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ABSTRACT

During the last decades, the European loess belt has been confronted with a significant increase in environmental problems due to erosion on agricultural land. Spatially distributed runoff and erosion models operating at the catchment scale are therefore needed to evaluate the impact of potential mitigation measures. Expert-based models offer an alternative solution to process-based and empirical models, but their decision rules are only valid for the local conditions for which they have been derived. The STREAM model, which was developed in Normandy (France), has been applied in two Belgian catchments having a similar soil texture, as well as in a catchment of southern France differing by soil, land use and climate characteristics. The performance of hydrological models can be assessed for instance by calculating the Nash–Sutcliffe efficiency criterion (E_{NS}). When applied to Belgium, the model results are satisfactory to good after an adaptation of the decision rules ($0.90 < E_{NS} < 0.93$ for runoff predictions and $0.85 < E_{NS} < 0.89$ for erosion predictions). Given the important environmental differences between Normandy and southern France, the model rules were also adapted for application in the latter environment. Unfortunately, the quality of runoff predictions was insufficient to simulate erosion in southern France. In conclusion, STREAM is a reliable model providing satisfactory runoff and erosion predictions in the regions where hortonian overland flow dominates. Nevertheless, an adaptation of decision rules based on local multi-scale (plot, field, catchment) data is needed, before running the model. STREAM can then serve as a decision support tool to design for instance flood control measures.

1. Introduction

During the last decades, a significant increase in environmental problems such as eutrophication, pollution of water bodies and reservoir sedimentation has been observed in Europe, as a result of soil erosion on agricultural land (Boardman and Poesen, 2006). Among these off-site impacts, muddy floods affect numerous villages of the European loess belt (Boardman et al., 2006) and induce high costs (e.g. between 16 and 172×10^6 € each year in central Belgium; Evrard et al., 2007a).

Mitigation measures are being implemented in some of the most affected areas, e.g. in Normandy, France (Souchère et al., 2003a), on the South Downs, UK (Boardman et al., 2003) and in central Belgium (Evrard et al., 2007a). Unfortunately, monitoring of runoff and erosion is rare and often implemented after mitigation measures have been established. Even if long term data representing the situation before establishing any mitigation measures would be available, these could hardly be used for an *ex-post* comparison because of the stochastic nature of heavy rainfall events dominating the erosion processes. In such a context, there is a need for reliable distributed models operating at the catchment scale and able to assess the impact of soil and water conservation measures. It is especially important to obtain good runoff/erosion predictions for heavy storms, as these storms generate the bulk sediment export from cultivated catchments (Steegen et al., 2000; Verstraeten et al., 2006a). Runoff and sediments produced by such storms also cause widespread muddy floods, leading to serious damage in downstream villages and infrastructures (Evrard et al., 2008a).

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Different types of erosion models have been developed in the past (see e.g. Jetten and Favis-Mortlock, 2006, for a review of models). The ability of empirical models (e.g. USLE) to integrate the dominant processes at the catchment scale is uncertain (Imeson and Kirkby, 1996), whereas process-based models require numerous input data that are generally not available and difficult to measure (Takken et al., 1999). In such a context, expert-based models (e.g. STREAM, Cerdan et al., 2002a) can offer an alternative solution. They focus on the dominant processes to avoid over-parameterisation and the associated uncertainties. The model simulations rely on decision rules derived by expert judgment from databases of field measurements carried out in a specific region. Even though the framework of these models is in theory applicable in similar areas, their main drawback is that these decision rules are only valid for the local conditions for which they have been derived. STREAM was designed on data from Normandy (Cerdan et al., 2002a) and it was successfully used to simulate the impact of different agri-environmental scenarios on runoff in this environment (Souchère et al., 2005). Soils in Normandy contain at least 60% silt in the topsoil and are very sensitive to soil crusting. Similar soil characteristics can be observed in other parts of the European loess belt, where the model should therefore be tested. Furthermore, this model should be applied to other contrasted environments differing by soil, land use or climate characteristics to evaluate its applicability after an adaptation of its decision rules.

The main objective of this paper is to test the expert-based erosion model STREAM in different European environments, after adapting the model decision rules to the local conditions. The exercise consists in modifying the model decision rules based on local databases. The model is then applied without any other way of calibration. The model will first be applied to two catchments in central Belgium. Secondly, STREAM will be run for a Mediterranean catchment. As a conclusion, the accuracy of the model predictions will be discussed, in function of the environment. The conditions to apply the model in other ungauged catchments will also be addressed.

2. Materials and methods

2.1. Description of the model

STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Management) is an expert-based runoff and erosion model at the small catchment scale (10–1000 ha). It is spatially-distributed, and lumped at the event-scale (Cerdan et al., 2002a). The model assumes that the following surface characteristics are the main determinants of runoff and infiltration at the field scale: soil surface crusting, surface roughness, total cover (crops and residues) and antecedent moisture content (Cerdan et al., 2002a). These characteristics are set for each field using classification rules developed by Le Bissonnais et al. (2005). This classification, derived from a database containing more than 5000 soil surface observations carried out in Normandy between 1986 and 1999, combines an evaluation of soil surface roughness [the height difference between the deepest part of microdepressions and the lowest point of their divide, in cm], soil cover by vegetation and residues [in %] and soil surface crusting [relying on the description of crusts provided by Bresson and Boiffin (1990)] for each field. A table is then used to assign a steady-state (i.e. the constant infiltration rate that is reached during prolonged rainfall) infiltration rate value to each combination of these soil surface characteristics. These values are obtained from field measurements under natural and simulated rainfall (e.g. Le Bissonnais et al., 1998; Evrard et al., 2008b). A runoff/infiltration balance (B_α) is then computed for each pixel α (Eq. (1)).

$$B_\alpha = R - IR - (I_\alpha \times t) \tag{1}$$

where R is the rainfall depth (mm); IR the amount of rainfall needed to reach soil saturation (mm) derived from rainfall depth during the 48 h before the event; I_α is the steady-state infiltration rate (mm h^{-1}) of the pixel α and t is the rainfall duration (h). Note that negative values of B_α correspond to infiltration and positive values to runoff.

For each event, the runoff flow network is then derived by combining two models: (i) a standard topographic runoff model (Moore et al., 1988) based on a DEM and redirecting runoff from one cell to the lowest of its eight neighbours and (ii) a tillage direction model developed by Souchère et al. (1998). This tillage direction model uses a discriminant function that drives runoff along linear landscape features (e.g. ditches, roads) and/or modifies the flow according to the tillage direction as observed in the field (Souchère et al., 1998). Based on the infiltration/runoff balance (Eq. (1)) calculated for each pixel, a Visual Basic Application (VBA) programme is then run in ArcGIS to determine flow accumulation at the catchment scale, taking account of the runoff flow network and allowing pixels to reinfiltrate the totality or a part of runoff generated upstream (Cerdan et al., 2002a).

Interrill and concentrated erosion modules have also been integrated into STREAM. Within the interrill erosion module, a table is used to assign a potential sediment concentration value (SC) to each combination of surface characteristics (Cerdan et al., 2002b). At the catchment scale, sediment is transported in proportion of the runoff volumes computed with the STREAM runoff module (Eqs. (2) and (3)), and is deposited as a function of topography (vertical curvature < −0.55, slope gradient <2%), or vegetation cover (Eqs. (4) and (5); see Cerdan et al., 2002c for details). Sediment is routed with the flow, and each pixel (having an area a) can correspond to (i) an area able to infiltrate a part or the totality of the upslope runon (Eq. (2)); and (ii) an area producing runoff (Eq. (3)).

(i) if $(R_e - I_\alpha t) < 0$, for a pixel α with i upslope pixels then:

$$md_\alpha = \sum mu_i + \frac{(R_e - I_\alpha t)a \sum mu_i}{\sum Vu_i} \tag{2}$$

where R_e is the effective rainfall and equals $R - IR$ (mm; see Eq. (1)); md_α is the mass of sediment leaving the pixel α (g); mu_i is the mass of sediment coming from upslope pixel i (g), Vu_i is the runoff volume from upslope pixels i (l), R is the rainfall depth (mm), I_α is the steady-state infiltration rate of the pixel α (mm h^{-1}), t is the rainfall duration (h) and a is the pixel area (m^2).

(ii) if $(R_e - I_\alpha t)a \geq 0$, for a pixel α with i upslope pixels:

$$md_\alpha = \sum mu_i + (R_e - I_\alpha t)aSC_\alpha \tag{3}$$

where SC_α is the potential sediment concentration (g l^{-1}) of pixel α.

For each pixel α, if:

$$\frac{md_\alpha}{(R_e - I_\alpha t)a + Vu_i} > SC_t \tag{4}$$

then

$$md_\alpha = [(R_e - I_\alpha t)a + Vu_i]SC_t \tag{5}$$

where SC_t is the threshold value (g l^{-1}) of sediment concentration above which deposition starts (see Cerdan et al., 2002c for details).

The module calculating gully erosion within the catchments (Souchère et al., 2003b) is based on slope gradient and parameters influencing runoff velocity or soil resistance (vegetation type, crop cover, soil roughness, soil surface crusting). It calculates the sensitivity to gully erosion (SGE) for each pixel α during a given rainfall event (Eq. (6)).

$$SGE_\alpha = B_\alpha \times S_\alpha \times F_\alpha \times C_\alpha \tag{6}$$

where B_α is the runoff/infiltration balance for the pixel α; S_α is a value based on the slope [%] of the pixel α; F_α is a friction value determined

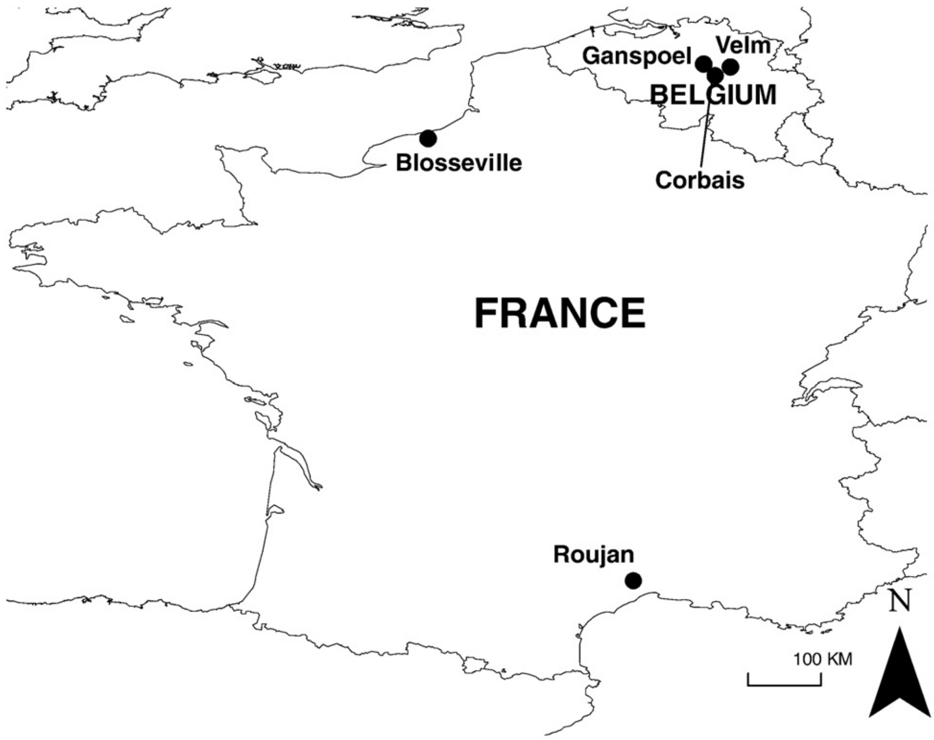

Fig. 1. Location of the sites (Ganspoel, Velm, Roujan) and the experimental field (Corbais) in Belgium and France. The Blosseville catchment where the STREAM model was developed is also mapped.

by a table based on winter land use, plant cover and soil surface roughness in the pixel α; C_α is a soil cohesion value determined by a table based on winter land use, plant cover and soil crusting stage in the pixel α (see Souchère et al., 2003b, for details).

A cross section of incision is then attributed to this SGE_α value, using a classification based on erosion field surveys (Ludwig et al., 1995). An erosion volume [m^3] is then obtained, by multiplying this cross section of incision [m^2] by the length of gullies [m] derived from the runoff flow network (Souchère et al., 2003b).

2.2. Study sites

The catchment where STREAM was developed (Blosseville, Northern France) as well as the study sites in central Belgium (Ganspoel, Velm) and Southern France (Roujan) are all located in regions where intensive agriculture dominates (Fig. 1). During the study period, the croplands in Belgium and northern France were ploughed using mouldboard ploughs (i.e. absence of conservation tillage). In Roujan (southern France), two types of agricultural practices are carried out

Table 1
Characteristics of the studied catchments.

Characteristic	Ganspoel	Roujan	Velm	Blosseville[a]
Location	Central Belgium	Southern France	Central Belgium	Normandy, France
Coordinates (outlet)	50°48′N, 4°35′E	43°30′N, 3°19′E	50°46′N, 5°8′E	49°51′N, 0°46′E
Topography	Plateau and valley	Succession Plateau(1)–Terrace(2)–Glacis(3)–Depression(4)	Dry valley	Dry valley
Area (ha)	111	91	300	94
Average field size (ha)	1	0.4	4.3	5
Geology	Loess	Marl–limestone	Loess	Loess
Soil classification[b]	Haplic Luvisols	(1)Chromic Luvisols (2)Calcaric Regosols (3)Calcaric Cambisols (4)Gleyic Cambisols	Haplic Luvisols	Haplic Luvisols
Soil surface texture				
% silt	70–80	15–58	78–80	57–61
% clay	7–15	10–38	8–12	11–13
% sand	5–23	4–75	10–12	25–27
% organic carbon	1	1–2	1	1
Average precipitation (mm yr^{-1})	750	650	750	850
Mean rainfall erosivity (MJ mm ha^{-1} yr^{-1} h^{-1})	580	1100	580	1050
Main land use	Intensive cropping	Vineyards	Intensive cropping	Intensive cropping

[a] The STREAM model was first developed in the Blosseville catchment.
[b] Soil classification after World Base Reference (1998).

in vineyards: (i) no tillage, with chemical weeding of the whole field or (ii) superficial tillage of the interrow and chemical weeding of the row (Léonard and Andrieux, 1998). A comparison of the main catchment characteristics is given in Table 1.

2.2.1. Blosseville catchment (Normandy, Northern France)

The Blosseville catchment (94.4 ha) is characterised by a humid temperate climate. Mean annual rainfall varies between 800 and 900 mm, with a high frequency of low to moderate intensity rainfall in winter. The most intense events occur in summer. Mean annual temperature reaches 13 °C, and annual potential evapotranspiration is 500 mm. The catchment has an undulating topography (mean slope of 4.6%), the slopes with a gradient between 5 and 10% covering less than 10% of the total surface. Soils are mainly Orthic Luvisols (World Reference Base, 1998). Main land uses are cropland (96%) and grassland (4%). Winter wheat (*Triticum aestivum* L.), high-protein and industrial crops have increased in the area over the last 30 years, at the expense of grassland and cereals such as rye (*Secale cereale* L.), leading to increased environmental problems, e.g. erosion and muddy floods (Souchère et al., 2003a). The water table is very deep (>7 m) and is therefore unlikely to generate saturation-excess flow. A detailed catchment description can be found in Cerdan et al. (2002d).

2.2.2. Ganspoel catchment (central Belgium)

Central Belgium is characterised by a humid temperate climate, with a mean annual rainfall of c. 800 mm. Rainfall is well distributed throughout the year, but erosivity shows a peak between May and September (Verstraeten et al., 2006a). Mean annual temperature ranges from 9 to 10 °C. The Ganspoel catchment (117 ha) is characterised by a dense network of dry valleys in a rolling topography, with slopes ranging between 0 and 20% (Van Oost et al., 2005). Most soils in the catchment are Haplic Luvisols (World Reference Base, 1998). Cropland is the main land use with a common rotation of winter cereals followed by sugar beets, potatoes or corn. A grassed ditch is installed in the thalweg. The water table is very deep (>10 m; K. Van Oost, personal communication) and is therefore unlikely to generate saturation-excess flow. A detailed description of the catchment can be found in Van Oost et al. (2005).

2.2.3. Velm catchment (central Belgium)

The Velm catchment (300 ha), described in detail by Evrard et al. (2007b) and characterised by the same climate conditions as the Ganspoel site (Section 2.2.2), is a dry valley characterised by gentle slopes (<5%). It is mainly covered by cropland and to a lesser extent by orchards (10% of the catchment surface). The acreage of row (corn *Zea Mays* L., potatoes *Solanum tuberosum* L., sugarbeets *Beta vulgaris* L.) and industrial (oilseed rape *Brassica napus* L., flax *Linum usitatissimum* L.) crops increased at the expense of winter cereals over the last decades in this catchment (Evrard et al., 2007a). The water table is very deep (>10 m; Flemish Environmental Agency, personal communication) and is therefore unlikely to generate saturation-excess flow. A grassed waterway has been installed in the downstream part of the thalweg in 2002 in order to mitigate muddy floods problems in the village located at the outlet (Evrard et al., 2008a).

2.2.4. Roujan (Southern France)

The Roujan catchment has a sub-humid Mediterranean climate with a long dry season in summer. Annual rainfall varies between 500 and 1400 mm, with two major rainy periods, in spring and autumn (Moussa et al., 2002). Rainfall mainly occurs as storm events in summer (Le Bissonnais et al., 2007). Heavy rainfall and soil degradation lead to a decrease of infiltration, which reduces agricultural productivity and can lead to catastrophic floods. The Roujan catchment (91 ha) is primarily agricultural, with hilly terraced slopes (15–20%) and a network of ditches (11 km) collecting runoff and conducting it up to the outlet. Soils in the catchment are classified as Luvisols, Calcisols and Cambisols (World Reference Base, 1998). It is divided into 160 fields and consists of four distinct geomorphologic units (Table 1; Léonard and Andrieux, 1998). There is a shallow phreatic aquifer with groundwater levels of 1–5 m below the surface on the plateau (Moussa et al., 2002). Vineyards are the most important land cover (70% of the catchment surface). The rest is occupied by fallow (16%), shrubland (6%), lucerne (*Medicago sativa* L.; 4%) and vegetables (3%). More information about the catchment can be found in Léonard and Andrieux (1998).

2.3. Adaptation of the STREAM decision rules based on field measurements

2.3.1. Surveys of soil surface characteristics

Soil surface characteristics data were available from field surveys carried out in the study sites during several years [see Le Bissonnais et al. (2005) for a detailed description of Blosseville surveys; Van Oost et al. (2005) for Ganspoel surveys; Evrard et al. (2008b) for Velm surveys; Louchart et al. (2001) and Moussa et al. (2002) for Roujan surveys]. All surveys were carried out according to the methodology developed by Le Bissonnais et al. (2005). Based on these surveys, the most common combinations of soil surface characteristics (i.e. those representing at least 2% of the fields surveyed) were retained, and their spatial distribution was mapped. Soil surface characteristics maps were thus available for the entire study period.

2.3.2. Rainfall simulations and plot measurements

STREAM decision rules have then been derived for the context of central Belgium, by associating I_α and SC_α values to the most common combinations of soil surface characteristics, based on two additional datasets:

(i) Steady-state infiltration rates determined by c. 60 rainfall simulations performed on 0.5 m^2-surfaces. They were carried out on the most common soil surface conditions, as determined by monthly field surveys in 65 fields located in three different catchments of central Belgium, in order to cover the variation of the soil surface characteristics throughout the year in fields where conventional tillage was applied (Evrard et al., 2008b). The rainfall simulations were systematically performed on three replicates.

(ii) 5-years observation (2001–2006) of soil surface characteristics, and measurement of rainfall and runoff from a single experimental field (3 ha) in central Belgium (Corbais, Fig. 1). This field has similar soil characteristics (Haplic Luvisol with 78% silt, 13% clay, 9% sand and 1% of organic matter; Hang, 2002) as the Belgian study catchments (Table 1). Evrard et al. (2008b) show that final infiltration rates in a plot and in a field remain of the same order of magnitude, given the calculated standard deviation (between 2 and 8 mm h^{-1}). A range of steady-state infiltration rates, determined during the rainfall simulations performed on three replicates can then be attributed to the corresponding combination of soil surface characteristics. Once the runoff remains constant, the steady-state infiltration is the difference between rainfall intensity and runoff rate.

For the Roujan catchment, I_α and SC_α values were attributed in the same way to the selected combinations of soil surface characteristics, based on the following local studies:

- Single ring infiltration experiments (Chahinian et al., 2006a,b);
- Rainfall simulations on 1 m^2-plots (Léonard and Andrieux, 1998; Andrieux, 2006).

Only the decision rules for runoff generation (I_α) and determination of potential sediment concentrations (SC_α) have been adapted for central Belgium and southern France. A range of values taking account of the variability of experimental measurements regarding infiltration and diffuse erosion is given for each combination of soil surface characteristics. The rules for ephemeral gully prediction described by Souchère et al. (2003b) have been applied without any modification, given they rely on slope and soil resistance characteristics.

2.4. Measurement of runoff and erosion export in the study sites

2.4.1. Runoff volume

Runoff volumes were measured in calibrated flumes installed at the catchment outlets, except in Velm where the flume was installed just upslope of the grassed waterway. Pressure sensors (i.e. ISCO-4220, ISCO, Lincoln, NE, USA) connected to data loggers were used to record the water height. Runoff discharge (Q; $m^3\ s^{-1}$) is calculated at each time step from the water height (H; m) in the flume using Eq. (7).

$$Q = a \times H^b = f(H, a, b) \tag{7}$$

where a and b are constants depending on the flume characteristics.

Lacas (2005) shows that the uncertainty on runoff discharge $\left(\frac{U(Q)}{Q}\right)$ is calculated using Eq. (8).

$$\frac{U(Q)}{Q} = \sqrt{\left(\frac{U(a)}{a}\right)^2 + (b \times \ln h)^2 \left(\frac{U(b)}{b}\right)^2 + b^2 \left(\frac{U(H)}{H}\right)^2 + \frac{2}{a}\ln(H) r U(a) U(b))} \tag{8}$$

where $r \sim -1$ (given a and b parameters are not independent and highly correlated).

Uncertainty on the water height measurements [$U(H)$] is provided by the manufacturers and typically ranges from 0.002 to 0.003 m for pressure sensors (ISCO documentation [$U(H) = 0.003$ m]). This error grows as water density increases (ISCO documentation), but we hypothesise that it remains negligible in our study, given the sediment concentrations measured at the outlets mostly remain under 10 g l^{-1}.

Cumulative runoff volume (V) during the i events is then calculated using Eq. (9).

$$V = \sum_i V_i = \sum_i Q_i \times \Delta t_i. \tag{9}$$

An uncertainty is also associated with this cumulative volume ($\frac{U(V)}{V}$; Eq. (10))

$$\frac{U(V)}{V} = \frac{\sqrt{\sum_i U(Q_i)^2}}{\sum_i Q_i} \text{ with } \Delta t = cst. \tag{10}$$

In our study catchments and based on Eqs. (8)–(10), errors associated with the measurement of runoff discharges and volumes typically reach 7–15%, which is consistent with errors obtained in studies carried out in similar catchments (e.g. Lacas, 2005).

2.4.2. Sediment export

Sediment samplers (i.e. ISCO 6700) were installed in the flumes at the catchment outlets. Rate of runoff sampling was flow-proportional. Numerous minor events occur whereas a few extreme events generate the bulk sediment export from cultivated catchments (Steegen et al., 2000; Evrard et al., 2008a). During these storms, sediment is considered to be well-mixed throughout the water column, which reduces the measurement errors when using samplers. Steegen and Govers (2001) investigated the problems related to the estimation of sediment export from cultivated catchments in central Belgium based on flow-proportional samples taken at a fixed height at the outlet. Since the slope of the energy line in the measurement section was assumed to be constant and equal to the slope of the thalweg where the measurements were carried out, errors on sediment concentration are mostly influenced by the water depth and the grain size distribution of the exported sediment. Steegen and Govers (2001) determined that the seasonal differences in crop type and rainfall characteristics resulted in different seasonal suspended sediment concentrations and grain size distribution in relation to water discharge (e.g. the percentage of grains > 63 µm is higher in winter than in summer for similar discharges). Based on these findings, they proposed a correction procedure. The measured sediment export (SE; t) can indeed be corrected (SE_{corr}; t) for each runoff event, depending on the season during which the event occurs as well as on the catchment characteristics. Steegen (2001) provided correction equations for Ganspoel (Eqs. (11), (12)) as well as for a 250-ha catchment which is similar to Velm catchment (Eqs. (13), (14)):

$$SE_{corr} = 0.936\,SE \quad \text{in summer (Ganspoel)} \tag{11}$$

$$SE_{corr} = 0.7836\,SE \quad \text{in winter (Ganspoel)} \tag{12}$$

$$SE_{corr} = 0.8594\,SE \quad \text{in summer (Velm)} \tag{13}$$

$$SE_{corr} = 0.7054\,SE \quad \text{in winter (Velm)}. \tag{14}$$

Based on Eqs. (11)–(14), we consider that we overestimated the sediment export values from the Belgian study sites by 7–15% in summer and by 22–30% in winter. Unfortunately, data required to calculate these equations are not available for the Roujan catchment.

2.5. Evaluation of the model results

The model has been run for those rainfall events recorded in the three catchments for which relevant surveys of soil surface characteristics were available (Table 2). Two single rainfall events are distinguished when there is a dry period of at least 6 h between them. Since a single I_α/SC_α value can be introduced into the model for each run, we successively ran simulations using the mean, maximum and minimum values for these parameters. Raster resolution of the model input data was 2–5 m, to take account of the linear landscape elements to derive the appropriate runoff flow networks. For each simulation, the accuracy of the simulated total runoff volume and sediment delivery has been assessed by calculating several goodness-of-fit indices.

Table 2
Characteristics of rainfall events used for STREAM evaluation.

Characteristic	Mean	Median	Standard deviation	Minimum	Maximum
(a) Ganspoel (n = 16)					
Rainfall (mm)	14.4	9.7	13.6	2.5	60.5
60 min-intensity (mm h^{-1})	23.1	15.5	21.8	7	82
Duration (h)	1.3	0.7	2.2	0.1	9.2
48 h-antecent rainfall (mm)	6.7	6.2	5	0	14
(b) Velm (n = 23)					
Rainfall (mm)	15.9	12	11.2	5	50
60 min-intensity (mm h^{-1})	52.3	45	24.6	15	120
Duration (h)	4.7	3	5.2	3	22
48 h-antecent rainfall (mm)	10.2	7.2	10.2	0	34.2
(c) Roujan (n = 20)					
Rainfall (mm)	31.7	30.1	23.6	3.7	96.1
60 min-intensity (mm h^{-1})	14.9	11.5	10.5	5	45
Duration (h)	3.5	2.4	4.4	0.3	18.8
48 h-antecent rainfall (mm)	6.8	1.4	10.8	0	34.5
(d) Blosseville (n = 18)					
Rainfall (mm)	14.7	10.5	10.9	3.3	40.9
60 min-intensity (mm h^{-1})	16.4	19.2	8.6	2.4	27.6
Duration (h)	3.6	3	2.7	0.7	9.6
48 h-antecent rainfall (mm)	29.8	32.8	17.4	2.9	58.1

Two single rainfall events are distinguished when there is a dry period of at least 6 h between them.

Table 3a
STREAM decision rules to derive the final infiltration rates (I_α; mm h^{-1}) in Normandy and central Belgium according to parameters of soil surface crust, roughness and vegetation cover [values for the silty soils of Normandy after Cerdan et al., 2002a; the infiltration values for the silty soils of central Belgium are given in brackets (after Evrard et al., 2008b)].

Roughness[a]	Crop cover[b]	Crusting stage[c]			
		F0	F11	F12	F2
R4	C3				
	C2				
	C1	45–55 (53–67)	15–25 (53–67)		
R3	C3				
	C2				
	C1	45–55 (53–67)	15–25 (53–67)	5–15 (43–57)	
R2	C3	45–55 (53–67)	45–55 (53–67)	15–25 (53–67)	
	C2	45–55 (53–67)	45–55 (53–67)	5–15 (43–57)	
	C1	45–55 (53–67)	15–25 (33–47)	5–15 (33–47)	
R1	C3	45–55 (53–67)	15–25 (53–67)	5–15 (43–57)	
	C2	45–55 (53–67)	15–25 (43–57)	5–15 (33–47)	
	C1	15–25 (53–67)	5–15 (33–47)	1–10 (15–25)	
R0	C3			5–15 (33–47)	1–10 (15–25)
	C2				1–5 (5–15)
	C1	5–15 (53–67)	5–15 (43–57)	1–10 (15–25)	1–5 (5–15)

[a] Soil surface roughness state (height difference between the deepest part of microdepressions and the lowest point of their divide). R0: 0–1 cm; R1: 1–2 cm; R2: 2–5 cm; R3: 5–10 cm; R4: >10 cm.
[b] Crop cover classes (defined after the soil surface percentage covered by canopy or litter). C1: 0–20%; C2: 21–60%; C3: 61–100%.
[c] Soil surface crusting stage. F0: initial fragmentary structure; F11: altered fragmentary state with structural crusts; F12: local appearance of depositional crusts; F2: continuous state with depositional crusts.

The coefficient of simulation efficiency (Nash and Sutcliffe, 1970) is given by Eq. (15).

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} (Y_{obs} - Y_{sim})^2}{\sum_{i=1}^{n} (Y_{obs} - Y_{mean})^2} \quad (15)$$

where Y_{obs} is the observed value; Y_{sim} is the simulated value and Y_{mean} is the mean observed value. E_{NS} values vary between minus infinity (poor model) and 1, with 1 indicating a perfect fit between observed and simulated values.

The coefficient of determination (R^2) indicates how well the Least Squares line fits the sample. The mean absolute error (MAE) enables to measure the estimation bias (Eq. (16)).

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} [\hat{y}_i - y_i] \quad (16)$$

where n is the number of observations; $\hat{y}_i$ and y_i represent respectively the calculated and the measured values of a variable.

The root mean square error (RMSE) enables to measure the accuracy of the estimation (Eq. (17)).

$$\mathrm{RMSE} = \left(\frac{1}{n}\sum_{i=1}^{n} [\hat{y}_i - y_i]^2\right)^{0.5}. \quad (17)$$

The average unsigned error (AUE) measures the error proportion in relation with the measured value (Eq. (18)).

$$\mathrm{AUE} = \frac{1}{n}\sum_{i=1}^{n} 100 \times \left|\frac{\hat{y}_i - y_i}{y_i}\right|. \quad (18)$$

2.6. Evaluation of the quality of spatial predictions

Runoff flow and erosion features have been mapped using a GPS in the Velm catchment directly after the event of June 14, 2006. This event has been surveyed because it consisted of a convective storm that activated an extensive runoff network within the catchment. Observed and simulated runoff patterns are compared.

3. Results

3.1. Central Belgium

3.1.1. Adaptation of the model decision rules

Among the 60 potential combinations of soil surface conditions, only 30 were observed in the field, and infiltration rates were therefore only defined for these 30 observed combinations. The range

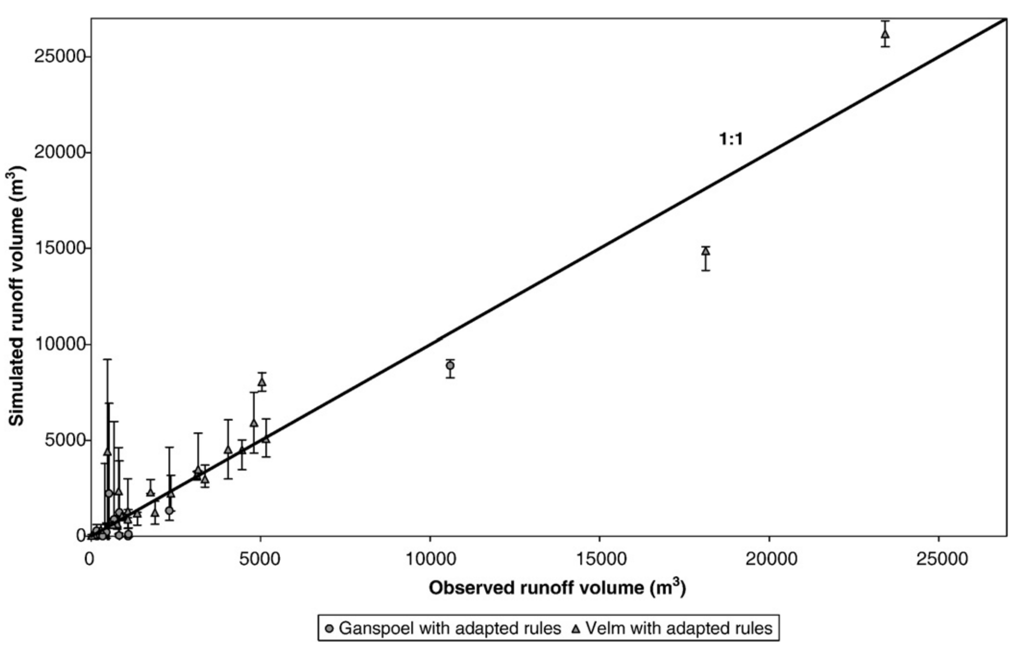

Fig. 2. Simulated vs. measured runoff volumes at the outlet of the Ganspoel catchment ($n = 16$) and at the upstream end of the grassed waterway (GWW) in the Velm catchment ($n = 23$) applying the adapted rules for central Belgium. Plotted volumes are calculated using the mean value of final infiltration (I_α) for each combination of soil surface characteristics. Vertical bars show the volume ranges obtained using the minimum and maximum infiltration rates.

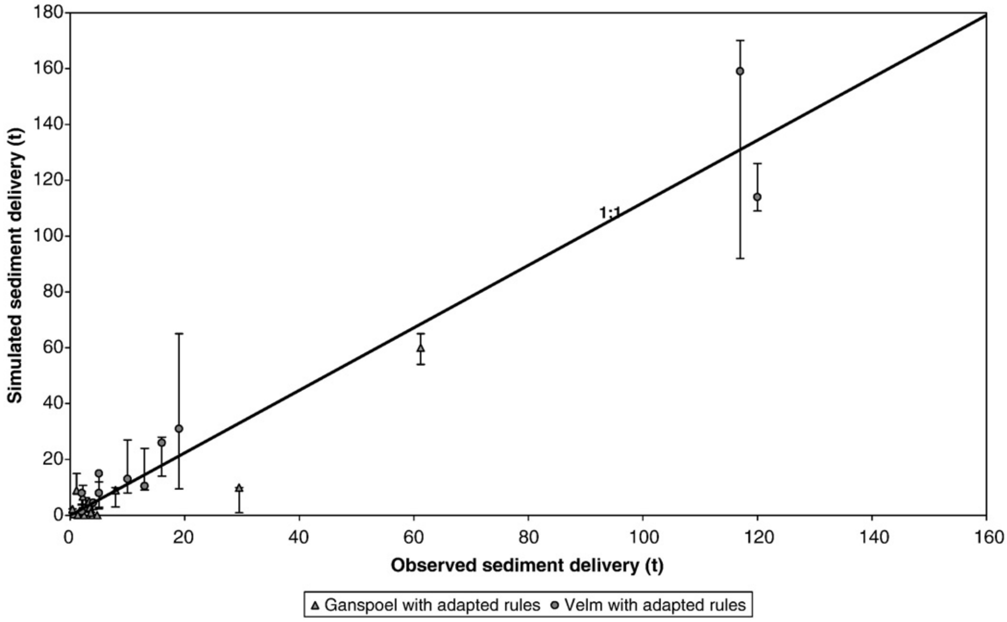

Fig. 3. Simulated vs. measured sediment exports at the outlet of the Ganspoel catchment ($n=16$) and at the upstream end of the GWW in the Velm catchment ($n=11$), applying the adapted rules for central Belgium. Plotted exports are calculated using the mean value of sediment concentration (SC_α) for each combination of soil surface characteristics. Vertical bars show the export ranges obtained using the minimum and maximum sediment concentrations.

of I_α values obtained for the three replicates of the rainfall simulations was attributed for each observed combination (Table 3a). Minor modifications were also made to SC_α values in a similar way, based on the results of the rainfall simulations (Table 4a).

3.1.2. Model simulations

The attribution of the maximum/minimum value of I_α/SC_α value ranges did not significantly modify the model results (generally up to 30% difference on average; which is for instance close to the uncertainty on sediment export measurements — 7–30% according to our estimations in Section 2.4). Similar results were obtained by Cerdan et al. (2002d) when applying the STREAM model in Normandy.

When the model is run with the rules adapted for the Belgian context, the best results are obtained when using the mean I_α/SC_α values into the model. Results regarding runoff are rather good, in both Velm ($E_{NS}=0.93$) and Ganspoel ($E_{NS}=0.90$; Fig. 2). Overall, the quality of the model predictions regarding runoff obtained after adaptation for central Belgium remains of the same order of magnitude as in Normandy ($E_{NS}=0.94$; Table 5). Sediment export is even better predicted in Belgium than in Normandy (Fig. 3; $E_{NS}=0.89$; for Velm; $E_{NS}=0.85$ for Ganspoel) when using the mean SC_α values. The quality of the erosion predictions (RMSE = 0.06 t ha^{-1} yr^{-1} in Velm and RMSE = 0.05 t ha^{-1} yr^{-1} in Ganspoel) is better than the error on sediment export measurements in these catchments (0.09–0.18 t ha^{-1} yr^{-1} in Velm; 0.5–1.8 t ha^{-1} yr^{-1} in Ganspoel).

3.2. Southern France

3.2.1. Adaptation of the model decision rules

The variation in surface roughness is lower for vineyards and therefore this parameter is not strictly required to explain runoff

Table 3b
STREAM decision rules to derive the final infiltration rates (I_α; mm h^{-1}) in Roujan catchment according to parameters of soil surface crust and vegetation cover.

Crop cover[a]	Crusting stage[b]		
	F0	F11	F2
C3		20–25	10–15
C2		15–20	5–10
C1	30–35	10–18	3–5

[a] Crop cover classes (defined after the soil surface percentage covered by canopy or litter). C1: 0–20%; C2: 21–60%; C3: 61–100%.
[b] Soil surface crusting stage. F0: initial fragmentary structure; F11: altered fragmentary state with structural crusts; F2: continuous state with depositional crusts.

Table 4a
STREAM decision rules to derive potential sediment concentrations (SC_α; g l^{-1}) in the flow for Normandy and central Belgium [rules for the silty soils of central Belgium are given in brackets].

Roughness	Crop cover	Crusting stage			
		F0	F11	F12	F2
R4	C3				
	C2				
	C1	10–15 (10–15)	25–35 (25–35)		
R3	C3				
	C2				
	C1	10–15 (10–15)	25–35 (25–35)	1–10 (1–10)	
R2	C3	5–10 (5–10)	15–25 (15–25)	10–15 (10–15)	
	C2	5–10 (5–10)	15–25 (15–25)	1–10 (1–10)	
	C1	10–15 (10–15)	20–30 (35–45)	5–15 (5–15)	
R1	C3	1–5 (1–5)	10–15 (10–15)	1–10 (1–10)	
	C2	1–5 (1–5)	10–20 (30–40)	1–10 (1–10)	
	C1	5–10 (5–10)	10–20 (30–40)	5–15(5–15)	
R0	C3			1–5 (1–5)	1–5 (1–5)
	C2				1–5 (1–5)
	C1	5–15 (40–50)	20–30 (35–45)	5–15(5–15)	1–5 (1–5)

Table 4b
STREAM decision rules to derive potential sediment concentrations (SC_α; g l^{-1}) in the flow for Roujan catchment.

Crop cover	Crusting stage		
	F0	F11	F2
C3		1–5	3–8
C2		3–8	5–10
C1	8–13	3–8	8–13

Table 5
Calculation of goodness-of-fit indices for the different evaluation datasets applying the rules adapted to the local context.

(a) Runoff volume

Index	Ganspoel			Velm			Roujan			Blosseville
	$n=16$			$n=23$			$n=20$			$n=17$
	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	
R^2	0.64	0.92	0.63	0.94	0.94	0.82	0.18	0.44	0.42	0.94
E_{NS}	−0.09	0.90	0.8	0.84	0.93	0.82	−7.89	−0.40	0.9	0.93
MAE (m^3)	781	−283	−147	1313	407	−424	575	−1613	−12.2	−121
RMSE (m^3)	1825	797	1528	2208	1446	2350	6097	2415	1843	397
AUE (%)	197	−24	−310	29	54	−21	173	91.7	−34	162

(b) Sediment export

Index	Ganspoel			Velm			Blosseville
	$n=16$			$n=11$			$n=11$
	Max.	Mean	Min.	Max.	Mean	Min.	
R^2	0.20	0.86	0.54	0.92	0.95	0.9	0.92
E_{NS}	−54	0.85	0.8	−39	0.89	0.89	−0.31
MAE (t)	4.4	−1.4	−4.35	14.7	7	−5.5	−4.9
RMSE (t)	14.3	5.8	11.5	22.6	14	8.9	7.9
AUE (%)	−15	144	−1966	42	63	−85	215

Maximum (Max.), mean and minimum (Min.) values of (a) I_α and (b) SC_α (Tables 3a, 3b, 4a, and 4b) were successively introduced when running the model.
Values for Blosseville catchment from Cerdan, 2001 (runoff) and Cerdan et al., 2002c (erosion). The number of events during which runoff volumes and sediment export were measured differs for Velm and Blosseville catchments because of the unavailability of erosion data during certain events.

generation and potential sediment concentration for fields located in Mediterranean areas where vineyards largely dominate the landscape. In vineyards under no-till, surface roughness remains constant throughout the year and is very low. In vineyards under superficial tillage, surface roughness is low after tillage and decreases afterwards along with the degradation of the soil surface (Corbane et al., 2008). A decay relationship of the steady-state infiltration rate due to cumulative rainfall after tillage was determined by Chahinian et al. (2006b) and used to attribute an infiltration value to vineyards. The low roughness is hence taken into account in an indirect way through the soil crusting parameter. Consequently, only the vegetation cover and the soil surface crusting parameters are taken into account to adapt the model decision rules for southern France (Tables 3b–4b). For the Roujan catchment, a range of I_α/SC_α values was also attributed to each combination of soil surface characteristics.

3.2.2. Model simulations

Runoff volumes are poorly predicted ($E_{NS}=-7.89$) when maximum I_α values are used (Table 5; Fig. 4). Overall, the average accuracy on prediction is rather low (RMSE = 6097 m^3) and runoff is overestimated (AUE = 173%). Sediment production was not simulated, given the bad quality of runoff predictions. However, when minimum I_α values corresponding to lower steady-state infiltration rates were used (Table 3b), the model results clearly improved ($E_{NS}=0.9$; Table 5). Unfortunately, these improvements were insufficient ($R^2=0.42$; Table 5) to simulate erosion within the catchment.

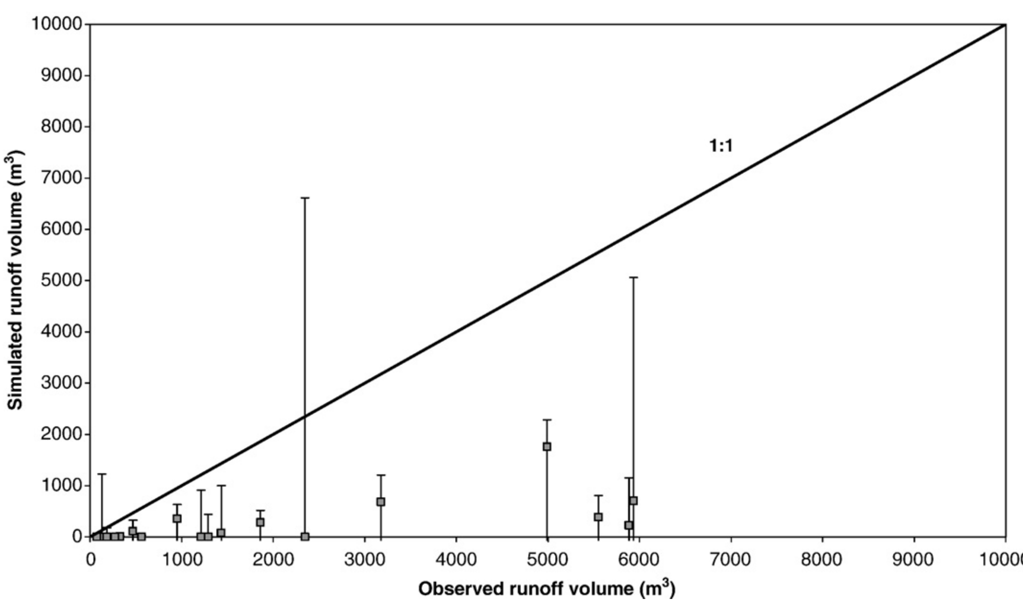

Fig. 4. Simulated vs. measured runoff volumes at the outlet of the Roujan catchment ($n=20$) applying the decision rules adapted for southern France. Plotted volumes are calculated using the mean value of final infiltration (I_α) for each combination of soil surface characteristics. Vertical bars show the volume ranges obtained using the minimum and maximum infiltration rates.

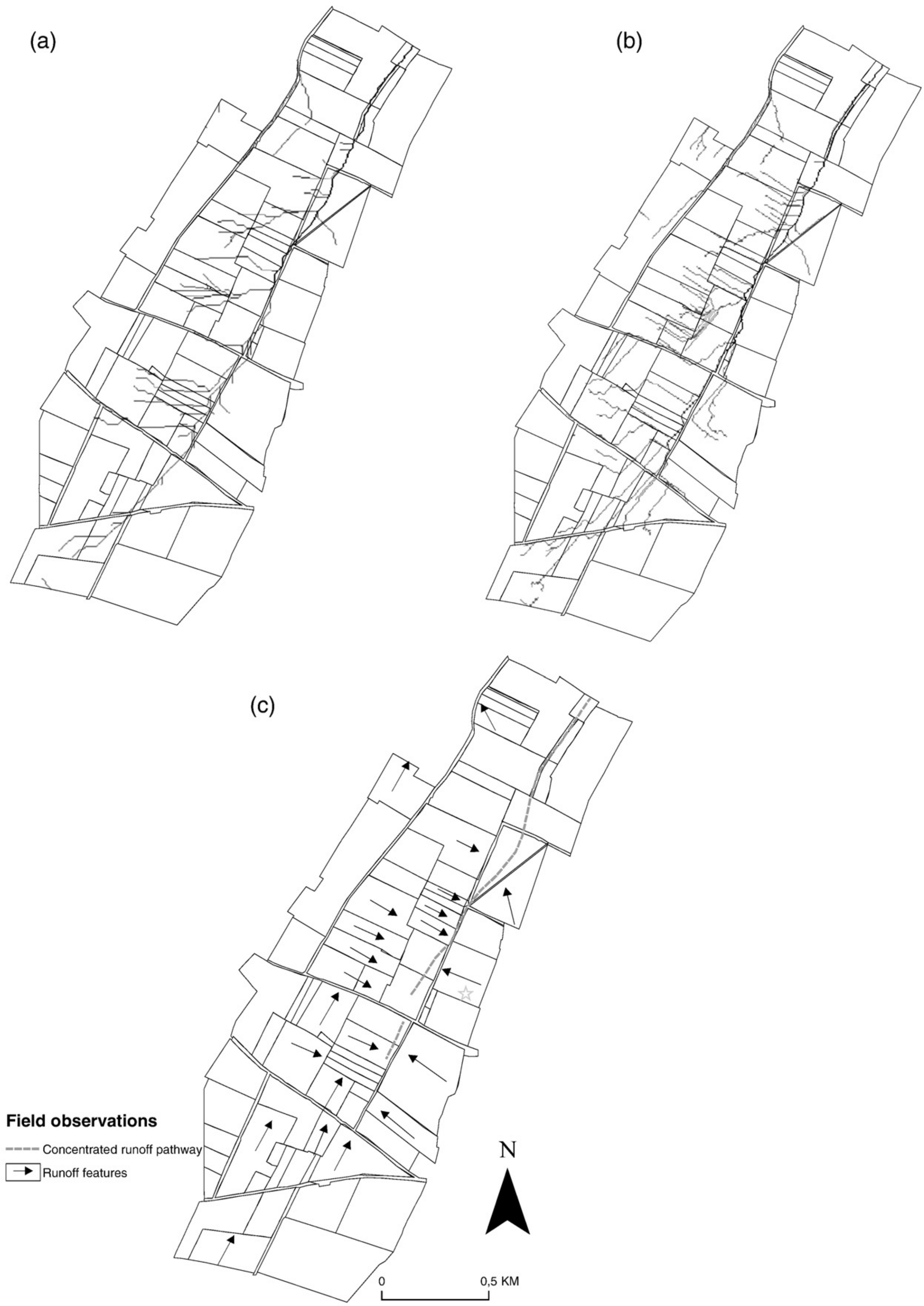

Fig. 5. Comparison of the maps of the runoff network for the event of June 14, 2006 in the Velm catchment. (a) Map provided by STREAM and derived from the DEM only; (b) map provided by STREAM and derived by combining the DEM, tillage direction and linear landscape features; (c) flow lines mapped in the field.

3.3. Quality of spatial predictions

During the event of June 14, 2006 in the Velm catchment, runoff was mainly generated on fields planted with summer crops (sugarbeets, peas *Pisum sativum* L., potatoes and carrots *Daucus carota* L.). Pathways of concentrated runoff have been mapped in the catchment after the event and are correctly predicted by the model (Fig. 5). The introduction of the tillage direction and landscape features (e.g. ditches, backfurrows, roads) in the model clearly improves its spatial predictions (Fig. 5b vs. a).

4. Discussion

4.1. Adaptation of STREAM to other catchments of the loess belt

Even though the process dynamics are rather complex as demonstrated by several laboratory experiments (see e.g. Fohrer et al., 1999), the cultivated soils in the European loess belt can be characterised by a decrease in infiltration rate following tillage and sowing, which is mainly driven by surface crusting. However, the range of final infiltration rates is consistently higher in Belgium as compared to Normandy (Table 3a). For instance, lowest mean infiltration rates reach 2 mm h^{-1} in Normandy vs. 10 mm h^{-1} in Belgium. Still there is no significant difference in soil texture between the two regions (Table 1). However, very slight differences in soil texture, such as the slightly coarser sand and loam in Belgium, could partly explain the different infiltration rates (Le Bissonnais, 1996; Legout et al., 2005). Most importantly, different local climate conditions and their interaction with the crop types and the farming practices can also explain the observed differences. In Normandy, an important area is planted with cereals, peas and flax in October and November (Joannon et al., 2006). Peas and flax require a very fine loosened seedbed, with highly fragmented clods. Such surface is prone to crusting due to the degrading action of cumulative rainfall. Since 55% of annual rainfall erosivity in Upper Normandy is observed between October and March, this leads to the progressive formation of a continuous soil crust (Fig. 6). Therefore, the lowest mean infiltration rate (2 mm h^{-1}) is observed in winter on such crusted fields in very humid conditions. In contrast, 72% of the annual rainfall erosivity in central Belgium is observed in spring and in summer (Fig. 6) and the lowest mean infiltration rates (10 mm h^{-1}) are observed on fields planted with summer crops in June (Le Bissonnais et al., 2005; Evrard et al., 2008b). During this period, the soil surface crust can also be locally disturbed by earthworm activity, which increases the soil infiltrability (Schröder and Auerswald, 2000; Lamandé et al., 2003). Moreover, large amounts of rainwater are absorbed by desiccation cracks during the early stages of rainstorms in summer (Schröder and Auerswald, 2000; Römkens and Prasad, 2006). In contrast, only minor differences are observed with respect to values of potential sediment concentration (SC_α) in the flow (Table 4a).

It must be stressed that the adaptation of the model decision rules for Belgium is based on independent measurements (Evrard et al., 2008b). The adaptation of the rules was achieved by introducing in the model final infiltration rates and potential sediment concentrations measured in the field. The best results are obtained when running the model after introducing the mean I_α/SC_α values, highlighting that these values are representative for a given combination of soil surface characteristics. Results obtained with the model are satisfactory to good in central Belgium after a local adaptation of the rules using those mean values ($0.90<E_{NS}<0.93$ for runoff; $0.85<E_{NS}<0.89$ for erosion). The model performance in central Belgium and in the area for which it was developed (Cerdan, 2001) are comparable for runoff. Erosion is globally overestimated by the model in central Belgium (63%<AUE<142%).

Furthermore, the model is much more efficient to predict runoff generated by convective storms ($E_{NS}=0.95$ for this type of events in Velm and Ganspoel) than during long-lasting and low-intensity events ($E_{NS}=-47$ for this type of events in Velm and Ganspoel; Fig. 7). This difference in model performance due to rainfall intensity can also explain the slightly better quality of runoff predictions in Velm (mean rainfall intensity of 52.3 mm h^{-1}; $E_{NS}=0.93$) compared to Ganspoel (mean rainfall intensity of 23.1 mm h^{-1}; $E_{NS}=0.90$). This is also reflected by a much higher variability of the runoff response, indicating a sort of 'staircase effect' when fields move up from one class of runoff to the one above. Even though saturation overland flow can be generated during winter wet periods in the European loess belt (e.g. Kwaad, 1991; Van Dijk and Kwaad, 1996), the occurrence of this type of events is unlikely in our catchments, given the groundwater table (generally >10 m). Furthermore, STREAM was not designed to simulate this type of low-intensity rainfall events. Obtaining good runoff/erosion predictions during low-intensity rainfall is beyond the scope of STREAM, since it has been designed to test different scenarios (e.g. crop changes, installation of erosion control measures) for which heavy thunderstorms are generally simulated (e.g. Souchère et al., 2005).

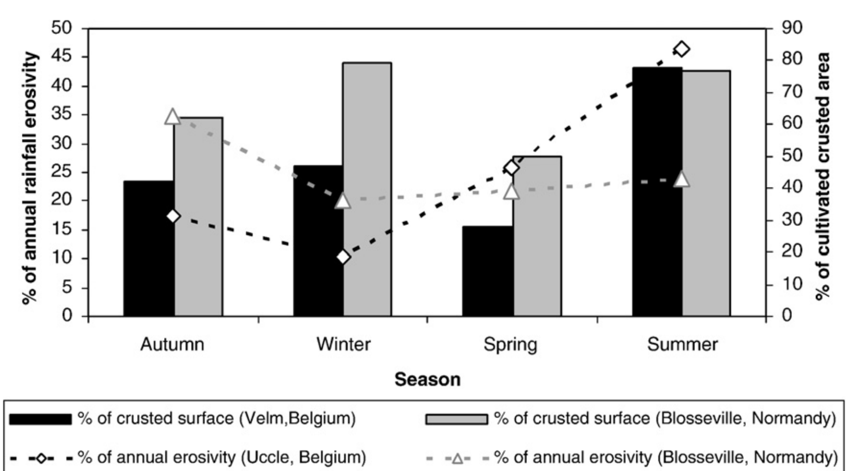

Fig. 6. Mean seasonal distribution of rainfall erosivity in central Belgium and Upper Normandy and percentage of crusted cultivated area (F12 and F2 crust stages). Belgian rainfall erosivity data from the Uccle station of the Royal Meteorological Institute, which is the reference meteorological station in central Belgium (Verstraeten et al., 2006b). French rainfall erosivity data (1993–2005) from the Blosseville catchment station (Guillaume Nord, personal communication). Soil crusting data available from field surveys carried out (i) on the 55 fields of the Velm catchment during the period 2003–2006 for central Belgium and (ii) on 600 fields of Upper Normandy during the period 1992–1998 (Le Bissonnais et al., 2005).

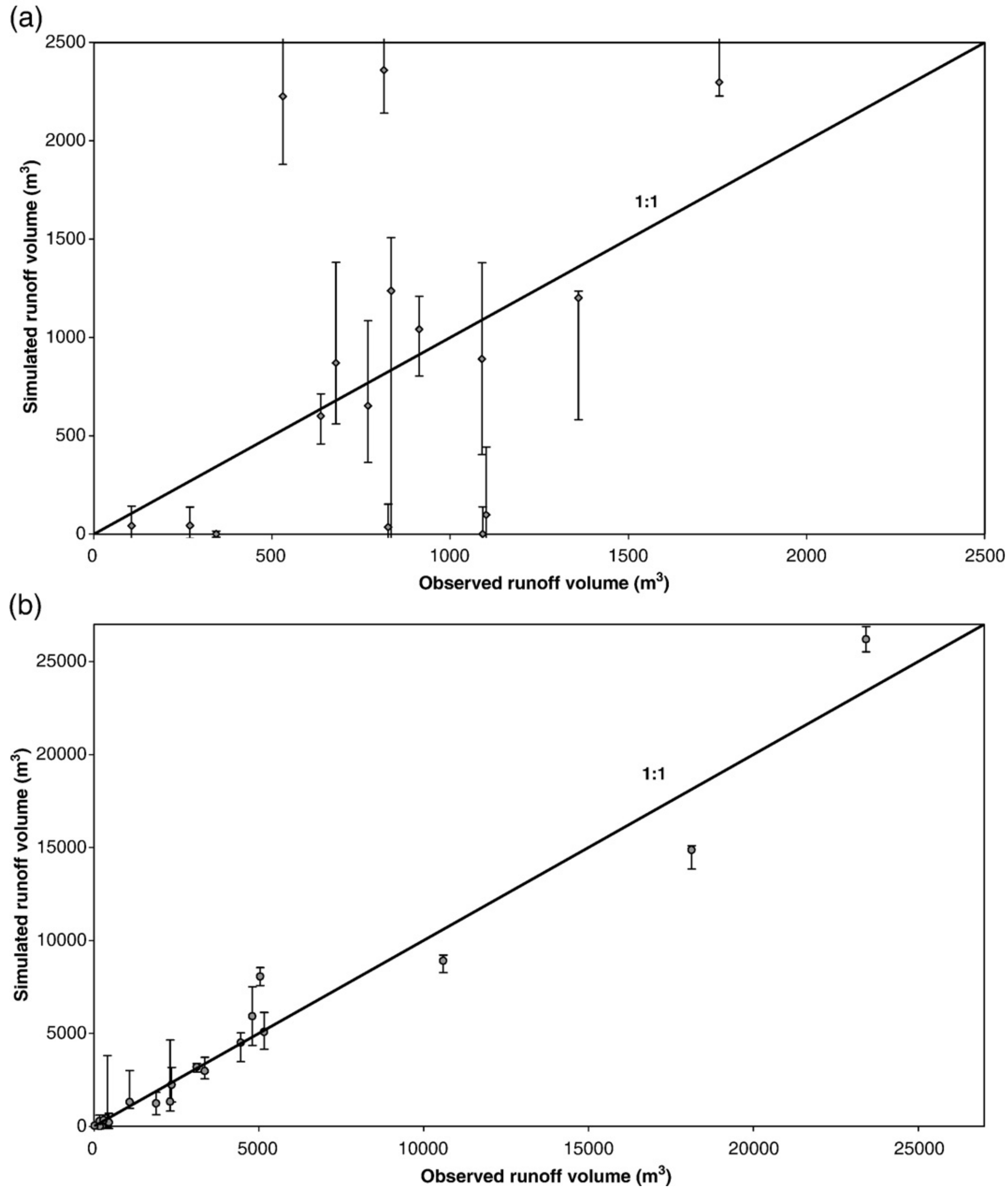

Fig. 7. Simulated vs. measured runoff volumes at the outlet of the Ganspoel catchment ($n = 16$) and at the upstream end of the GWW in the Velm catchment ($n = 23$), (a) for long lasting and low-intensity rainfall ($n = 19$); (b) for convective storms ($n = 20$). Plotted volumes are calculated using the mean value of final infiltration (I_α) for each combination of soil surface characteristics. Vertical bars show the volume ranges obtained using the minimum and maximum infiltration rates.

4.2. Adaptation of STREAM to a Mediterranean catchment

When applied to Roujan, the model is used in a very different climatic context than the one it was initially designed for. There is a larger variation in soil type within this Mediterranean catchment than in the European loess belt (Table 1), and the land use is dominated by vineyards. The hydrological processes involved are different. In the Roujan catchment, the groundwater level fluctuates between 1 and 5 m depth on the plateau, and hence temporary springs occur on the slopes to the valley bottom (Louchart et al., 2001). The model results for runoff using maximum and mean I_α values were unsatisfactory in Roujan. STREAM predicted no runoff when a small runoff volume was observed at the outlet. This runoff underestimation can be due to the fact that the ground water reaches the surface during some events (Moussa et al., 2002). This process generally occurs in winter, after long rain periods. In such saturated conditions, the water table feeds a base flow in the grassed ditches, which can explain the runoff underestimation by the model. However, even during winter, runoff is generally hortonian because of the occurrence of heavy rainfall on dry soils. Steady-state infiltration rates on these soils were probably overestimated when using maximum I_α values. By introducing the minimum I_α values (Table 3b), results regarding runoff in Roujan are clearly improved (Fig. 4; $E_{NS} = 0.9$).

4.3. Reliability of STREAM predictions and guidelines for further application

STREAM only provides satisfactory to good runoff/erosion predictions for events dominated by processes of hortonian overland flow, whatever the local climate conditions. In contrast, the model poorly predicts runoff/erosion in areas or during events dominated by saturation processes or rising of groundwater. The quality of the model runoff predictions (397 m^3 < RMSE < 1446 m^3) is satisfactory to simulate convective storms events (generating up to c. 25,000 m^3 in a 300-ha catchment for a 150 yr-event in June). Errors regarding sediment exports (0.04 t ha^{-1} yr^{-1} < RMSE < 0.05 t ha^{-1} yr^{-1}) are also acceptable for these events given the imprecision (0.09–0.49 t ha^{-1} yr^{-1}) on estimations based on measurements at the outlet.

There was no previous consultation between the French modellers and the Belgian users to adapt the model to the context of central Belgium. In the modellers' mind, the Belgian catchments were *a priori* located in the area where the decision rules developed for Normandy could be applied without any modification. However, the differences outlined in this paper show that a direct application of the French rules to other catchments in the European loess belt is not possible. A survey of soil surface characteristics similar to the one proposed by Le Bissonnais et al. (2005) must first be carried out. The observed combinations of soil surface characteristics must then be associated with steady-state infiltration rates, e.g. by the way of rainfall simulations. A classification of the monthly runoff/erosion risk associated with the common crops planted in the study area can then be carried out (see e.g. Evrard et al., 2008b for central Belgium) to avoid further field surveys and allow a widespread use of the model in a given area. This work can, however, be time-consuming if surveys of soil surface characteristics are not available *a priori*. After these preliminary steps, STREAM can provide estimations of the runoff volume/sediment export generated during a given storm in a cultivated catchment. Such results can help in designing flood control measures (e.g. a grassed waterway and earthen dams in a thalweg; Evrard et al., 2008a) or soil and water conservation measures in ungauged catchments.

5. Conclusions

STREAM provides satisfactory to good runoff/erosion predictions in environments or during events dominated by processes of hortonian overland flow, which is the case in the European loess belt. In contrast, the model results are poorer in environments dominated by hortonian runoff, but influenced by groundwater ridging. As shown in this study, expert-based models can perform satisfactorily if (i) the model rules are based on a good concept (i.e. decrease in infiltration rate of cultivated soils after sowing/tillage, mainly driven by surface crusting processes) and (ii) if the rules are adapted to the local context by assigning a measured final infiltration rate to the classes. Indeed, even though Normandy and central Belgium, both located in the European loess belt, are characterised by similar soil textures, differences in the range of final infiltration rates are observed between both regions. These differences mainly arise from a different distribution of rainfall throughout the year and its interaction with the crop type and the farming practices. The model framework is hence applicable in regions where hortonian runoff processes dominate, but the model decision rules first need to be adapted to the regional context, by combining plot, field and catchment measurements.

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