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Incorporating Surface Crusting and its Spatial Organization in Runoff and Erosion Modeling at the Watershed Scale

V. Souchere, O. Cerdan, Y. Le Bissonnais, A. Couturier, D. King and F. Papy*

ABSTRACT

In loamy areas of Northern Europe, soil erosion is a widespread phenomenon, despite low rainfall intensity and a gentle topography. Interactions between meteorological conditions, farming operations and topsoil texture bring about rapid and significant changes in the hydraulic properties of topsoil.

The processes involved in surface crusting are extremely dynamic and crust characteristics are often difficult to measure. Modeling infiltration into these crusts has led to the development of equations of varying complexity, ranging from simple empirical equations to numerical solutions of the Richards equation. Obtaining the parameters for the more mechanistic approaches remains a challenge.

The objective of our work is to develop a simple runoff and erosion model based on field experiments and knowledge about crusting and agricultural practices (tillage direction, roughness, location of dead furrows, etc.). The model calculates the total runoff volume for a rainfall event at any point in the watershed. This model is able to serve as a simulation tool in order to test several anti-erosion schemes and choose the more efficient scheme for a given context.

INTRODUCTION

In the Northern Paris Basin and in many areas of the loessian belt in Northern Europe, erosion is a widespread phenomenon, notwithstanding low rainfall intensity and a mild topography (Fullen and Reed, 1987; Boardman, 1990; Poesen and Govers, 1990; Papy and Douyer, 1991). Erosion results from interactions between meteorological conditions, farming operations and topsoil texture that bring about rapid and significant changes in the hydraulic properties of topsoil (Boiffin et al., 1988; Imeson and Kwaad, 1990; King and Le Bissonnais, 1992; Ludwig et al., 1995; Auzet et al., 1995; Auzet et al., 1998). Deterioration of soil infiltrability and surface water storage leads to the appearance of runoff at the origin of erosive problems.

The prediction of soil erosion by water has played an important role in the use, management, and assessment of land in most regions of the world. The major prediction tool used has been the Universal Soil Loss Equation (USLE) developed by Wischmeier (1978). In USLE and in other factor-based equations, the soil loss amount is approximated by a series of factors that quantify one or more processes and their interactions. Their utilization is accepted for erosion prediction at the field scale (Huang, 1995) but their ability to be used at another scale (watershed for example) in which the runoff-contributing areas can differ spatially from the areas contributing to sediment supply is uncertain (Wischmeier, 1976; Foster, 1990; Imeson and Kirkby, 1996).

For a better understanding of these spatial interactions, modelers are focusing on more physically based approaches sometimes supported by Geographic Information Systems (GIS) (Moore et al., 1993). Even in these more fundamental approaches that use mathematical representations, empiricism often remains as some of the factors are USLE-based (Laflen et al., 1991; de Roo, 1996) or deduced from statistical analysis. Many existing methods need equations of varying complexity, ranging from simple empirical equations to numerical solution of the Richard's equation. Theses methods require a large number of empirical inputs. Obtaining parameters for the more mechanistic approaches still remains a challenge.

Harris and Boardman (1990) considered an alternative approach to those mentioned above: the expert-system approach. It can handle databases containing qualitative information that is analyzed on a basis of expert knowledge. Two preliminary conditions have to be considered. Firstly, this approach operates most effectively within a local domain. Secondly, an important assumption is that some non-random relationship between the different parameters of the database exists. This approach offers the possibility to make database or expert knowledge directly applicable to field conditions.

This study has a dual aim. First, following the philosophy of the last approach, we develop a new runoff model based on field experiments and knowledge about crusting and agricultural practices (tillage direction, roughness, location of dead furrows, etc.). This expert-based model must allow the calculation of total runoff volume for a rainfall event at any point in the watershed. Secondly, this model must be able to serve as a simulation tool in order to test several anti-erosion schemes and choose the best for each situation.

After describing the studied area, we present a method, stemmed from experiments, that incorporates the rules of infiltration and runoff direction into the new model: STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Management). Then, we show an

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*V. Souchere, INRA-SAD Ile de France, RN 10 (Route de Saint-Cyr), 78026 Versailles cedex (France); O. Cerdan, Y. Le Bissonnais, A. Couturier, and D. King; INRA-Science du sol, Centre de recherche d'Orléans, BP 20619, 45166 Ardon cedex (France); F. Papy, INRA-SAD Ile de France, BP 1, 78850 Thiverval Grignon (France). *Corresponding author: souchere@versailles.inra.fr

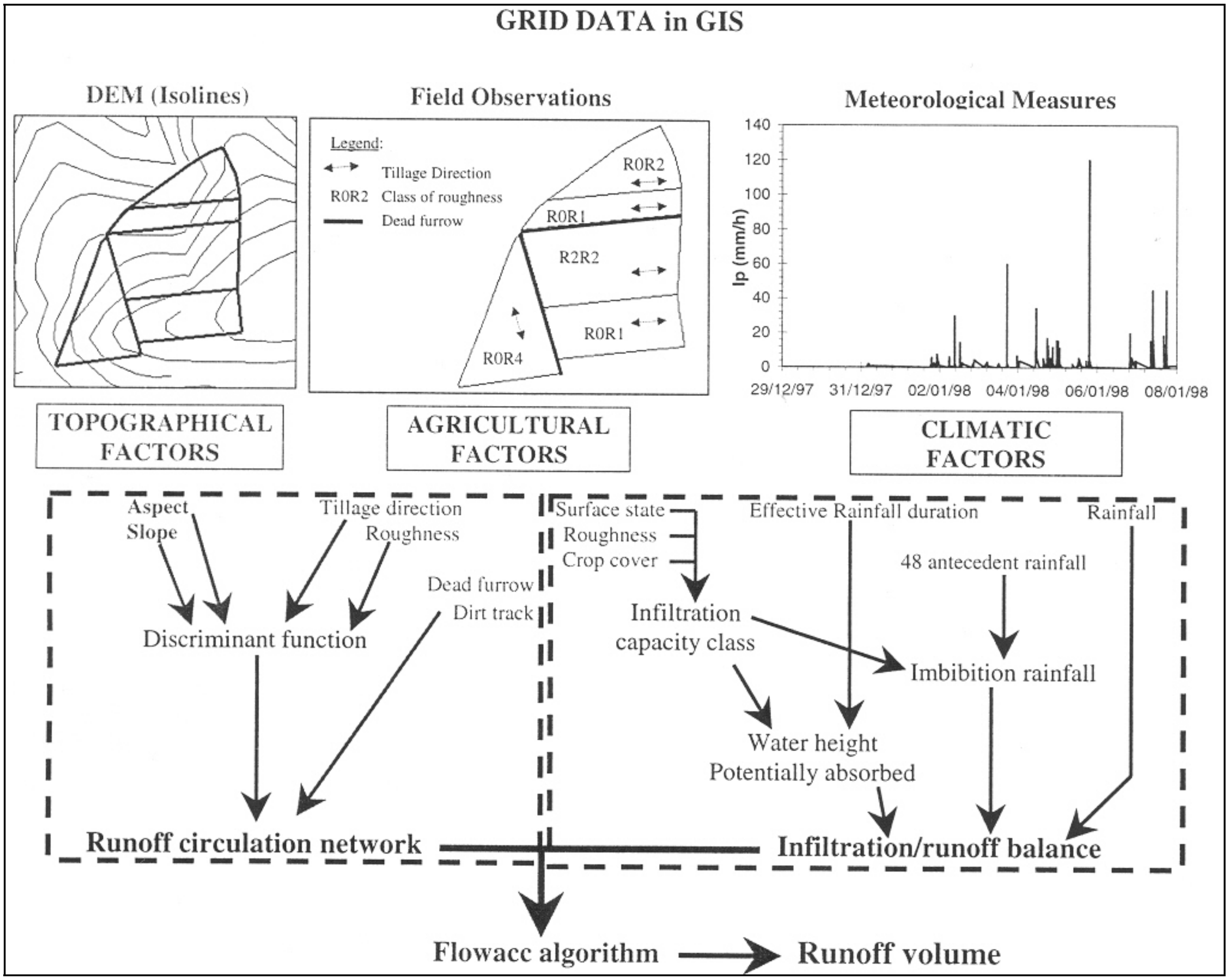

Figure 1. Outline of STREAM model with data inputs and outputs.

example of a simulation in order to test the effects of a land use modification in a watershed.

MATERIALS AND METHODS

The model was implemented with the Blosseville watershed (90 ha) located in the Pays de Caux region. The area is covered by loamy soils developed on the loess quaternary deposit and containing at least 60 % silt in the surface horizons. These soils are very sensitive to soil crusting resulting from low clay content (13 to 17%) and low organic matter content (1 to 2 %). The topography is gentle with 80 % of the slopes less than or equal to 2 %. The watershed consists of 99% intense cultivation and 1% grassland. Rainfall intensities are generally moderate (1 to 10 mm h^{-1} for 80 % of the rain amount). The mean annual precipitation varies from 800 to 900 mm.

The outlet of the watershed was equipped with a calibrated flume and an automatic water level gauge allowing continuous runoff output measurements. There were 143 rainfall events, including 93 where runoff occurred, identified during the period of study (the 93/94 agricultural year).

In addition to rainfall and runoff monitoring, each farm field of the Blosseville watershed was observed twice a month during the period of study. The observations had the objectives of monitoring the evolution of parameters inputted in STREAM.

The STREAM Model

The STREAM model is incorporated in a raster Geographical Information System (GRID module of the Arc/Info GIS). The advantages of linking the STREAM model with a GIS is that runoff and soil erosion processes vary spatially, so that cell sizes should be used that allow spatial variation to be taken into account (de Roo, 1998). Also, the data for the large number of cells required is enormous and cannot easily be entered by hand, but it can be obtained by using GIS. For example, it is the case for topographic data. One of the applications of STREAM is for planning and evaluating various strategies for controlling soil erosion and pollution from intensively cropped areas. Therefore, another advantage of using a GIS is the capability to rapidly produce modified input-maps with different land use patterns or conservation measures to simulate alternative scenarios.

The development and structure of the STREAM model is based on the synthesis of laboratory and field experiments carried out in the Pays de Caux for 15 years. Rainfall, infiltration and overland flow are incorporated in the form of an expert-system approach. STREAM is made up of two separate modules and a final algorithm that calculates total runoff volume for a rainfall event at any point in the watershed. Figure 1 shows the outline of the STREAM model with data inputs and outputs.

Infiltration module

The main parameters influencing infiltration in the studied context are: soil surface state, roughness, crop cover and moisture content (Le Bissonnais et al., 1998). These parameters will be discussed separately before we present the method used to combine them into an infiltration decision rule.

Because of soil texture, the soil surface state is a prevailing parameter that influences both the runoff rate and soil erodibility. The processes influencing surface crusting have been well studied, but their dynamic nature and their high spatial and temporal variability makes quantitative modeling extremely complex. Qualitative descriptions of crusting processes showed that it is possible to quantify the initial fragmentary stage - F0, structural crust - F1 and sedimentary crust - F2 (Boiffin, 1986; Bresson and Boiffin, 1990). Similar experimental studies showed that it is possible to assign an infiltration capacity to each stage (Boiffin and Monnier, 1986; Bradford et al., 1987; Le Bissonnais and Singer, 1993). In STREAM, a classification into four crusting stages has been used to monitor this parameter (Table 1).

Surface roughness is a dynamic property that influences numerous processes on the soil surface such as infiltration, temporary storage capacity, reflectance, deposition, or detachment of particles, etc. It has a rapid evolution under the influence of climatic agents and soil tillage (Zobeck and Onstad, 1987). Boiffin et al. (1988) made field observations that distinguished between several roughness classes. This classification, which was further refined by Ludwig et al. (1995), was used for characterizing soil roughness in the tillage direction as well as perpendicular to it (Table 2).

It is established that the interception of the rainfall by canopy cover has two main consequences. It provides protection from rain splash impact and it decreases the volume of water reaching the soil surface. In addition,vegetation (annual or perennial crops) and crop residues slowdown the overland flow. So, to take into account these effects, we distinguished three classes of crop cover: 1 from 0 to 20%, 2 from 21 to 60%, and 3 from 61 to

Table 1. Surface state evaluation.

Notation	Description
F0	Initial fragmentary structure, all particles are clearly distinguishable
F11	Altered fragmentary state with structural crusts
F12	Transitional: local appearance of depositional crusts
F2	Continuous state with depositional crusts

Table 2. Soil surface roughness evaluation.

Grade	Roughness index [a]	Typical agricultural situation
R0	0-1 cm	Strongly crusted sown fields, harvested fields with intense compacting
R1	1-2 cm	Sown fields with fine loosened or moderately crusted seedbeds
R2	2-5 cm	Recently sown fields with a cloddy surface, crusted tilled fields without residues
R3	5-10 cm	Stubble-ploughed fields and recently sown fields with a very cloddy surface
R4	> 10 cm	Ploughed fields

[a] Difference in the heights of the deepest part of microdepressions and the lowest point of their divide.

Table 3. Runoff sensitivity relative category according to the main parameters. In brackets are the infiltration value for the silty soils from the Pays de Caux region (mm/h).

		Crusting Stage			
Roughness	Crop Cover	F0	F11	F12	F2
4	3	0 (50)	0 (50)	0 (50)	2 (10)
	2	0 (50)	0 (50)	1 (20)	2 (10)
	1	0 (50)	1 (20)	1 (20)	2 (10)
3	3	0 (50)	0 (50)	0 (50)	2 (10)
	2	0 (50)	0 (50)	1 (20)	2 (10)
	1	0 (50)	1 (20)	2 (10)	3 (5)
2	3	0 (50)	0 (50)	1 (20)	2 (10)
	2	0 (50)	1 (20)	2 (10)	3 (5)
	1	0 (50)	1 (20)	2 (10)	3 (5)
1	3	0 (50)	1 (20)	2 (10)	3 (5)
	2	0 (50)	1 (20)	2 (10)	3 (5)
	1	1 (20)	2 (10)	3 (5)	4 (2)
0	3	0 (50)	1 (20)	2 (10)	3 (5)
	2	1 (20)	2 (10)	3 (5)	4 (2)
	1	2 (10)	2 (10)	3 (5)	4 (2)

Table 4. Evaluation of the imbibition rainfall height (mm) as a function of antecedent rainfall and runoff sensitivity category for the Pays de Caux silty soils.

Runoff sensitivity category	48 hours antecedent rainfall height (mm)			
	0	1 to 15	16 to 40	> 40
0	20	15	12	8
1	15	12	8	5
2	12	8	5	2
3	8	5	2	1
4	5	2	1	0

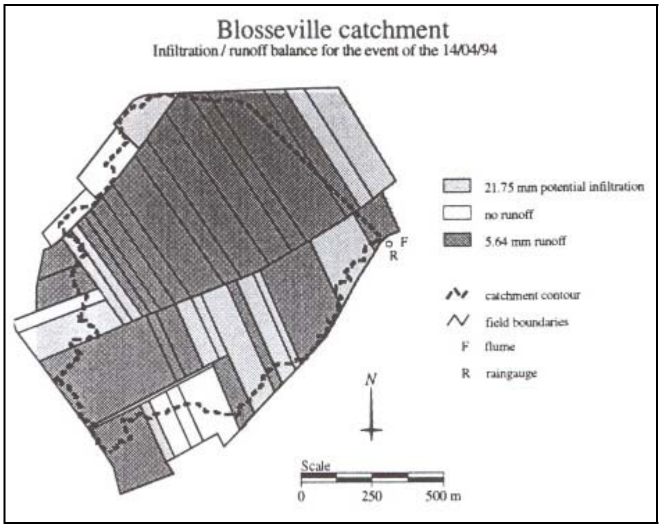

Figure 2. Infiltration / Runoff Balance values map.

Table 5. Runoff direction as a function of the types of objects.

Types of objects		**Runoff direction**
Field Crop (including headlands)	Difference in roughness > 2	Tillage direction
	Difference in roughness ≤ 2	Tillage or slope direction (decision as a function of statistical analysis)
Dead furrow		Furrow direction
Dirt tracks, roads		Direction of greatest slope

100%. These classes are expressed as a percentage of the area covered either by canopy or crop residues.

The potentially infiltrated water height for all the pixels and for a given rain is calculated by equation (1):

$$\text{Infiltration/Runoff Balance} = R - IR - \left(IC * t\right) \qquad (1)$$

With *R:* the rainfall amount in mm, *IR:* the imbibition rainfall amount in mm, *IC:* the infiltration capacity class in mm h^{-1}, and *t*: the duration of the rainfall in min.

For each cell, this equation indicates whether it will generate runoff (positive value) or on the contrary will infiltrate a potential upstream runoff in addition to the rainfall (negative value). Figure 2 show an example of Infiltration/Runoff Balance values map.

To characterize each field by an infiltration capacity for a given rainfall event, we combine the surface state, the roughness and the crop cover accordingly to their respective degrees of influence. For each combination of the parameters, we assigned an average potential value of infiltration capacity ranging from 2 mm h^{-1} to 50 mm h^{-1} (Table 3). Category 4 represents the combination having the best potential to generate runoff.

Working at the time step of the rainfall event implies the necessity to characterize the soil moisture content at the beginning of the rain. Several antecedent rainfall indexes exist that can be used without direct measurements of this parameter. In our context where evapotranspiration is reduced, we obtain a good approximation with the antecedent rainfall amount. A good correlation between runoff and antecedent rainfall amount was achieved with the 48 hours antecedent rainfall amount (R48) (Benkhadra, 1997). The imbibition rainfall height for each field was established from the combination between antecedent rainfall and infiltration capacity class (Table 4).

Runoff flow-direction module

The preferential pathways for water circulation are influenced by man-made agricultural factors (Ludwig et al., 1995; Auzet et al., 1998). Some of the factors are permanent, such as roads and ditches dug for evacuating water. Other factors appear and disappear as part of agricultural practices, such as dead furrows, ruts, ridges left by certain cropping operations such as the harvesting of sugar beets or digging up potatoes and the roughness induced by tillage operations.

Data obtained from the watershed plots was introduced into the GIS in order to modify runoff circulation directions according to rules based on field observations or resulting from statistical analysis (Table 5). Dirt tracks are linear elements that retain the usual behavior of the standard model towards water flow movement when converted to raster form. In other words, runoff from one cell is directed to the lowest surrounding cell. On the contrary, well identified dead furrows, ditches and embankment slopes behave as streams: runoff is forced along the down sloping direction imposed by these linear features. In raster form, for each cell, unless direction of the feature coincides with that to the lowest surrounding cell, the flow will be forced into another direction.

Within agricultural plots, modeling of runoff direction employs data derived from the DEM (aspect and slope intensities) and data from farm fields (tillage direction and roughness). Tillage direction was converted to raster from the parcel data layer and then combined with aspect in order to compute the slope angle. Slope intensity and angle were used by a discriminant function. This function determines whether flow directions for slopes of up to 15% are imposed by slope direction or tillage direction. It can be applied to any location where roughness, slope intensity, aspect and tillage azimuth are known. A detailed description of the discriminant function is referred to by Souchère et al. (1998). Outputs of this module are a flow-direction grid.

Flow-accumulation algorithm

This last step is the calculation of the flow accumulation for each pixel of a watershed by combining the outputs of each module: Flow-direction grid and Runoff/Infiltration balance grid.

A FORTRAN program was written and incorporated in ARC/INFO. This new function uses the Runoff/Infiltration Balance grid to calculate the infiltration ration of the upstream runoff. The flow-direction grid serves as a reference to respect transfer between cells. Figure 3 shows an example of the STREAM output: the runoff accumulation for an event and for the Blosseville watershed.

RESULTS AND DISCUSSION

Evaluation of the Simulated Overland Flow Patterns

To appreciate the changes induced by the introduction of man-made agricultural factors, we compared Simulated runoff Circulation Network (SCN) with the Circulation

Network derived from the DEM (DEMCN). Clear differences appear between the two overland flow patterns (Fig 4, line a and b). These modifications cause differences in the location of water concentration points in the watershed. This also indicates a modification in the location of erosive phenomena.

To be sure that the introduction of agricultural activities is relevant for better reflecting real water flow, we have also compared Observed runoff Circulation Network (OCN) to the two others simulated patterns (Fig 4, line c with line a and b). The area (1) stands for a convincing example that the determination of the runoff network of a watershed only based on topographical data is not sufficient. Field observations (OCN) show that the movement of water over the ground surface is partially determined by the orientated roughness direction. DEMCN with runoff always follows the slope direction, which does not allow it to reproduce the real patterns. On the contrary, in the areas (2) and (3), both DEMCN and SCN are in conformity with the field observations. For area (2), this is due to the thalweg, which is well marked in the topography. For area (3), this is due to the tillage direction, which is parallel to the main slope aspect. Except for localized areas, the runoff circulation network is accurately simulated by SCN.

The main drawback for the SCN is the drift induced by the use of the raster mode. The pixel, being square, only allows eight possible directions for the water to flow from aspect. Except for localized areas, the runoff circulation network is accurately simulated by SCN.

The main drawback for the SCN is the drift induced by the use of the raster mode. The pixel, being square, only allows eight possible directions for the water to flow from one cell to another. This means there is an approximation between two directions that form an angle of 45 degrees and thereby creates a maximal error of 22.5 degrees. When the water flows along the topography, the drift is limited. From one cell to another, the slope aspect and direction change and the drift compensates itself. On the other hand, when the water follows the tillage direction, the drift is transmitted along the flow path.

The comparison between observed and simulated overland flow patterns is an initial way to validate the STREAM Model. It is also being validated in the Blosseville watershed by comparing measured and simulated values of runoff volume at the watershed outlet. For the moment, we selected only eight representative hydrological data thatinclude a wide range of climatic conditions from rainfall events with no runoff response to heavy a storm that led to the flooding of downstream areas. For this first dataset of rainfall-runoff, the initial results are in satisfactory accordance (Table 6). It appeared that the model was sensitive to the definition of the duration of a rainfall event (Cerdan et al., in press). As a calibration, we calculated the «effective duration» of an event removing the momentary no-rainfall lapses in function of the mean rainfall intensity.

Other validations are currently in progress, on larger watersheds with a more diversified land use. Detailed validation results will be published in the future.

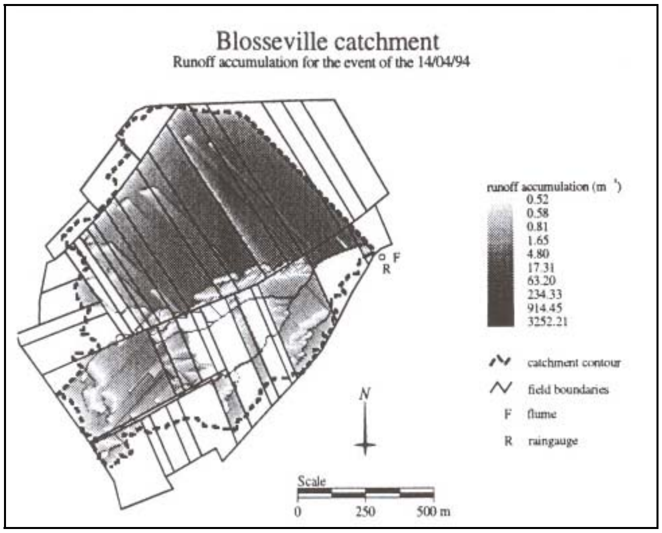

Figure 3. Runoff accumulation map.

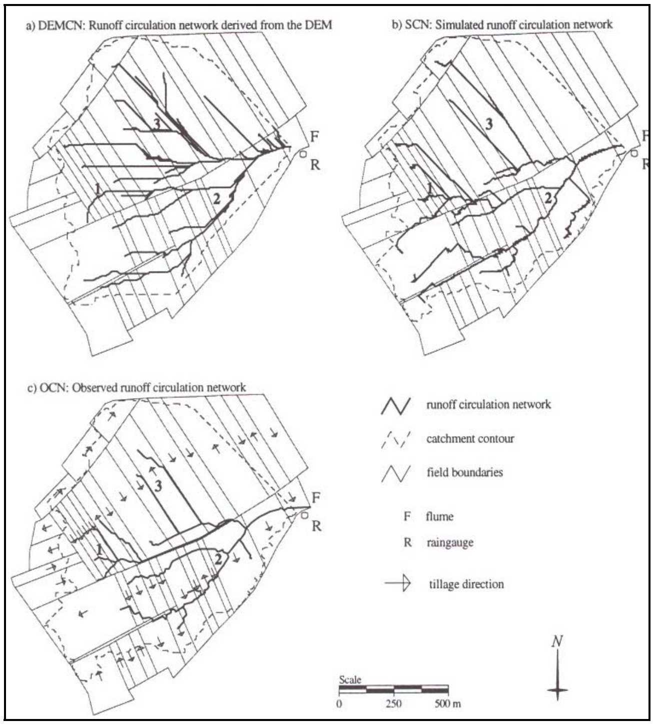

Figure 4. Runoff circulation networks map.

Application of STREAM

The prevailing economic context causes farmers to pursue productive and individual goals. They tend to consider erosion damage only insofar as it affects theirs outputs. So, it is difficult to enforce the adoption of practices designed to limit runoff, in the frequent cases where runoff does not trigger erosion on their own land. 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). The spatial response of the STREAM model in the form of runoff circulation maps can help farmers to become sensitive to the influence of their agricultural practices at the watershed scale.

When a farmer cultivates several neighboring fields, he will allocate the same crop to all the fields for reasons of labor organization and management. In the pays de Caux, this is often the case with the wheat crop. To show farmers the influence of this usual behavior, two different scenarios were simulated. For each scenario, we have only two types of fields but the location of runoff contributing areas (RCA) is different (Figure 5). In the first simulation, the RCA stand for 31 % of the watershed surface and fields generating runoff are scattered throughout the watershed surface. In the second simulation, the RCA stand for 30 % of the watershed surface and fields generating runoff are concentrated in the center of the watershed surface. Then, to compute flow accumulation for the two scenarios, we used the same real rainfall event. This event is characterized by a rainfall amount equal to 36 mm, a 48 hour antecedent rainfall amount equal to 0.7 mm and an effective duration of the rainfall equal to 13.98 hours.

For each scenario, the computed flow accumulations show the prevailing effect of the spatial organization of the fields (Figure 6). When the RCA are dispersed, the emitted runoff is progressively infiltrated. Only the runoff coming from the field close to the outlet is contributing to the total runoff volume. On the contrary, when the RCA are gathered, connectivity processes take place and the accumulated runoff concentrates. In this case, at the outlet, the total runoff volume is more than twice the amount.

CONCLUSION

Experimental results were used in the conception of an expert-based runoff model. This was done by taking into account the crusting phenomenon, which is known to have a prevailing effect on erosion processes and the modifications in the circulation network induced by the agricultural features. The results obtained with an initial set of validation data demonstrate the pertinence of this approach, particularly regarding the runoff accumulation network. The simplicity of parameterization allows the model to be run without extensive and time consuming experimental measurements. To change the values or the parameters of table 3 is enough to fit the model to another context. The simulation results show that STREAM is able to serve as a simulation tool as long as global response, in terms of event runoff amount, is sufficient.

When sediment detachment, transport and sedimentation processes are integrated, the model will allow the elaboration of several watershed scale management schemes in order to control soil erosion and pollution from intensively cropped areas. Research on more deterministic hydrological and erosion models is still needed in order to get a better dynamic response of a watershed within a rainfall event.

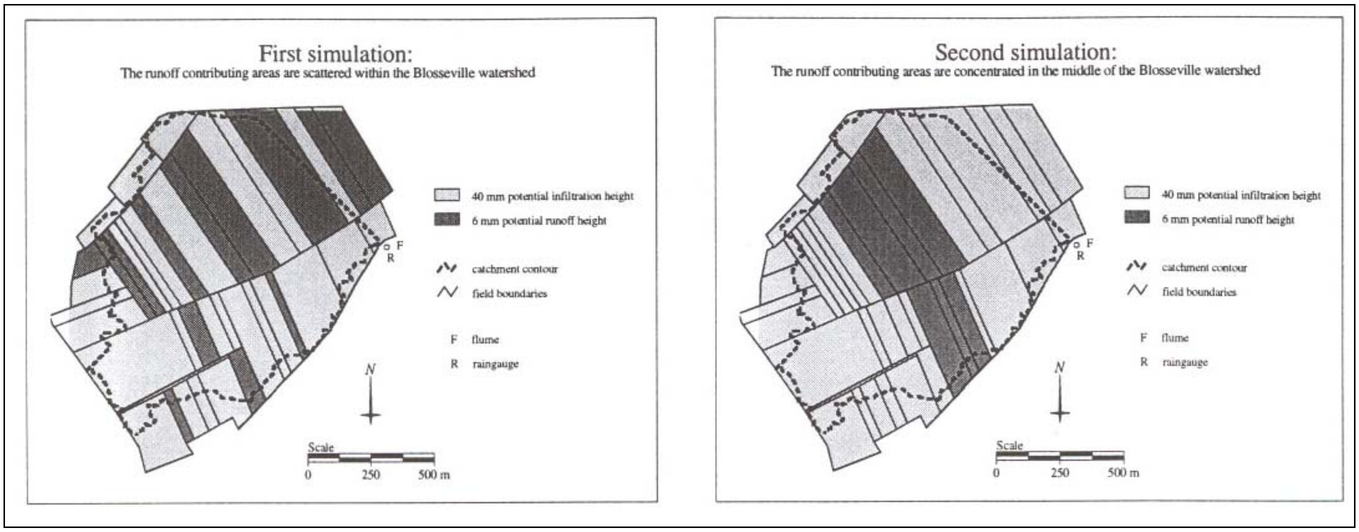

Figure 5. Simulated Infiltration / Runoff values map

Table 6. Comparison between observed and simulated water runoff height

Event n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Date	13/10/93	1/1/94	19/3/94	21/3/94	14/4/94	22/10/94	23/10/94	27/10/94
Total duration	24h19	6h30	4h54	8h07	32h03	2h42	19h25	24h32
Effective duration	8h13	2h03	2h42	3h52	9h18	2h42	5h37	7h07
Mean intensity (mm h^{-1})	1.68	1.37	1.55	1.02	0.75	2.97	0.77	0.88
Rainfall (mm)	40.9	8.9	7.6	8.3	23.9	8	15	21.7
Measured Runoff (mm)	6.82	1.48	0	0.04	1.81	0	0	0.84
Simulated Runoff (mm)	4.66	1.59	0	0	1.46	0	0.01	2.38

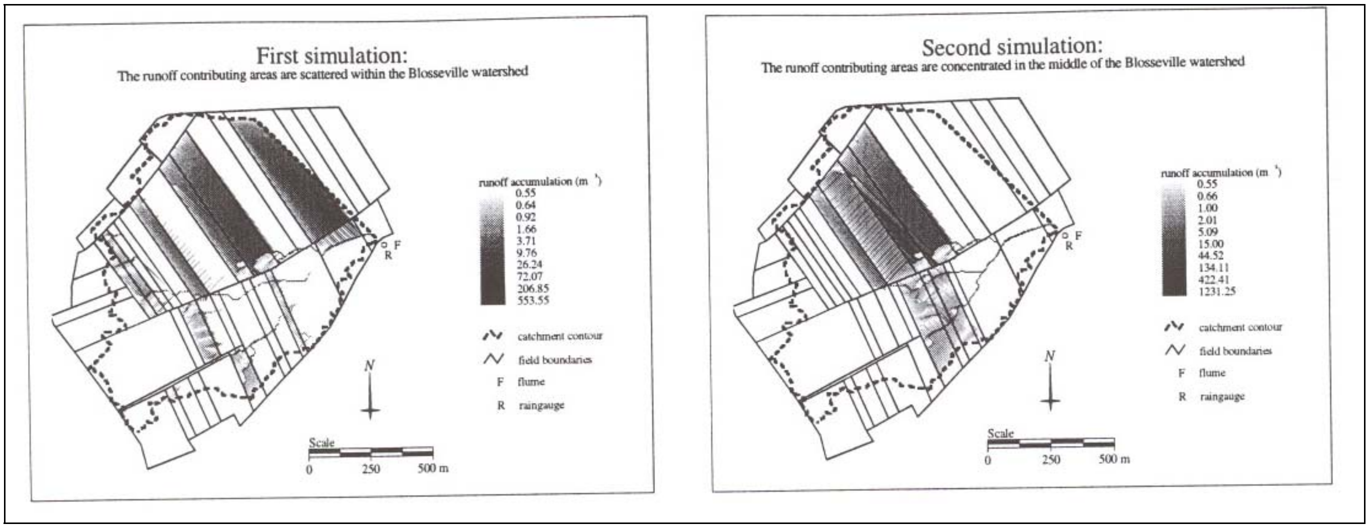

Figure 6. Simulated runoff accumulation maps.

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