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Seasonal evolution of runoff generation on agricultural land in the Belgian loess belt and implications for muddy flood triggering

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Abstract

Muddy floods due to agricultural runoff are a widespread and frequent phenomenon in the European loess belt, and particularly in central Belgium. These floods are triggered when high quantities of runoff are generated on cropland and cause severe erosion. Three soil surface characteristics are relevant to determine the runoff potential of cultivated soils: soil cover by crops and residues, soil surface crusting and roughness. These characteristics have been observed on 65 cultivated fields throughout 2005. A heavy rainfall event representative for events triggering muddy floods in the region (60 mm h\textsuperscript{-1} during 30 minutes) has been simulated using a 0.5 m\textsuperscript{2} simulator on fields with the 17 most observed combinations of soil surface characteristics in central Belgium. In the case of (ploughed) bare uncrusted soils, runoff is not observed, nor in the case of soils covered by crops, showing a transitional crust and a moderate roughness (1-2 cm). In the cases where runoff has been observed, mean runoff coefficients ranged from 13\% (wheat in July) to 58\% (sugar beet or maize in May and June). Grassed buffer strips (GBS) and grassed waterways (GWW) show a higher runoff coefficient (62\% for GBS and 73\% for GWW) than most cultivated soils (13-58\%). Furthermore, it is demonstrated that small plot measurements can be used to estimate runoff generation at the field scale. A classification of runoff generation risk based on the surveys of soil surface characteristics has been applied to common crops of central Belgium. February as well as the period between May and September are the most critical for runoff at the field scale. However, it appears from monitoring of a 16ha-catchment that the highest

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runoff volumes and peak discharges are recorded between May and August after heavy rainfall, explaining why 85% of muddy floods are recorded during this period in central Belgium.

Key words:
runoff coefficient, steady infiltration rate, muddy floods, grassed areas, scale effect

1 Introduction

A muddy flood is defined as water flowing from agricultural fields carrying large quantities of soil as suspended sediments or bedload (Boardman et al., 2006). It is therefore a fluvial process rather than a mass movement one. In central Belgium, numerous villages are frequently affected by such floods (Vandaele and Poesen, 1995; Verstraeten and Poesen, 1999; Bielders et al., 2003; Evrard et al., 2007a). This situation is also reported from other countries in the European loess belt (Boardman et al., 1994), especially in Northern France (Souchère et al., 2003) and in the UK (Boardman et al., 2003). In central Belgium, about 90% of muddy floods are generated on hillslopes (10-30 ha) and in small catchments (30 - 300 ha; Evrard et al., 2007a). Rommens et al. (2006) calculated the Holocene alluvial sediment storage in a small river catchment (52 km²) of the Belgian loess belt. They found that sediment supply towards the flood plain has occurred at rates of 1.3 t.ha⁻¹.yr⁻¹ since the Medieval period, resulting in a gradual filling up of the Pleistocene river valleys. Since 50% of the sediment that was eroded from the hillslopes during the Holocene was stored in colluvial deposits mainly located in dry zero-order valley bottoms, muddy floods are the mostly likely process carrying sediments from the dry valleys and transporting them to the flood plains.

Nowadays, these floods occur when large amounts of runoff are generated on crusted cultivated soils. Mean rainfall depths required to trigger muddy floods are lower in May and June (25±12 mm) than between July and September (46±20 mm; Evrard et al., 2007a). Runoff and erosion are mainly produced in spring and early summer on fields with summer crops at an early development stage (Vandaele and Poesen, 1995). Processes such as slaking of aggregates, raindrop impact, microcracking and physico-chemical dispersion lead to the formation of a soil crust (Bresson and Boiffin, 1990). Several stages of crust development have been characterised. First, a structural crust is formed by local rearrangement of particles. Then, when particles are transported and

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For Peer Review deposited further away, a depositional crust can be observed (Valentin and Bresson, 1992). Crust development reduces the infiltration capacity as well as surface roughness. Oriented roughness describes the systematic variations in topography due to farm operations. Random roughness is related to soil clodiness and determines depressional storage (Onstad, 1984). Such soil surface features are important controlling factors for runoff. A typology of soil surface conditions of cultivated soils has been proposed in the context of the French silt loam soils (e.g. Bresson and Boiffin, 1990; Le Bissonnais et al., 2005). According to this method, surface crust development, roughness and vegetation cover are considered the most relevant dynamic characteristics for describing and classifying cultivated soils with respect to their potential for generating runoff and erosion (Le Bissonnais et al., 2005). This typology has been developed in the framework of a runoff/erosion expert-based model (STREAM, Cerdan et al., 2001). This model focuses on the dominant runoff/erosion processes to avoid over-parameterisation and the associated uncertainties. It is used as a decision support tool for the design of control measures against runoff and muddy floods. The main advantage of expert-based models is that they do not need as many input parameters and variables as physically-based models (e.g. LISEM, De Roo et al., 1996) which require for instance parameters for crust hydraulic properties. STREAM only needs steady infiltration rate and sediment concentration data. However, the main drawback of expert-based models is that the decision rules are only valid for the local conditions for which they have been derived. Although input parameters such as runoff coefficients fitted by trial and error yield reasonable results in hydrological models (e.g. Evrard et al., 2007b), this approach can lead to an equifinality problem (i.e. obtaining the right results for the wrong reasons), and should be avoided where possible (Beven, 2001). The measurement of the model input parameters in the field using a consistent methodology should decrease the risk of equifinality.

Several techniques exist to determine the field-saturated infiltration rate. Constant head infiltrometers have extensively been used, but the estimates are unreliable for stratified soils or when the crust is disturbed to install the infiltrometer (Léonard et al., 2006). In other studies, rainfall simulations have been carried out in the laboratory (Pan and Shangguan, 2006), or experimental plots exposed to natural rainfall have been monitored for runoff during several years (Léonard et al., 2006). However, to cover the whole range of soil surface conditions related to different types of land cover, numerous plots are needed. Furthermore, the occurrence of runoff remains highly uncertain over a period of a few years only. Consequently, rainfall simulations performed on selected surfaces representing the range of surface conditions observed throughout the year are more efficient. The problem is that rainfall simulations are carried out on small plots (generally up to 1 m$^2$) while required input (e.g. for STREAM) must characterise an entire field (typically 1 to 6 ha). Since a scale effect is likely to occur, the reliability of using micro-plot measurements to characterise...
a field must be investigated. For instance, Cerdan et al. (2004) calculated a significant decrease in runoff coefficient when the study area increased from 500 m$^2$-plots to catchments (90-1100 ha).

The objective of this paper is to characterise runoff generation on agricultural land in the Belgian loess belt, based on surveys of soil surface characteristics, rainfall simulations on microplots and field monitoring. More precisely, this paper aims: (i) to document the temporal variation of soil surface properties of agricultural fields in the Belgian loess belt by identifying the dominant combinations of characteristics observed throughout the year, (ii) to relate these combinations of soil surface characteristics to a final runoff coefficient and (iii) to develop a simple index to assess runoff generation risk at field and catchment scales. The implications of these findings for muddy flood triggering at the catchment scale will be discussed.

2 Materials and methods

2.1 Study area

The Belgian loess belt (c. 9,000 km$^2$) is a plateau with a mean altitude of 115 m and a topography gently sloping to the North (Fig. 1a). It is dissected by valleys having generally a North-South orientation. Most soils are loess-derived haplic luvisols (World Reference Base, 1998). Mean annual temperature ranges from 9 to 10 °C, while mean annual precipitation in central Belgium varies between 700 and 900 mm (Hufty, 2001). Rainfall is evenly distributed throughout the year, but erosivity shows a peak between May and September (Verstraeten et al., 2006). Arable land covers on average 65% of the total surface (Statistics Belgium, 2006). Main crops are winter wheat, industrial and fodder crops (sugar beets, maize, oilseed rape, and flax), as well as potatoes. Orchards are restricted to the northeastern part of the loess belt, around the town of Sint-Truiden (covering up to 65% of the total area in this region, vs. less than 5% elsewhere in the loess belt).
2.2 Experimental sites

The monitoring of soil surface characteristics and the rainfall simulations have been carried out in an experimental field (6 ha; Fig. 1 b), a hillslope (16 ha; Fig. 1c) and a catchment (300 ha; Fig. 1d) of the Belgian loess belt. These sites consist entirely of cropland, except for the largest one, which is also covered by c. 10% of orchards (Fig. 1d). They are characterised by common crop rotations alternating winter cereals and summer crops. In addition, several grass buffer strips (GBS) and a grassed waterway (GWW) have been installed in the 300 ha-catchment (Fig. 1d). Grass species consist of a mix of *Lolium multiflorum* Lam., *Lolium perenne* L., *Festuca rubra* L. subsp. rubra and *Dactylis glomerata* L. Haplic luvisols and haplic regosols are present in the three sites. A topsoil sample of haplic luvisols contains on average 18% sand (SD=14%), 60 % silt (SD= 31%) and 22% clay (SD=18%), as documented in the Aardewerk database restricted to the Belgian loess belt (Van Orshoven et al., 1988). Surface layers of haplic regosols contain on average 20% sand (SD=16%), 56 % silt (SD= 32%) and 24% clay (SD=18%). Mean soil organic matter content reaches c. 2% (Goidts and van Wesemael, in press). All study sites are equipped with tipping-bucket raingauges. Calibrated sharp-crested weirs and automatic water level gauges (Easylog 3000, Microware Software, Villanova d’Asti, Italy) are installed downstream of the 6-ha experimental field and the 16-ha hillslope. A crest stage recorder has been installed at the outlet of Sint-Truiden catchment to measure water level when runoff occurred. Such a recorder consists of a plastic tube with a length of water-sensitive tape which changes colour on contact with water (Table 1).

2.3 Soil surface characterisation

According to Le Bissonnais et al. (2005), the most relevant dynamic characteristics for characterising runoff and erosion potential of cultivated fields at a given time are: (i) surface roughness (Table 2a); (ii) the development of soil surface crusts (Table 2b); (iii) the vegetation and plant residue cover (Table 2c) and (iv) the presence of wheel tracks. These characteristics were determined by visual observation each month throughout 2005 in all 65 fields of the three study sites. Each field is characterised by one combination of surface features. Field observations were then summarised to select the most frequent combinations on which rainfall simulations should be performed. Selected plots for rainfall simulation tests always had a slope gradient between 3 and 5%, which is common in the Belgian loess belt. Before the experiment, soil moisture varied between 15 and 20%.
2.4 Rainfall simulations

For each selected combination of soil surface characteristics, the rainfall simulations have been performed on three replicates using an Amsterdam-type simulator. A detailed description of this type of simulator is given by Bowyer-Bower and Burt (1989). The dripping plate is 105 x 55 cm in size and the runoff area covers 0.5 m$^2$. Below the dripping plate a randomiser is attached. It scatters, breaks up and coalesces water drops into a wider distribution of drop sizes than a spray-type simulator. A gutter is installed downstream of the simulator to collect runoff. Water-based sealants (e.g. acrylate kit, silicone) are used to obtain a good seal and prevent leakage into the soil. Before the simulation, a soil sample is taken to determine its moisture content. Simulated rainfall reaches 60 mm.h$^{-1}$ during 30 minutes. Such a rainfall event has a 100-year return period after Delbeke (2001). According to a long-term (1977-2001) database on muddy flood occurrence in a 285 km$^2$ river basin of central Belgium, 85% of muddy floods occur between May and September. They are triggered by heavy thunderstorms (e.g. 60 mm in one hour, Evrard et al., 2007a). At an intensity of 60 mm.h$^{-1}$, medium drop size equalled 5 mm and, after a fall height of 1.70 m, kinetic energy reached 13 J.m$^{-2}$.mm$^{-1}$. Intensity is controlled using a graduated scale on the water reservoir and a chronometer. A wind shield can also be installed if necessary.

Soil infiltration capacity decreases during rainfall, due to the reduction of pressure gradients within the soil and to the degradation of the soil surface structure (Selby, 1993). The steady infiltration rate is one of the parameters required by the STREAM model. It is determined by subtracting measured runoff from the applied rainfall after runoff has reached a steady state. Infiltration into loess soils is mainly controlled by soil surface crust development (Römkens et al., 1995), which demonstrates the dominance of Hortonian overland flow processes in the region. In the results section, mean values are given ± one standard deviation.

Tukey-Kramer’s Honestly Significant Difference (HSD) test is computed using the SAS Enterprise Guide statistical package (SAS Institute Inc., Cary, NC, USA) to compare the means of runoff coefficient and final infiltration rate obtained for the different rainfall simulations. This test is performed after the ANOVA null hypothesis of equal means has been rejected to determine which means are significantly different.
2.5 Comparison of measured runoff coefficients with other methods

The aim of this section is to confront the results of the rainfall simulations with the ones obtained by other studies carried out in similar loess areas of northwestern Europe (Cerdan et al., 2001; Van Oost, 2003). For two different crops (winter wheat and sugar beet), runoff coefficients have been calculated for a 30 minutes rainfall event with an intensity of 60 mm.h\(^{-1}\). The evolution of soil surface characteristics throughout the year has been taken into account to evaluate runoff coefficients for the two crops. Runoff coefficients at constant infiltration rates derived from the results of the rainfall simulations are compared with (i) the ones obtained using infiltration values proposed by Cerdan et al. (2001) for the context of Normandy and with (ii) the ones calculated according to the SCS Curve Number (CN) technique (USDA-SCS, 1973) modified by Van Oost (2003). The CN technique is used to estimate runoff depth from rainfall depth (Eq.1 and 2).

\[ R_{CN} = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{for} \quad P > I_a \]  
\[ R_{CN} = 0 \quad \text{for} \quad P < I_a \]  

Where \( R_{CN} \) is the estimated direct surface runoff (mm), \( S \) is the potential maximum retention (mm), \( I_a \) is the initial abstraction (mm) and \( P \) is the total precipitation (mm).

The CN is related to the retention parameter \( S \) for which the empirical equation \( I_a = 0.2S \) was adopted (Eq.3).

\[ CN = \frac{25400}{(S + 254)} \]  

The modification developed by Van Oost (2003) aims to take the evolution of crop cover and crusting stage of arable land into account to compute the Curve Number (Eq.4).

\[ CN = C_{NSCS} - (C_c/100 \cdot c_1) + (C_r/4 \cdot c_2) \]  

Where \( C_{NSCS} \) is the maximum CN derived from USDA-SCS (1973); \( C_c \) is the crop cover percentage; \( C_r \) is the crusting stage (Le Bissonnais et al., 2005) and \( c_1 \) and \( c_2 \) are coefficients (Van Oost, 2003).
2.6 Estimation of runoff risk at field and catchment scales and implication for muddy flood triggering

Monthly evolution of mean infiltration rates measured on the 6 ha-field has been calculated for winter crops (winter cereals) and summer crops (sugar beets, maize). These rates are compared to the ones based on the results of the rainfall simulations performed on 0.5 m²-plots. A classification of runoff risk at the field scale is then applied to the common crops of central Belgium. A simple index is also developed to evaluate runoff risk at the catchment scale. Relevance of the runoff risk classification is checked, based on the monitoring of runoff in the 16ha-hillslope and the 300 ha-catchment. The implications for muddy flood triggering at the catchment scale are finally discussed.

3 Results and discussion

3.1 Identification of dominant soil surface combinations throughout the year

Among the 60 possible combinations of crust, roughness and soil cover by crop and residues (Table 2), only 38 have been observed in the field and 15 represented more than 2% of the fields throughout the year (accounting for 85% of fields in total; Fig. 2). Technical problems have prevented to carry out rainfall simulations during winter. The lack of simulations in winter is acceptable since according to an exhaustive database of muddy floods for the 1977-2002 period in a 285 km² area of central Belgium, 90 % of floods occur between April and October (Evrard et al., 2007a) and c. 70 % of rainfall erosivity is concentrated between May and September (Verstraeten et al., 2006). The simulated rainfall event is highly unlikely in winter. Consequently, rainfall simulations have been performed between April and October on the fields having one of the 15 most common combinations of soil surface characteristics (Fig. 2).

Only bare soils (C1) and soils with a dense cover (C3) are represented among these 15 selected combinations (Fig. 3). This is due to the rapid crop growth between monthly surveys. However, to take the crop cover effect fully into account, simulations have also been carried out on two soil surface state combinations with an intermediate soil cover by vegetation (C2). They correspond to growing maize and sugarbeet or cover crops in spring and autumn.
Moreover, rainfall has also been simulated on maize lines as well as on wheel tracks. In total, simulations have hence been carried out on 19 different soil surface states.

Ploughed and bare fields are common in winter and spring (e.g. C1-F0-R4, C1-F0-R3 right after tillage; Fig. 3). Between April and June, soils are prepared for the sowing of maize or row and industrial crops. Ploughing and preparation of a seedbed destroy the crust and increase roughness. This leads to an evolution of the soil surface conditions from C1-F11-R3, C1-F11-R2 and C1-F12-R2 before sowing to C1-F0-R1 and C1-F0-R2 right after sowing. At the end of spring, two main types of fields can be observed: (i) soils with a dense crop cover in the case of winter cereals, flax or oilseed rape (C3-F12-R1, C3-F12-R0, C3-F2-R0); and (ii) soils poorly covered by growing crops, mainly sugar beets, maize, potatoes and carrots (C1-F11-R1; C1-F12-R1). In summer, most soils are densely covered by the crops but the crust is disturbed by earthworm activity and dessication (e.g. C3-F12-R1 for winter wheat and sugar beet). Finally, in autumn, soils are generally covered by crop residues (C3-F11-R1) or cover crops (C2-F11-R2, C2-F12-R2, C3-F12-R1, C3-F2-R2). A few bare soils have also been observed during this season (C1-F0-R1, C1-F11-R1).

3.2 Runoff generation on cultivated soils

Among the 17 selected combinations of soil surface characteristics, only 8 have produced runoff during the rainfall simulations (Table 3). Runoff has also been observed on maize lines as well as on wheel tracks (Table 4). In winter and early spring, bare and rough surfaces with a fragmentary state have not produced runoff (C1-F0-R4, C1-F0-R3, C1-F0-R2, C1-F11-R3). Such ploughed fields are not crusted and infiltration rates are very high. Moreover, no runoff has been observed for surfaces with a dense crop cover that are not completely crusted (C3-F11-R1). On rough and imperfectly crusted fields with growing crops (C2-F11-R2) or fully developed crops (C3-F11-R2, C3-F12-R2), no runoff has been observed either.

A high runoff coefficient (58±8%) has been observed for sugar beets and maize (C1-F12-R1) in May and June. Strongly crusted surfaces with a dense crop cover (C3-F12-R0, C3-F2-R0) are also characterised by runoff coefficients of c. 50%. The runoff coefficient strongly decreases when the soil is less crusted or rougher (13±5% for C3-F12-R1). This is typically the case of winter wheat before the harvest in July and early August. This increase of infiltration is explained by the seasonal activity of burrowing animals as well as the appearance of dessication cracks due to shrinkage in the soil surface (Schröder and Auerswald, 2000; Lamandé et al., 2003). This crust cannot be regenerated.
by splash erosion during subsequent rainfall because of the dense crop cover intercepting rainfall.

Runoff coefficients on the maize lines where runoff preferentially concentrates are much higher (90±3%) than on the surrounding area. On wheel tracks, runoff coefficients are very high (95±3% on average) because the soil is fully crusted and compacted.

The runoff coefficients of the cultivated surfaces have been plotted for the different classes of crop cover, surface crusting and roughness (Fig. 4). Runoff increases with crust development. No runoff has been observed for the fragmentary (F0) rough and bare soils. In contrast, the highest runoff coefficients are observed for the strongly crusted soils (F12, F2). Roughness increases the apparent infiltrability by decreasing the runoff contributive area (Léonard et al., 2006). Rougher soils produce less runoff and runoff has never been observed on very rough soils (R3-R4; Fig. 4). A dense vegetation cover leads to a high interception of raindrops, reducing the kinetic energy of the raindrops and hence preventing soil crusting (Morgan, 1995). In addition, the runoff coefficient of soils with scattered depositional crust and a low roughness (C1-F12-R1) is reduced by c. 60% when the crop cover increases (C3-F12-R1), mainly because of dessication cracks and the activity of soil fauna creating pores at the soil surface.

### 3.3 Runoff generation on grassed areas

Overall, grassed areas have a higher runoff coefficient (62±5% for GBS and 73±3% for GWW) than cultivated soils (between 13±5 and 58±8%), except for maize lines (90±3%) and wheel tracks (95±3%; Table 4). A possible explanation is that soils where grass has been sown are not ploughed anymore. The soil surface is hence progressively compacted. This is particularly true for GWWs with agricultural traffic. These are used by farmers as access to their fields. Bulk density was measured on the GBS and GWW where rainfall simulations had been carried out. They reach 1.50±0.05 g.cm⁻³ in GBS and 1.59±0.06 g.cm⁻³ in GWW. These values are very high in comparison with mean bulk densities measured for cropland (1.43 ±0.1 g.cm⁻³) and grassland (1.29 ±0.05 g.cm⁻³) in the Belgian loess belt (Goidts and van Wesemael, in press).

GBSs and GWWs are generally known to reduce runoff, sediments and pollutants from cultivated areas (Fiener and Auerswald, 2003a; Le Bissonnais et al., 2004). Previous studies concluded that the infiltration capacity of grassed buffer strips is higher than that of arable land. Runoff reinfiltration in GBSs...
and GWWs is however very variable (10-91%) depending on the experimental conditions and the rainfall characteristics (Mersie et al., 2003; Le Bissonnais et al., 2004; Vianello et al., 2005). GWWs are generally wider than GBSs and are installed in thalwegs. According to research conducted between 1994 and 2001 on a 290 m-long and 37 m-wide GWW in Germany, runoff was reduced by 87% and sediment delivery by 93% (Fiener and Auerswald, 2005b). Our rainfall simulations show that the runoff coefficient of grassed areas with heavy agricultural traffic is higher than that of cultivated fields (Table 4). Grassed areas have hence a more important role in reducing sediment concentration than in enhancing infiltration. Furthermore, they lead to a decrease in runoff velocity because of their high hydraulic roughness (Fiener and Auerswald, 2003a; Prosser et al., 1995; Fiener and Auerswald, 2003b, 2005a). Sedimentation is thus likely to occur. The subsequent decrease of peak discharge also reduces the flood risk in the downstream villages (Evrard et al., 2007b).

Runoff generation is very heterogeneous in orchards. Three soil surface states having a different behaviour can be distinguished (Fig. 5). Runoff is first of all generated on grassed wheel tracks (runoff coefficient of 78±5%), given the high soil compaction. Infiltrability is higher on the grassed rows between trees (runoff coefficient of 33±9%). In contrast, runoff has not been observed on the tilled soil under the trees and is unlikely to occur, given the high roughness and the absence of a crust.

3.4 Comparison of measured runoff coefficients with other methods

Evolution of the runoff coefficient for a 30 mm-rainfall event throughout the year has been calculated for winter wheat and sugar beet (Fig. 6). The runoff coefficient on a winter wheat field is at its maximum in winter (Fig. 6a). Runoff coefficients calculated based on the tables of Cerdan et al. (2001) and the CN method adapted by Van Oost (2003) follow the same evolution as the ones obtained during our rainfall simulations. However, runoff coefficients obtained based on Cerdan et al. (2001) are overestimated by 60% on average in spring and summer. For instance, for wheat in July (C3-F12-R1), Cerdan et al. (2001) estimated a runoff coefficient of 45%, while we obtained a value of c. 15%. This justifies the local parameterisation for central Belgium. Runoff coefficients calculated with the CN method adapted by Van Oost (2003) are very close to the ones measured during the rainfall simulations, except in autumn. This can be explained by the fact that the roughness parameter is not taken into account in Eq. 4. Runoff coefficient is hence incorrectly high in November and December, although the soils are quite rough (R2) and enable thereby much infiltration.
In the case of sugar beet (Fig. 6b), runoff coefficients obtained with the three methods are in the same order of magnitude and follow a similar evolution throughout the year. Again, the coefficients calculated from the infiltration values proposed by Cerdan et al. (2001) overestimate runoff in summer.

Overall, runoff coefficients measured during the rainfall simulations are consistent with the ones obtained with the two other methods. However, our results show the necessity to derive data valid for the local conditions even if similar studies are available for other regions located within the European loess belt (e.g. Le Bissonnais et al., 2005). The importance of soil surface roughness to explain runoff triggering is also demonstrated.

3.5 Estimation of runoff risk at the field and catchment scales and implications for muddy flood triggering

Monthly evolution of mean infiltration rates has been calculated for winter crops and summer crops, based on the 4-years monitoring of the 6 ha-field. The measurements obtained on 0.5 m² plots and the 6-ha field remain in the same order of magnitude and are very well correlated (Pearson’s correlation coefficient of 0.94, Fig. 7). This homogeneity is explained by homogeneous soil surface characteristics and farming practices at the field scale, confirming the results obtained in a former study carried out in the European loess belt (Cerdan et al., 2004). However, on average, infiltration rates derived from the results of the rainfall simulations are 25% higher than field measurements (Fig. 7). This effect is explained by runoff transmission losses. With increasing plot length, runoff flow depth increases due to upslope runoff accumulation, submerging a larger area downslope (Dunne et al., 1991; Joel et al., 2002). Furthermore, there is an increasing probability of observing preferential infiltration pathways (cracks, macropores) with increasing plot size (Le Bissonnais et al., 1998).

Runoff generation risk has been evaluated for common crops in central Belgium based on the monthly surveys of soil surface characteristics (Table 5a). Risk classes have been defined based on infiltration rates measured at the field scale (Table 5b). For the combinations of soil surface characteristics containing at least one of the three parameters whereby runoff was never observed during the rainfall simulations (F0, R3, R4), an infiltration rate higher than 60 mm.h⁻¹ has been attributed. Crops with a high risk are mainly observed between May and September (sugar beet, maize, potatoes). It coincides with the period when rainfall intensity is at its highest in central Belgium (Verstraeten et al., 2006).
Large quantities of runoff can then be generated when a heavy rainfall event occurs. High risk is also observed on bare and crusted soils in February, but it is unlikely to observe large quantities of runoff because of low intensity rainfall.

An index of runoff risk can be calculated at the catchment scale, taking the relative surface covered by the different crops into account (Eq. 5).

\[ I_{CATCHMENT} = \frac{1}{A} \sum_{i} I_{RUNOFFi} \cdot S_i \]  

Where \( I_{CATCHMENT} \) is the runoff risk at the catchment scale, \( A \) is the catchment area (ha), \( I_{RUNOFFi} \) is the runoff risk of the crop \( i \) given in Table 5b, \( S_i \) is the area of catchment cropland surface (ha) covered by the crop \( i \). Runoff risk classification at the catchment scale is given in Table 5b.

Runoff risk has been mapped for the fields of the Sint-Truiden catchment (Fig. 8). Mean runoff risk index for the entire catchment reached 2 (high risk) in May 2002, while it equalled 1.5 (medium risk) in May 2006. Furthermore, high risk fields were concentrated in the lower part of the catchment in May, 2002 (Fig. 8a). A muddy flood affected the village after a thunderstorm on May 9. The situation observed in May, 2006 is very different (Fig. 8b). Fields with a high risk are less numerous and evenly distributed, and a grassed waterway has been installed in the catchment thalweg. The GWW has been classified as a low risk area, given its high potential to slow down runoff (Fiener and Auerswald, 2005a; Evrard et al., 2007b). Even though several thunderstorms occurred with a rainfall intensity and duration similar to 2002, no muddy flood affected the village downstream.

Monthly distribution of heavy rainfall and runoff events has been plotted for the hillslope and catchment databases (Fig. 9). Given these datasets cover 4 and 5 years respectively (Table 1), we assume that the effect of crop rotation is taken into account (Table 7). It appears from Fig. 9 that most runoff events have been recorded between May and September (60% in Walhain and 68% in Velm). This confirms the runoff risk classification at the field scale (Table 5c). The rather high number of runoff events recorded during Winter in Walhain is explained by very wet winter months in 2001 and 2002. This situation caused the generation of saturation overland flow. This finding is in agreement with former studies carried out in the Netherlands (Kwaad, 1991; Van Dijk and Kwaad, 1996). However, the saturation flow produced by long-duration rainfall of low intensity was distributed over entire days. Large quantities of runoff must be generated over a much shorter period to generate a muddy flood (Boardman et al., 2006). This situation occurs after local convective thunderstorms in spring and summer (Fig. 9). This is illustrated by the monthly distribution of mean runoff volumes and peak discharges recorded at the outlet of the 16ha-hillslope (Fig. 10). The largest quantities of runoff and the highest peak discharges are recorded between May and August. This is
consistent with the muddy flood data available for central Belgium, showing 
that 90% of floods are recorded between May and September (Vandaele and 
Poesen, 1995; Verstraeten and Poesen, 1999; Evrard et al., 2007a).

4 Conclusions

The simulation of a heavy rainfall event (60 mm.h$^{-1}$ during 30 minutes) has 
been carried out on 17 representative combinations of soil surface characteris-
tics (crop cover, surface crusting and roughness) throughout the year, as well 
as on maize lines and on wheel tracks. Runoff has been observed in 10 cases 
only, rainfall infiltrating completely in the case of (ploughed) bare soils that 
are not yet crusted and soils with a dense crop cover, a moderate roughness 
and an incomplete crust. The highest runoff coefficients have been observed for 
wheel tracks (95±3%) and fields with maize lines in May and June (90±3%). 
In May and June, sugar beet as well as crusted soils with a dense crop cover 
also generate runoff (mean runoff coefficients of 57 and 58%, respectively). 
Overall, grassed areas have a higher runoff coefficient (63% for GWWs and 
72% for GBSs, on average) than cultivated fields (13-58% on average).

The obtained database allows parameterising erosion and runoff models (e.g. 
STREAM). Such an expert-based model requires a local calibration and val-
idation. The different values obtained in this study in comparison with the 
one observed in Normandy justify the local parameterisation and the use of 
a portable rainfall simulator in the field. Measurements obtained thanks to 
rainfall simulations on 0.5 m$^2$-plots can be used to estimate runoff generation 
at the field scale. A runoff risk classification has been applied to common crops 
in central Belgium. It is shown that February as well as the period between 
May and September are the most critical months for runoff generation at 
the field scale. However, runoff monitoring at the catchment scale shows that 
muddy floods are most likely to occur between May and September. During 
this period, local convective thunderstorms producing large quantities of hor-
tonian runoff over a short period on fields with a high runoff risk (e.g. maize, 
sugarbeet, potatoes) occur.
5 Acknowledgements

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References

Dunne, T., Zhang, W., Aubry, B., 1991. Effects of rainfall, vegetation and
microtopography on infiltration and runoff. Water Resources Research 27, 2271–2285.


URL http://www.statbel.fgov.be/


6 Figure captions

Figure 1. (a) Location of the study sites in Belgium; (b) Louvain-la-Neuve field (6 ha); (c) Walhain catchment (5 fields; 16 ha); (d) Sint-Truiden catchment (58 fields and a grassed waterway - GWW; 300 ha).

Figure 2. Combination of soil surface characteristics for all observed fields (n=65) in 2005. The classification of soil surface characteristics in given in Table 2.

Figure 3. Combination of soil surface characteristics for the observed fields (n=65) and for each season in 2005.

Figure 4. Relative importance of soil surface characteristics for runoff generation. Bars represent one standard deviation.

Figure 5. Different soil surface conditions in orchards (A=tilled soil under the trees; B=grassed wheel tracks; C=grassed rows between trees).

Figure 6. Evolution of runoff coefficient calculated after three methods for a 30 mm-rainfall event on (a) a winter wheat field and (b) a sugar beet field.

Figure 7. Comparison of infiltration rates obtained for monthly soil surface characteristics of fields planted with summer and winter crops based on (i) rainfall simulations and (ii) long-term monitoring of the 6 ha-field. Error bars represent one standard deviation.

Figure 8. Spatial distribution of runoff generation risk in the Sint-Truiden catchment. Risk estimated according to the distribution of crops as observed
in (a) May, 2002 and (b) May, 2006.

Figure 9. Monthly distribution of the observed rainfall events with more than 15mm of cumulative precipitation, and number of recorded runoff events in (a) Walhain hillslope and (b) Sint-Truiden catchment.

Figure 10. Monthly distribution of (a) mean runoff volumes ($m^3$) and (b) mean peak discharges ($l.s^{-1}$) measured at the outlet of the 16ha-hillslope. Error bars represent the maximal range of measurements over the 4 year period.
Table 1: Characteristics of the rainfall-runoff events recorded in the three monitored sites.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Louvain-la-Neuve (6 ha)</th>
<th>Walhain (16 ha)</th>
<th>St-Truiden (300 ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>71</td>
<td>83</td>
<td>46</td>
</tr>
<tr>
<td>Mean rainfall (mm)</td>
<td>11.4</td>
<td>12.4</td>
<td>18.6</td>
</tr>
<tr>
<td>Mean runoff volume (mm)</td>
<td>0.3</td>
<td>0.7</td>
<td>NA</td>
</tr>
</tbody>
</table>
Table 2: Classification of soil surface characteristics according to Le Bissonnais et al., 2005.

(a) Classes of soil surface roughness. Roughness is defined as the difference in the heights of the deepest part of microdepressions and the lowest point of their divide.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Roughness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>0 - 1</td>
</tr>
<tr>
<td>R1</td>
<td>1 - 2</td>
</tr>
<tr>
<td>R2</td>
<td>2 - 5</td>
</tr>
<tr>
<td>R3</td>
<td>5 - 10</td>
</tr>
<tr>
<td>R4</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>

(b) Classes of soil surface crusting.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>Initial fragmentary structure</td>
</tr>
<tr>
<td>F11</td>
<td>Altered fragmentary state with structural crusts</td>
</tr>
<tr>
<td>F12</td>
<td>Local appearance of depositional crusts</td>
</tr>
<tr>
<td>F2</td>
<td>Continuous state with depositional crusts</td>
</tr>
</tbody>
</table>

(c) Classes of crop cover.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Area covered by canopy or litter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C 1</td>
<td>From 0 to 20%</td>
</tr>
<tr>
<td>C 2</td>
<td>From 21 to 60%</td>
</tr>
<tr>
<td>C 3</td>
<td>From 61 to 100%</td>
</tr>
</tbody>
</table>
Table 3: Soil surface combinations selected for rainfall simulation, typical agricultural situations and observation of runoff during the simulations.

<table>
<thead>
<tr>
<th>Combinations</th>
<th>Period(s) of observation</th>
<th>Typical agricultural situations</th>
<th>Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-F0-R4</td>
<td>January</td>
<td>bare and ploughed fields</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>April</td>
<td>bare field with ridges</td>
<td></td>
</tr>
<tr>
<td>C1-F0-R3</td>
<td>March-April</td>
<td>bare and ploughed field</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>bare field</td>
<td></td>
</tr>
<tr>
<td>C1-F0-R2</td>
<td>April-June</td>
<td>bare field with fine seedbed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>August-December</td>
<td>bare field with crop residues</td>
<td></td>
</tr>
<tr>
<td>C1-F0-R1</td>
<td>April</td>
<td>bare field with fine seedbed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>growing maize</td>
<td></td>
</tr>
<tr>
<td></td>
<td>October-November</td>
<td>bare field with mulch</td>
<td></td>
</tr>
<tr>
<td>C1-F11-R3</td>
<td>December-February</td>
<td>bare field</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>April</td>
<td>bare and ploughed field</td>
<td></td>
</tr>
<tr>
<td>C1-F11-R2</td>
<td>From November to June</td>
<td>bare field</td>
<td>Yes</td>
</tr>
<tr>
<td>C1-F11-R1</td>
<td>May-June</td>
<td>row crops</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>November-December</td>
<td>bare field or field with growing crop</td>
<td></td>
</tr>
<tr>
<td>C1-F12-R2</td>
<td>January-March</td>
<td>growing winter cereals</td>
<td>Yes</td>
</tr>
<tr>
<td>C1-F12-R1</td>
<td>January-March</td>
<td>winter cereals</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>growing peas or sugar beets</td>
<td></td>
</tr>
<tr>
<td>C2-F11-R2</td>
<td>April</td>
<td>growing crops</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>cover crops</td>
<td></td>
</tr>
<tr>
<td>C2-F12-R2</td>
<td>April</td>
<td>growing crops</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>cover crops</td>
<td></td>
</tr>
<tr>
<td>C3-F11-R2</td>
<td>February</td>
<td>winter cereals</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>October-December</td>
<td>cover crops</td>
<td></td>
</tr>
<tr>
<td>C3-F11-R1</td>
<td>June-July</td>
<td>sugar beets, maize, chicory</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>November-December</td>
<td>maize residues, cover crops</td>
<td></td>
</tr>
<tr>
<td>C3-F12-R2</td>
<td>February</td>
<td>winter cereals</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>cover crops</td>
<td></td>
</tr>
<tr>
<td>C3-F12-R1</td>
<td>January-March</td>
<td>winter cereals</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>July-October</td>
<td>row crops and cover crops</td>
<td></td>
</tr>
<tr>
<td>C3-F12-R0</td>
<td>April-October</td>
<td>winter cereals (April-May); row crops and flax (June-October)</td>
<td>Yes</td>
</tr>
<tr>
<td>C3-F2-R0</td>
<td>April-October</td>
<td>winter cereals (April-May); row crops and flax (June-October)</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 4: Mean runoff coefficient and steady infiltration rate for the cultivated soils and grassed areas. Standard deviation (SD) is indicated for each characteristic. Means within a column followed by the same letter are not significantly different at $\alpha=0.05$ level using the Tukey-Kramer’s Honestly Significant Difference (HSD) test.

<table>
<thead>
<tr>
<th>Soil surface Combination</th>
<th>Runoff coefficient (%) Mean value</th>
<th>SD</th>
<th>Infiltration rate (mm.h$^{-1}$) Mean value</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-F11-R1</td>
<td>35$^b$</td>
<td>5</td>
<td>39$^d$</td>
<td>3</td>
</tr>
<tr>
<td>C1-F12-R1</td>
<td>58$^c$</td>
<td>8</td>
<td>25$^c$</td>
<td>7</td>
</tr>
<tr>
<td>C1-F11-R2</td>
<td>42$^b$</td>
<td>6</td>
<td>35$^d$</td>
<td>4</td>
</tr>
<tr>
<td>C1-F12-R2</td>
<td>33$^b$</td>
<td>8</td>
<td>40$^d$</td>
<td>8</td>
</tr>
<tr>
<td>C2-F12-R2</td>
<td>25$^b$</td>
<td>2</td>
<td>45$^d$</td>
<td>2</td>
</tr>
<tr>
<td>C3-F12-R0</td>
<td>45$^b$</td>
<td>3</td>
<td>33$^d$</td>
<td>2</td>
</tr>
<tr>
<td>C3-F2-R0</td>
<td>57$^c$</td>
<td>3</td>
<td>26$^c$</td>
<td>3</td>
</tr>
<tr>
<td>C3-F12-R1</td>
<td>13$^a$</td>
<td>5</td>
<td>52$^e$</td>
<td>3</td>
</tr>
<tr>
<td>Wheel track</td>
<td>95$^e$</td>
<td>3</td>
<td>3$^a$</td>
<td>3</td>
</tr>
<tr>
<td>Maize line</td>
<td>90$^e$</td>
<td>3</td>
<td>6$^a$</td>
<td>2</td>
</tr>
<tr>
<td>Grassed buffer strip</td>
<td>62$^c$</td>
<td>5</td>
<td>23$^c$</td>
<td>3</td>
</tr>
<tr>
<td>Grassed waterway</td>
<td>73$^d$</td>
<td>3</td>
<td>16$^b$</td>
<td>3</td>
</tr>
<tr>
<td>Orchard (wheel track)</td>
<td>78$^d$</td>
<td>5</td>
<td>13$^b$</td>
<td>3</td>
</tr>
<tr>
<td>Orchard (grass)</td>
<td>33$^b$</td>
<td>9</td>
<td>40$^d$</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 5: Classification of monthly runoff risk for common crops in central Belgium.

(a) Combination of soil surface characteristics observed each month for five common crops in central Belgium. Characteristics observed during the intercrop period are in italics.

<table>
<thead>
<tr>
<th>Crop</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>C1-F12-R2</td>
<td>C1-F12-R2</td>
<td>C2-F12-R2</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C1-F0-R2</td>
<td>C1-F11-R2</td>
<td>C1-F11-R2</td>
</tr>
<tr>
<td>Flax</td>
<td>C1-F11-R5</td>
<td>C1-F11-R4</td>
<td>C1-F2-R2</td>
<td>C1-F0-R2</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C1-F0-R1</td>
<td>C1-F0-R2</td>
<td>C3-F11-R2</td>
<td>C3-F11-R2</td>
<td>C3-F11-R2</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>C1-F11-R1</td>
<td>C1-F12-R1</td>
<td>C1-F0-R3</td>
<td>C1-F11-R3</td>
<td>C1-F12-R1</td>
<td>C1-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R1</td>
<td>C3-F12-R2</td>
<td>C1-F11-R1</td>
<td>C3-F11-R2</td>
</tr>
<tr>
<td>Maize</td>
<td>C2-F11-R1</td>
<td>C1-F2-R0</td>
<td>C1-F0-R3</td>
<td>C1-F11-R3</td>
<td>C1-F12-R1</td>
<td>C1-F12-R1</td>
<td>C3-F2-R1</td>
<td>C3-F2-R1</td>
<td>C3-F2-R1</td>
<td>C1-F0-R1</td>
<td>C3-F12-R1</td>
<td>C3-F11-R2</td>
</tr>
<tr>
<td>Potatoes</td>
<td>C1-F11-R3</td>
<td>C1-F12-R2</td>
<td>C1-F11-R3</td>
<td>C1-F12-R0</td>
<td>C2-F12-R0</td>
<td>C3-F2-R0</td>
<td>C3-F2-R0</td>
<td>C1-F2-R0</td>
<td>C3-F15-R0</td>
<td>C3-F11-R1</td>
<td>C3-F11-R1</td>
<td>C3-F11-R2</td>
</tr>
</tbody>
</table>

(b) Classification of runoff risk

<table>
<thead>
<tr>
<th>Runoff risk</th>
<th>Infiltration rate (mm.h$^{-1}$)</th>
<th>$I_{RUNOFF}$</th>
<th>$I_{CATCHMENT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No risk</td>
<td>&gt; 60</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Low risk</td>
<td>40 - 60</td>
<td>1</td>
<td>0 - 0.9</td>
</tr>
<tr>
<td>Medium risk</td>
<td>20 - 39</td>
<td>2</td>
<td>1 - 1.9</td>
</tr>
<tr>
<td>High risk</td>
<td>&lt; 20</td>
<td>3</td>
<td>2 - 3</td>
</tr>
</tbody>
</table>

(c) Classification of runoff risk for common crops in central Belgium.

<table>
<thead>
<tr>
<th>Crop</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flax</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar beet</td>
<td>Intercrop</td>
<td>Intercrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>Intercrop</td>
<td>Intercrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potatoes</td>
<td>Intercrop</td>
<td>Intercrop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6: Surface (%) covered by the different crops in the Walhain and Sint-
Truiden study sites.

<table>
<thead>
<tr>
<th></th>
<th>Walhain (16 ha)</th>
<th></th>
<th></th>
<th></th>
<th>Sint-Truiden (300 ha)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>26</td>
<td>74</td>
<td>55</td>
<td>37</td>
<td>11</td>
<td>44</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Flax</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>0</td>
<td>26</td>
<td>34</td>
<td>35</td>
<td>46</td>
<td>16</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td>Maize</td>
<td>74</td>
<td>0</td>
<td>11</td>
<td>8</td>
<td>21</td>
<td>1</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Potatoes</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>16</td>
<td>12</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Other crops</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>11</td>
<td>18</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 1
Soil roughness and crop cover

Figure 2
Figure 3

Sparse vegetation cover (C1)
Dense vegetation cover (C3)
Dense vegetation cover (C3)
Sparse vegetation cover (C1)

Winter Spring Summer Autumn

% of fields

Crusted (F12-F2) / Smooth (R0-R1)
Not crusted (F0-F11) / Rough (R2 to R4)
Figure 4

Runoff coefficient (%) vs. Crusting stage

Key:
- □ C1-R0/C1-R3/C1-R4/C3-R2
- ● C1-R1
- ▲ C1-R2
- ● C2-R2
- ○ C3-R0
- ○ C3-R1
Figure 6

(a) Runoff coefficient (%) over the months

(b) Runoff coefficient (%) over the months

- Cerdan et al., 2001
- Adapted CN
- This study
Figure 7

Infiltration rate (mm/h) estimated from the results of the rainfall simulations vs. infiltration rate (mm/h) measured on the 6 ha-experimental field.

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Figure 8

Value of runoff risk index

0 1 2 3
Permanent land cover

(a) (b)
Figure 9

(a) Number of rainfall/runoff events by month

(b) Number of runoff events and rainfall/runoff events by month

Legend:
- 15 - 24 mm
- 25 - 34 mm
- 35 mm and more
- Number of runoff events
Figure 10

(a) Mean total runoff volume (m³)

(b) Mean peak discharge (l/s)

Month

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