 1996; De Roo, 1998; Desmet et al., 1999). Following this logic, we decided to develop a model simulating only the dominant processes operating in the catchment. To reproduce these processes, we have focused on the most integrative parameters and defined an expert-based approach by developing decision rules. These parameters are extracted from a knowledge base represented by matching tables in order to combine them.

The objective of this paper is to describe the model called *STREAM Ephemeral gully*. The model is used to estimate the erosion level of the main runoff collector networks within several agricultural catchments during the winter period and is integrated in the GRID raster module of the ARC/INFO GIS software. First, we present the model structure including the description of each factor. We will then describe the method used to extract the runoff collector network. In the second part of the paper, we present the results given by the model.

2. Material and methods

2.1. Model description

Ephemeral gully erosion occurs in a cultivated catchment in point where overland flow discharge exceeds the critical shear stress for gully initiation and development (Govers, 1985; Rauws and Govers, 1988; Moore and Foster, 1990). The first step of the model consisted in characterising overland flow discharge and critical shear stress from easily accessible information. This characterisation is based on the synthesis of laboratory and field experiments carried out at different scales in the Pays de Caux in Normandy (Gallien et al., 1995; Le Bissonnais et al., 1995,1998; Ludwig et al., 1995; Martin et al., 1997; Chaplot and Le Bissonnais, 1999).

2.1.1. Flow discharge

The permanent monitoring of flow discharge is not possible at each point of a catchment. Flow discharge has therefore to be evaluated from field observations. Flow discharge depends on the runoff volume and flow velocity. To estimate the runoff volume, we used the STREAM model (Cerdan et al., 2002). This is an expert-based runoff model, which takes into account crusting and the changes in the runoff collector network induced by agricultural features. The model proceeds in three steps. First, from a set of reference infiltration and runoff data obtained under a variety of situations (weather conditions, surface state, land use and agricultural practices), decision rules represented through matching tables were developed to characterise the infiltration capacity of agricultural fields. The parameters used are soil surface crusting, surface roughness, crop cover and moisture content. Second, characteristics of a rainfall event (rainfall amount and duration) were combined with the infiltration capacity to calculate an infiltration/runoff balance value, which indicates whether a pixel will generate runoff or will infiltrate a potential upstream runoff, in addition to the rainfall. Finally, a runoff collector network, calculated from a Digital Elevation Model (DEM) combined with information on agricultural practices (tillage direction), allowed calculation of the total runoff volume for a rainfall event at any point of the catchment. The advantage of the STREAM model lies in the availability of the input data, which can be collected directly from field observations. It can be used for total runoff amount prediction, but not for peak discharge prediction.

Two factors need to be taken into account for the evaluation of flow velocity through field observations: (i) slope intensity and (ii) a parameter accounting for the influence of soil surface on overland flow velocity. Four classes are distinguished for slope intensity (Table 1). The other factor, a global friction factor, is estimated by combining three main parameters in the form of a matching table. The first two parameters are winter land use and plant cover because they affect the ground cover, and because surface vegetation can slow down the overland flow. According to the crop and agricultural practices, canopy cover percentage and height vary differently with time. Residue mass and coverage after harvest are also different. We have therefore distinguished five main types of land use: permanent pasture, winter crop, cover crops, tillage and harvesting operations. For the last land use case, we took

Table 1
Values of SLOPE factor

Slope intensity (%)	Value
< 2	1
[2–4]	2
[4–8]	3
>8	4

into account the difference between harvesting operations for cut crops and harvesting operations for lifted crops because residue mass can be very different. The parameter called plant cover is expressed as a percentage of the area covered either by canopy or by litter. We identified only three classes: 1–20%, 21–60% and 61–100%. The third parameter is surface roughness. This is a dynamic characteristic that influences numerous processes on the soil surface such as infiltration, temporary storage capacity and also spatial distribution of overland flow (Govers et al., 2000; Helming et al., 1998). Moreover, it evolves rapidly under the influence of climatic agents and of soil tillage (Zobeck and Onstad, 1987). Surface roughness was assessed from visual observations and a classification, which was defined by Boiffin et al. (1988) and further refined by Ludwig et al. (1995). We distinguished five classes according to the difference in the heights of the deepest part of microdepressions and the lowest point of their divide. R0 grade is assigned to slight roughness (< 2 cm), while R4 grade is assigned to strong roughness (>10 cm). As Zhang and Cundy (1989) pointed out, the surface runoff is forced to flow around roughness elements, increasing the sinuosity and decreasing the velocity where the vertical amplitude of roughness elements is of the same order of magnitude as overland flow depth. For this reason, the probability of reducing velocity should be higher for R4 than for R0.

Table 2 shows the combination of these three parameters, which gives us the factor called FRICTION. The values vary between 1 and 5. We consider that the positive influence on the velocity declines when the assigned value increases.

Table 2
FRICTION factor values according to winter land use, plant cover and roughness

Winter land use	Plant cover (%)	Roughness				
		R0	R1	R2	R3	R4
Permanent pasture	0–20	5	4	3	2	1
	21–60	3	2	1	1	1
	61–100	2	1	1	1	1
Winter crops (wheat, barley and rape)	0–20	5	4	3	2	1
	21–60	5	3	2	1	1
	61–100	3	2	1	1	1
Crop cover (mustard, etc.)	0–20	5	4	3	2	1
	21–60	5	3	2	1	1
	61–100	3	2	1	1	1
Superficial tillage or ploughing	0–20	5	5	4	3	2
	21–60	5	4	3	2	1
	61–100	4	3	2	1	1
Harvesting operations						
For cut crops	0–20	5	5	4	3	2
	21–60	4	3	2	1	1
	61–100	3	2	1	1	1
For lifted crops	0–20	5	5	4	3	2
	21–60	5	5	4	3	2
	61–100	5	4	3	2	1

Class 1: maximum friction, i.e. maximum reduction of the runoff velocity.
Class 5: minimum friction, i.e. maximum increasing of the runoff velocity.

2.1.2. Critical shear stress

Critical shear stress represents the soil resistance to the shearing forces of water flow. If shear stress at the given location is lower than critical shear stress, no soil is detached, and vice versa. Critical shear stress values have been related to a variety of soil properties including topsoil texture, density, moisture content and others (Govers et al., 1990; Guerif, 1990). Reported values vary strongly even for similar conditions, which suggest that critical shear stress values are difficult to define precisely (Foster, 1986).

To estimate the critical shear stress, we considered three parameters: land use, plant cover and soil surface crusting stage, in order to take into account the effect of topsoil texture and density. Because runoff is supposed to occur under saturated conditions, moisture content is considered constant during the rainfall event. The first two parameters are winter land use and plant cover, in order to take into account the effect of root density and compaction of subsurface soil layers. The same land use classes are used including the two types of harvesting operations. The distinction remains pertinent because the harvesting operations for lifted crops (sugar beet, potatoes, etc.) lead to the export of underground parts and to the destruction of aerial parts. In the absence of roots, soil resistance to the shearing forces of water flow is reduced. Permanent pasture is well known for its strong efficacy in increasing soil resistance. The efficacy of each land use must be adjusted according to the crop growth. This is the reason why we take the plant cover into account with the three classes as described above. Canopy evolution is used as an indicator of root growth. Another important parameter is the soil surface crusting stage. Boiffin (1984), quoted by Mualem et al. (1990), found that the bulk density of the upper layer of a bare soil, subjected to raindrop impact, increases with time, the rate of change being dependent upon the initial bulk density. The formation of a sedimentary crust at the soil surface leads to decreased infiltration rate and therefore to increased runoff. During the rain event, this layer consolidates as a result of drop impacts and gains significant resistance to shearing forces (Mualem et al., 1990). Crusting increases surface critical shear stress. To take into account this parameter, we used qualitative descriptions of crusting processes. These descriptions originated from the work carried out by Boiffin (1986) who defined several crusting stages, which were further refined by Bresson and Boiffin (1990). Four main stages of crusting were distinguished: initial fragmentary stage (F0), structural crust (F11), structural crust with local presence of sedimentary crust (F12) and general sedimentary crust (F2).

The three parameters are combined according to a second matching table which gives us the factor called COHESION (Table 3). The values vary between 1 and 5. We consider that the positive influence on soil resistance declines with increasing assigned value. For any type of land use, when the plant cover percentage increases and soil surface deteriorates, soil resistance to the shearing forces of water flow is assumed to increase.

2.1.3. Calculation of the sensitivity to gully erosion for a given rainfall event

The sensitivity to gully erosion for a pixel and for a given rainfall event is calculated using the following equation:

$$\begin{aligned}\text{Sensitivity to gully erosion} &= \text{Runoff volume} \times \text{SLOPE factor}\\ &\quad \times \text{FRICTION factor} \times \text{COHESION factor} \qquad (1)\end{aligned}$$

Table 3
COHESION factor values according to winter land use, plant cover and crusting stage

Winter land use	Plant cover (%)	Crusting stage			
		F0	F11	F12	F2
Permanent pasture	0–20	5	4	3	2
	21–60	4	3	2	1
	61–100	3	2	1	1
Winter crops (wheat, barley and rape)	0–20	5	5	4	3
	21–60	5	4	3	2
	61–100	4	3	3	2
Crop cover (mustard, etc.)	0–20	5	5	4	3
	21–60	5	4	3	2
	61–100	4	3	3	2
Superficial tillage or ploughing	0–20	5	5	4	3
	21–60	5	4	3	2
	61–100	4	3	3	2
Harvesting operations					
For cut crops	0–20	4	3	3	2
	21–60	4	3	3	2
	61–100	4	3	2	1
For lifted crops	0–20	5	5	4	3
	21–60	5	5	4	3
	61–100	5	4	3	2

Class 1: highest cohesion values, i.e. minimum sensibility to erosion.
Class 5: lowest cohesion values, i.e. maximum sensibility to erosion.

where SLOPE, FRICTION and COHESION values (see Tables 1–3) result from combining the parameters (slope intensity, soil surface roughness, plant cover and crusting stage) observed in a particular pixel on a plot and where runoff volume is the value calculated by the STREAM model in the same particular pixel on the same plot. We thereby obtain a value that indicates the sensitivity to gully erosion for the corresponding pixel. High value indicates high gully erosion sensitivity. When the variables FRICTION and COHESION represent alleviating values to erosion, sensitivity to gully erosion depends only on the slope class and runoff volume. On the contrary, when they have a negative influence, the sensitivity to gully erosion may be 25 times higher.

2.2. Runoff concentration network modelling

Ephemeral gully erosion results from the hydrological connection between a runoff contributing area and a runoff collecting network (Ludwig et al., 1995). This network is composed of the major topographical waterways and of agriculture-induced waterways such as back furrows, ditches or wheel tracks. These topographical and agricultural linear features are prone to concentrate overland flow and to guide runoff towards the catchment outlet. The risk of ephemeral gully erosion is higher along this network; it is therefore important to locate it precisely before applying the model.

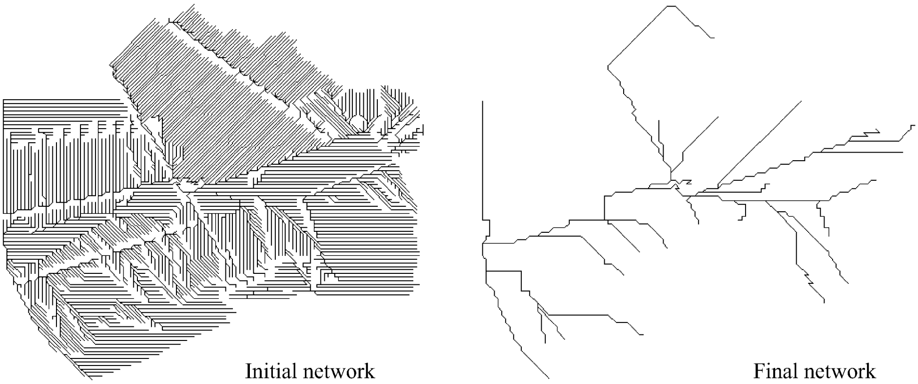

Fig. 1. Extraction of the runoff collector network (catchment 1).

To extract automatically the runoff collector network, we calculated the runoff flow direction at each point in the catchment using the discriminant function described by Souchère et al. (1998). This function determines whether the flow directions for slopes of up to 15% are dictated by the slope direction or the tillage direction. It can be applied to any location where roughness, slope intensity, aspect and tillage azimuth are known. The left side of Fig. 1 shows a general view of the runoff flow directions for a catchment. This is the initial situation with all the segments. The next step consists in defining two thresholds: the minimum drainage area and the minimum segment length, in order to keep only the main segments corresponding to the runoff collector network (Ludwig et al., 1996). The minimum drainage area threshold depends on the catchment morphology and field size. Its values are defined by the user until the resulting drawn network is comparable to the observed one. In the example given in Fig. 1, the drained area threshold is 0.6 ha. The intermediate network obtained is further simplified by applying the minimum segment length threshold based on the elimination of smaller peripheral segments (segments less than or equal to 80 m in this example). This last procedure enables us to obtain the final network (right side of Fig. 1) which is used by the *STREAM Ephemeral gully* module.

3. Application of the model to experimental catchments

3.1. Site description

The survey was conducted on four adjacent cultivated catchments (13–90 ha). Auzet et al. (1993) defined these units as areas hydrologically related to a relatively well-marked talweg (longitudinal profile) in the relief and corresponding to the ultimate ramification of a dry valley network. These catchments are located near Etretat, Normandy, France (latitude 49°40′N, longitude 0°15′E). They were selected because of their uniform loamy topsoil texture, which makes them particularly sensitive to crusting. Priority was given to catchments with a high erosion risk.

3.2. Method of field investigation

Each catchment was monitored by Ludwig (1992) during the 1991/1992 winter season, from October (beginning of sowing for winter crops) to February (beginning of seedbed preparation for spring crops). During this period, five observation rounds (one per month) were made to collect parameters for the runoff and erosion model (land use, soil surface crusting stage, roughness, plant cover, tillage direction). We have considered the aforementioned parameters as homogeneous at the field scale when soil characteristics were homogeneous. Hence, one observation per field was carried out during each observation round.

All the data listed above were prepared, digitized and structured into a geographical database integrated in the GRID raster module of the ARC/INFO GIS software. A 10-m grid cell size was chosen as a compromise between the original data precision and the degradation of the vector features accuracy when converted to raster. All the topographical data (slope intensity, aspect) are derived from a digital terrain model calculated using the contours from the 1:25,000-scale IGN maps.

In the five observation rounds, we located the ephemeral gullies on the runoff collector network. Measurement of the cross-sectional area was carried at least every 10 m along the gullies, where the cross-sectional area varied irregularly. Otherwise, measurements were more spaced out. Fig. 2 shows that erosion varies with catchments. For catchments C2 and C3, the percentage of eroded runoff collector network never exceeded 20% during the study period. The runoff collector network of catchment C3 remained erosion-free until February 1992, whereas erosion of catchment C1s network rose steadily from November 1991.

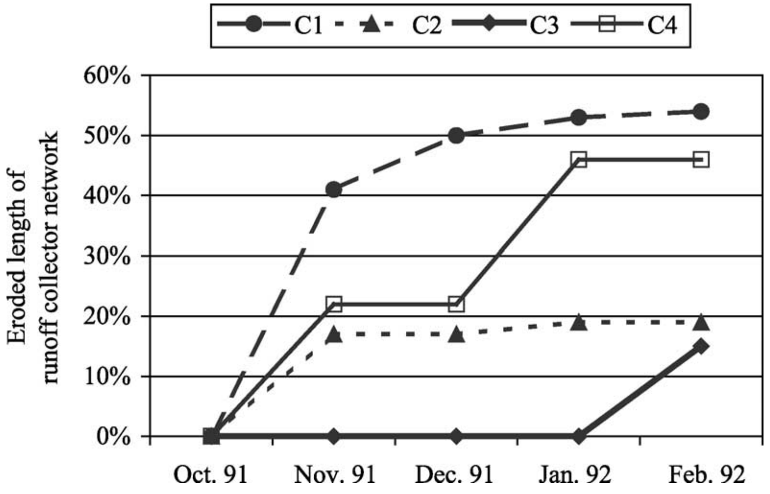

Fig. 2. Percentage of eroded runoff collector network during the study period.

Table 4
Characteristics of rainfall events

Rainfall event number	Date	Rainfall amount (mm)	Rainfall duration (h)	Average rainfall intensity (mm/h)	48-h antecedent rainfall amount (mm)
1	27/09/91	27.1	3.68	7.4	21.1
2	04/11/91	22.7	3.7	6.1	21.8
3	18/11/91	38.1	0.5	76.2	0.4
4	26/11/91	18.2	0.15	121.3	0
5	19/12/91	17.0	4.12	4.1	7
6	11/02/92	21.7	9.17	2.4	4.9

3.3. *Characteristics of rainfall events*

Within the study zone, an automatic rain gauge measured the rainfall intensity during the entire study period with a resolution of 0.1 mm. Analysing the data enabled us to identify rainfall events likely to account for modifications of topsoil layers and variations in the erosion level between each observation data. Table 4 shows the characteristics of rainfall events which have been used. Three rainfall events were selected in November 1991 (Numbers 2, 3 and 4). Event Number 2 was assumed to account for the November erosion while it was not possible to determine the contribution of the other two November rainfall events to the December erosion (no field observations were conducted between the 18th and 26th of November 1991). Therefore, we successively tested events 3 and 4.

4. Model results and discussion

To estimate the quality of the model, measured gully cross-sectional areas were compared with values calculated by the model. The measured data varied between 0 and 0.77 m^2 while simulated index calculated as the product of four parameters ranged between 0 and 10^7. To carry out a comparison between the measured cross-section areas and simulated index, they were distributed in six classes. Table 5 shows the class limits

Table 5
Class limits for each type of data and associated erosion level

Classes	Measured gully cross-section (m^2)	Estimated data	Erosion level
1	No erosion	0	No erosion
2	[0–0.1]	[0–1000]	Very low erosion
3	[0.1–0.2]	[1000–10,000]	Low erosion
4	[0.2–0.3]	[10,000–100,000]	Medium erosion
5	[0.3–0.5]	[100,000–1,000,000]	High erosion
6	>0.5	>1,000,000	Very high erosion

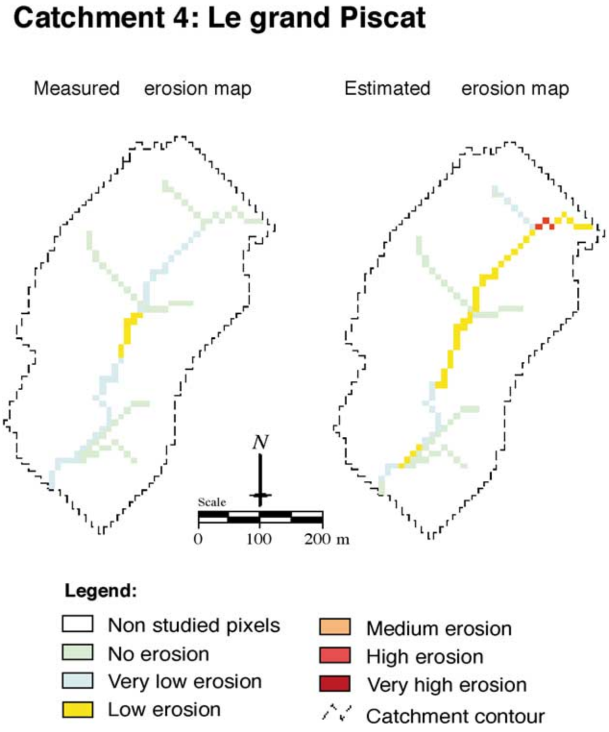

Fig. 3. Comparison between measured and estimated erosion.

which were selected for the measured data and simulated index. The first class is reserved for segments with no erosion. The five other classes are used to describe an increasing level of erosion. The selection of these class limits is based on the analysis of data distribution.

Fig. 3 is an example of the comparison between observed and simulated erosions according to previously defined classes. The map on the right side of the figure shows the erosion levels recorded during the January observation round. The other map shows the erosion level simulated by the *STREAM Ephemeral gully* model with December rainfall data (event Number 5). For easier comparison of the two previous maps, we calculated the difference between observed and simulated classes. For a pixel with a simulated erosion level higher than the observed erosion level, the calculated value is negative. The more negative this value, the more the model underestimates erosion. On the contrary, if the simulated erosion level is lower than the observed erosion level, the calculated value is positive. The more positive this value, the more the model overestimates erosion. When the difference is null, the simulated erosion shows very good coincidence with the observed erosion. Fig. 4 is an example of the difference between the two maps in Fig. 3. For the December rainfall event (event Number 5), the model can be seen to give rather good results. Over 91% of the pixels belong to the categories [− 1;1] which we consider as correct prediction.

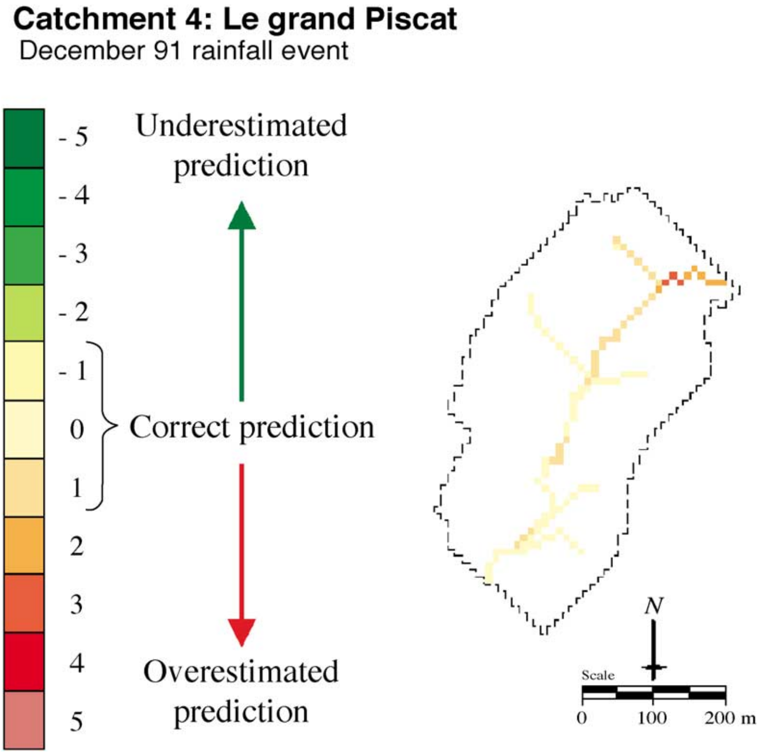

Fig. 4. Difference between measured and estimated erosion maps.

For each catchment and for each rainfall event investigated in this study, we calculated this difference between observed and simulated classes. Table 6 shows all the results. For all the catchments, the best correlation was obtained with the two last rainfall events: Number 5 in December and Number 6 in January. Our model can also be seen to have a tendency to overestimate the cross-sectional area of the simulated gully. The small number of measured data did not enable us to produce two sets of data. The first could have been used to develop the model and the second to calibrate it, and hence prediction could have been improved. However, Fig. 5 shows that the model allows correct estimation of the high cross-sectional areas. Most pixels relating to medium, high or very high erosion on the left map belong to the categories $[-1;1]$ on the right map. So, they are correctly estimated. On the other hand, this figure and also Table 6 confirm that the selected parameters of the model are not sufficient to predict no or low erosion.

For all the catchments, the first rainfall event used to estimate October erosion produced strong overestimated erosion. The model predicted erosion when there was no observed erosion in October. This is not surprising because the input data are those observed in October (no observation before this date), i.e. after the September rainfall event used for the simulation. Fig. 6 shows that 40% of the catchment area is already runoff contributing

Table 6
STREAM ephemeral gully result according to catchment and rainfall event

Rainfall event number	Surface state date	Measured erosion date	High underestimated prediction (values -5 and -4)	Underestimated prediction (values -3 and -2)	Correct prediction (values -1 to 1)	Overestimated prediction (values 2 and 3)	High overestimated prediction (values 4 and 5)
Catchment no. 1: La Ferme du Moulin (C1)							
1	Oct. 1991	Oct. 1991	0	0	26	55	20
2	Oct. 1991	Nov. 1991	0	0	50	48	2
3	Nov. 1991	Dec. 1991	0	0	10	59	31
4	Nov. 1991	Dec. 1991	0	0	16	73	11
5	Dec. 1991	Jan. 1992	0	2	43	53	2
6	Jan. 1992	Feb. 1992	0	5	56	40	0
Catchment no. 2: L'épine froidure (C2)							
1	Oct. 1991	Oct. 1991	0	0	9	73	18
2	Oct. 1991	Nov. 1991	0	0	13	85	2
3	Nov. 1991	Dec. 1991	0	0	0	67	33
4	Nov. 1991	Dec. 1991	0	0	17	83	0
5	Dec. 1991	Jan. 1992	0	0	0	99	1
6	Jan. 1992	Feb. 1992	0	0	3	97	0
Catchment no. 3: Le petit Piscat (C3)							
1	Oct. 1991	Oct. 1991	0	0	3	81	16
2	Oct. 1991	Nov. 1991	0	0	10	78	12
3	Nov. 1991	Dec. 1991	0	0	1	54	45
4	Nov. 1991	Dec. 1991	0	0	2	73	26
5	Dec. 1991	Jan. 1992	0	0	38	54	9
6	Jan. 1992	Feb. 1992	0	0	44	56	0
Catchment no. 4: Le grand Piscat (C4)							
1	Oct. 1991	Oct. 1991	0	0	31	68	1
2	Oct. 1991	Nov. 1991	0	0	45	55	0
3	Nov. 1991	Dec. 1991	0	0	14	76	10
4	Nov. 1991	Dec. 1991	0	0	21	78	1
5	Dec. 1991	Jan. 1992	0	0	91	9	0
6	Jan. 1992	Feb. 1992	0	8	87	5	0

areas in October. This percentage is sufficient to trigger off erosion as shown for catchment C4 with data from the November field round (Figs. 2 and 6). Therefore, to predict the erosion level more accurately, we should have used data observed before the rainfall event of 27/09/91, which was not available.

We have also detected other overestimated predictions, which are common to all the catchments. This overestimated prediction concerns the results obtained with rainfall events 3 and 4. In these two cases, poor prediction is probably due to the rainfall characteristics. Mean rainfall intensities, which can be calculated from data in Table 4 (76.2 and 121.3 mm h^{-1}), are well above seasonal average, and the runoff module of the STREAM model is not designed to account for such extreme events.

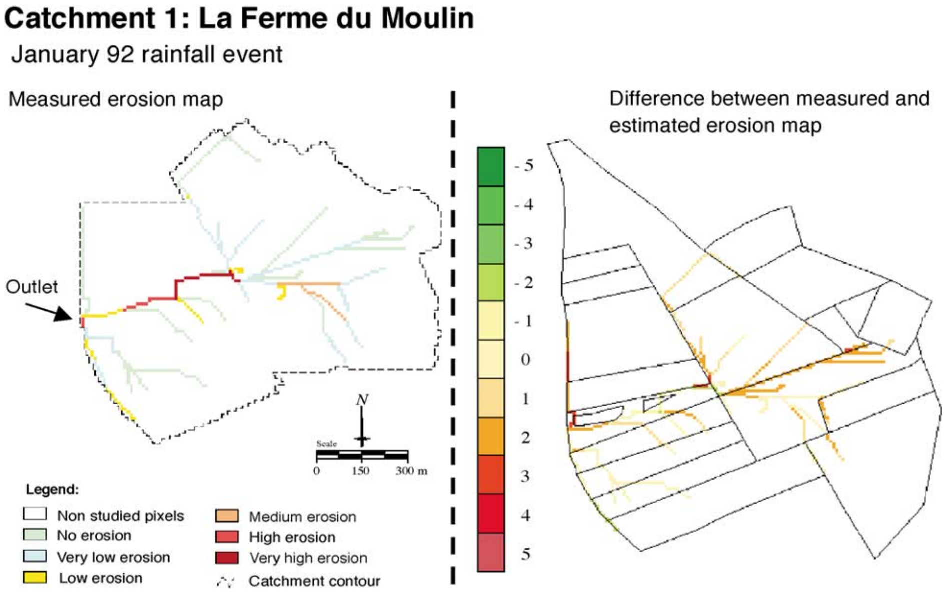

Fig. 5. Spatial location of correct estimation.

For catchments C2 and C3, the results, on the whole, are poor. As these two catchments are small (just five or eight plots per catchment), it is easier to analyse the situation and to find the source of the problem. Land use was the same (i.e. harvesting operation) for the two catchments during the November field tour (Fig. 7), but in December, the situation

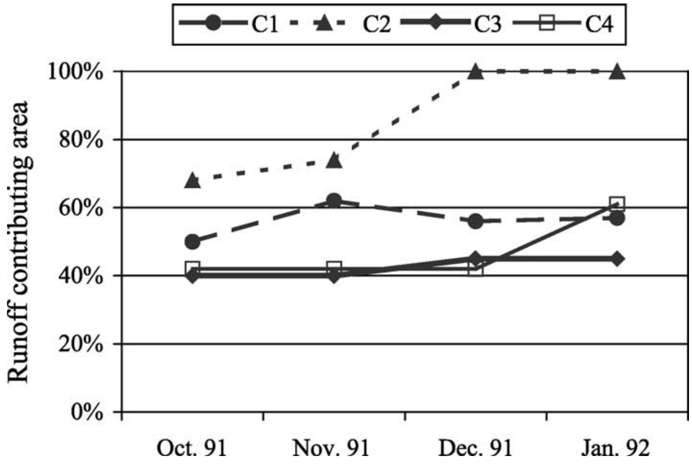

Fig. 6. Percentage of runoff contributing areas during the study period.

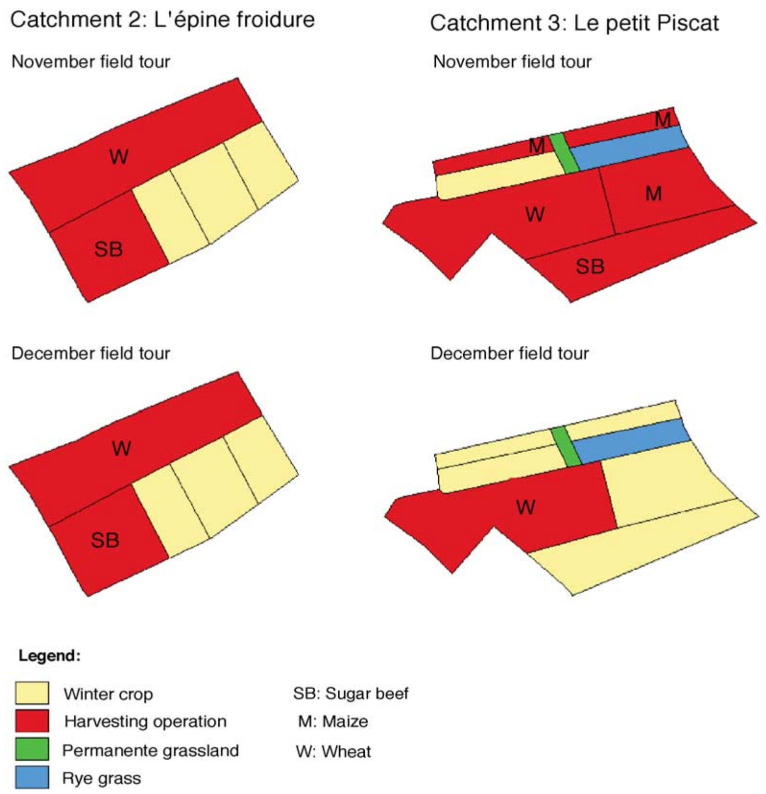

Fig. 7. Evolution of land use between November and December in catchments C2 and C3.

changed in catchment C3. Two land uses (sugar beet and maize harvesting operation) were replaced with winter wheat (Fig. 7). As this change coincides with a significant increase in the prediction quality (Table 6), the factor called COHESION was probably not well estimated for harvesting operations characterised by a high percentage of the field having compacted soil caused by agricultural machinery. The fact that the prediction for catchment C2, which kept the same land use during all the study period, was never improved confirms this assumption. The factor called COHESION needs to be revised and calibrated for all the land use classes. It must also take into account the effects of compaction due to agricultural machinery.

5. Conclusion and future prospects

The first results of this study show that the *STREAM Ephemeral gully* module, although not yet fully calibrated, could be used to predict ephemeral gully erosion level. The simplicity of the parameterization allows the model to be run without extensive and time-consuming experimental measurements. It should be possible to quickly integrate a change in agricultural practice for example. In addition, the prevailing economic context causes farmers to pursue productive and individual goals. In being individualistic, these goals result in a land management approach that is limited to the farm territory and does not take into account the continuity of the physical processes involved (Papy and Souchère, 1993). A model based on simple parameters which can be noticed by farmers themselves could encourage them to be aware of the influence of their agricultural practices at the catchment scale.

Other results show that the *STREAM Ephemeral gully* module is inclined to overestimate the cross-sectional area of the gully in some cases. The analysis of results enabled us to determine what probably caused the case of poor predictions, and we therefore have several directions in which to improve the model. Firstly, we must revise the values of Table 3 for some land use. We saw that the actual version of COHESION factor did not take into account the reduction of soil erosion risk due to compaction induced by the weight of agricultural machinery. When there are a lot of plots with harvesting operations, results are highly overestimated. Therefore, we will complete our knowledge database through new experimental results. We will study, for example, states of topsoil layers after harvesting operations and their consequences to runoff. Secondly, we have chosen a multiplication-of-factor type model for greater convenience, but we are not satisfied with this model structure. As Huang (1995) pointed out, this model structure implies that the effects of each factor on soil loss are independent of each other and the effects can be individually quantified if all other factors are kept constant. That is clearly not the case. For example, the effect of FRICTION factor is highly dependent on the SLOPE factor and on the runoff volume.

Thus, a new version of the model is being developed. This new model structure will include sediment detachment, transport and sedimentation processes (Cerdan, current thesis) in order to estimate combined ephemeral gully erosion and sheet erosion.

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