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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⁻¹ during 30 minutes) has been simulated using a 0.5 m² 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

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

30 Several techniques exist to determine the field-saturated infiltration rate. Con-
31 stant head infiltrometers have extensively been used, but the estimates are
32 unreliable for stratified soils or when the crust is disturbed to install the in-
33 filtrometer (Léonard et al., 2006). In other studies, rainfall simulations have
34 been carried out in the laboratory (Pan and Shangguan, 2006), or experimental
35 plots exposed to natural rainfall have been monitored for runoff during several
36 years (Léonard et al., 2006). However, to cover the whole range of soil surface
37 conditions related to different types of land cover, numerous plots are needed.
38 Furthermore, the occurrence of runoff remains highly uncertain over a period
39 of a few years only. Consequently, rainfall simulations performed on selected
40 surfaces representing the range of surface conditions observed throughout the
41 year are more efficient. The problem is that rainfall simulations are carried out
42 on small plots (generally up to 1 m²) while required input (e.g. for STREAM)
43 must characterise an entire field (typically 1 to 6 ha). Since a scale effect is
44 likely to occur, the reliability of using micro-plot measurements to characterise

1 a field must be investigated. For instance, Cerdan et al. (2004) calculated a
2 significant decrease in runoff coefficient when the study area increased from
3 500 m²-plots to catchments (90-1100 ha).

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

14 2 Materials and methods

15 2.1 Study area

16 The Belgian loess belt (c. 9,000 km²) is a plateau with a mean altitude of
17 115 m and a topography gently sloping to the North (Fig. 1a). It is dis-
18 sected by valleys having generally a North-South orientation. Most soils are
19 loess-derived haplic luvisols (World Reference Base, 1998). Mean annual tem-
20 perature ranges from 9 to 10 °C, while mean annual precipitation in central
21 Belgium varies between 700 and 900 mm (Hufty, 2001). Rainfall is evenly dis-
22 tributed throughout the year, but erosivity shows a peak between May and
23 September (Verstraeten et al., 2006). Arable land covers on average 65% of
24 the total surface (Statistics Belgium, 2006). Main crops are winter wheat, in-
25 dustrial and fodder crops (sugar beets, maize, oilseed rape and flax), as well
26 as potatoes. Orchards are restricted to the northeastern part of the loess belt,
27 around the town of Sint-Truiden (covering up to 65% of the total area in this
28 region, vs. less than 5% elsewhere in the loess belt).

1 2.2 Experimental sites

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

25 2.3 Soil surface characterisation

26 According to Le Bissonnais et al. (2005), the most relevant dynamic char-
27 acteristics for characterising runoff and erosion potential of cultivated fields
28 at a given time are : (i) surface roughness (Table 2a); (ii) the development
29 of soil surface crusts (Table 2b); (iii) the vegetation and plant residue cover
30 (Table 2c) and (iv) the presence of wheel tracks. These characteristics were
31 determined by visual observation each month throughout 2005 in all 65 fields
32 of the three study sites. Each field is characterised by one combination of
33 surface features. Field observations were then summarised to select the most
34 frequent combinations on which rainfall simulations should be performed. Se-
35 lected plots for rainfall simulation tests always had a slope gradient between
36 3 and 5%, which is common in the Belgian loess belt. Before the experiment,
37 soil moisture varied between 15 and 20%.

1 2.4 Rainfall simulations

2 For each selected combination of soil surface characteristics, the rainfall sim-
3 ulations have been performed on three replicates using an Amsterdam-type
4 simulator. A detailed description of this type of simulator is given by Bowyer-
5 Bower and Burt (1989). The dripping plate is 105×55 cm in size and the
6 runoff area covers 0.5 m^2 . Below the dripping plate a randomiser is attached.
7 It scatters, breaks up and coalesces water drops into a wider distribution of
8 drop sizes than a spray-type simulator. A gutter is installed downstream of
9 the simulator to collect runoff. Water-based sealants (e.g. acrylate kit, sili-
10 cone) are used to obtain a good seal and prevent leakage into the soil. Before
11 the simulation, a soil sample is taken to determine its moisture content. Sim-
12 ulated rainfall reaches 60 mm.h^{-1} during 30 minutes. Such a rainfall event
13 has a 100-year return period after Delbeke (2001). According to a long-term
14 (1977-2001) database on muddy flood occurrence in a 285 km^2 river basin of
15 central Belgium, 85% of muddy floods occur between May and September.
16 They are triggered by heavy thunderstorms (e.g. 60 mm in one hour, Evrard
17 et al., 2007a). At an intensity of 60 mm.h^{-1} , medium drop size equalled 5
18 mm and, after a fall height of 1.70 m, kinetic energy reached $13 \text{ J.m}^{-2}.\text{mm}^{-1}$.
19 Intensity is controlled using a graduated scale on the water reservoir and a
20 chronometer. A wind shield can also be installed if necessary.

21 Soil infiltration capacity decreases during rainfall, due to the reduction of
22 pressure gradients within the soil and to the degradation of the soil surface
23 structure (Selby, 1993). The steady infiltration rate is one of the parameters
24 required by the STREAM model. It is determined by subtracting measured
25 runoff from the applied rainfall after runoff has reached a steady state. Infil-
26 tration into loess soils is mainly controlled by soil surface crust development
27 (Römken et al., 1995), which demonstrates the dominance of hortonian over-
28 land flow processes in the region. In the results section, mean values are given
29 \pm one standard deviation.

30 Tukey-Kramer's Honestly Significant Difference (HSD) test is computed using
31 the SAS Enterprise Guide statistical package (SAS Institute Inc., Cary, NC,
32 USA) to compare the means of runoff coefficient and final infiltration rate
33 obtained for the different rainfall simulations. This test is performed after the
34 ANOVA null hypothesis of equal means has been rejected to determine which
35 means are significantly different.

1 2.5 Comparison of measured runoff coefficients with other methods

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

$$R_{CN} = (P - I_a)^2 / [(P - I_a) + S] \quad \text{for} \quad P > I_a \quad (1)$$

$$R_{CN} = 0 \quad \text{for} \quad P < I_a \quad (2)$$

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

18 The CN is related to the retention parameter S for which the empirical equa-
 19 tion $I_a = 0.2S$ was adopted (Eq.3).

$$CN = 25400 / (S + 254) \quad (3)$$

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

$$CN = CN_{SCS} - (C_c/100 \cdot c_1) + (C_r/4 \cdot c_2) \quad (4)$$

23 Where CN_{SCS} is the maximum CN derived from USDA-SCS (1973); C_c is the
 24 crop cover percentage; C_r is the crusting stage (Le Bissonnais et al., 2005) and
 25 c_1 and c_2 are coefficients (Van Oost, 2003).

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3 2.6 *Estimation of runoff risk at field and catchment scales and implication*
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7 *for muddy flood triggering*
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10 Monthly evolution of mean infiltration rates measured on the 6 ha-field has
11 been calculated for winter crops (winter cereals) and summer crops (sugar
12 beets, maize). These rates are compared to the ones based on the results of
13 the rainfall simulations performed on 0.5 m²-plots. A classification of runoff
14 risk at the field scale is then applied to the common crops of central Belgium.
15 A simple index is also developed to evaluate runoff risk at the catchment scale.
16 Relevance of the runoff risk classification is checked, based on the monitoring
17 of runoff in the 16ha-hillslope and the 300 ha-catchment. The implications for
18 muddy flood triggering at the catchment scale are finally discussed.
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26 **3 Results and discussion**
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32 3.1 *Identification of dominant soil surface combinations throughout the year*
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36 Among the 60 possible combinations of crust, roughness and soil cover by crop
37 and residues (Table 2), only 38 have been observed in the field and 15 repre-
38 sented more than 2% of the fields throughout the year (accounting for 85% of
39 fields in total; Fig. 2). Technical problems have prevented to carry out rainfall
40 simulations during winter. The lack of simulations in winter is acceptable since
41 according to an exhaustive database of muddy floods for the 1977-2002 period
42 in a 285 km² area of central Belgium, 90 % of floods occur between April and
43 October (Evrard et al., 2007a) and c. 70% of rainfall erosivity is concentrated
44 between May and September (Verstraeten et al., 2006). The simulated rainfall
45 event is highly unlikely in winter. Consequently, rainfall simulations have been
46 performed between April and October on the fields having one of the 15 most
47 common combinations of soil surface characteristics (Fig. 2).
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51 Only bare soils (C1) and soils with a dense cover (C3) are represented among
52 these 15 selected combinations (Fig. 3). This is due to the the rapid crop
53 growth between monthly surveys. However, to take the crop cover effect fully
54 into account, simulations have also been carried out on two soil surface state
55 combinations with an intermediate soil cover by vegetation (C2). They corre-
56 spond to growing maize and sugarbeet or cover crops in spring and autumn
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1 (C2-F11-R2 and C2-F12-R2; Table 3). Moreover, rainfall has also been sim-
2 ulated on maize lines as well as on wheel tracks. In total, simulations have
3 hence been carried out on 19 different soil surface states.

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

19 3.2 Runoff generation on cultivated soils

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

30 A high runoff coefficient ($58 \pm 8\%$) has been observed for sugar beets and maize
31 (C1-F12-R1) in May and June. Strongly crusted surfaces with a dense crop
32 cover (C3-F12-R0, C3-F2-R0) are also characterised by runoff coefficients of
33 c. 50%. The runoff coefficient strongly decreases when the soil is less crusted
34 or rougher ($13 \pm 5\%$ for C3-F12-R1). This is typically the case of winter wheat
35 before the harvest in July and early August. This increase of infiltration is
36 explained by the seasonal activity of burrowing animals as well as the ap-
37 pearance of desiccation cracks due to shrinkage in the soil surface (Schröder
38 and Auerswald, 2000; Lamandé et al., 2003). This crust cannot be regenerated

1 by splash erosion during subsequent rainfall because of the dense crop cover
2 intercepting rainfall.

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

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

21 3.3 Runoff generation on grassed areas

22 Overall, grassed areas have a higher runoff coefficient ($62\pm 5\%$ for GBS and
23 $73\pm 3\%$ for GWW) than cultivated soils (between 13 ± 5 and $58\pm 8\%$), except
24 for maize lines ($90\pm 3\%$) and wheel tracks ($95\pm 3\%$; Table 4). A possible ex-
25 planation is that soils where grass has been sown are not ploughed anymore.
26 The soil surface is hence progressively compacted. This is particularly true
27 for GWWs with agricultural traffic. These are used by farmers as access to
28 their fields. Bulk density was measured on the GBS and GWW where rainfall
29 simulations had been carried out. They reach 1.50 ± 0.05 g.cm⁻³ in GBS and
30 1.59 ± 0.06 g.cm⁻³ in GWW. These values are very high in comparison with
31 mean bulk densities measured for cropland (1.43 ± 0.1 g.cm⁻³) and grassland
32 (1.29 ± 0.05 g.cm⁻³) in the Belgian loess belt (Goidts and van Wesemael, in
33 press).

34 GBSs and GWWs are generally known to reduce runoff, sediments and pollu-
35 tants from cultivated areas (Fiener and Auerswald, 2003a; Le Bissonnais et al.,
36 2004). Previous studies concluded that the infiltration capacity of grassed
37 buffer strips is higher than that of arable land. Runoff reinfiltration in GBSs

1 and GWWs is however very variable (10-91%) depending on the experimental
2 conditions and the rainfall characteristics (Mersie et al., 2003; Le Bissonnais
3 et al., 2004; Vianello et al., 2005). GWWs are generally wider than GBSs and
4 are installed in thalwegs. According to research conducted between 1994 and
5 2001 on a 290 m-long and 37 m-wide GWW in Germany, runoff was reduced
6 by 87% and sediment delivery by 93% (Fiener and Auerswald, 2005b). Our
7 rainfall simulations show that the runoff coefficient of grassed areas with heavy
8 agricultural traffic is higher than that of cultivated fields (Table 4). Grassed
9 areas have hence a more important role in reducing sediment concentration
10 than in enhancing infiltration. Furthermore, they lead to a decrease in runoff
11 velocity because of their high hydraulic roughness (Fiener and Auerswald,
12 2003a; Prosser et al., 1995; Fiener and Auerswald, 2003b, 2005a). Sedimen-
13 tation is thus likely to occur. The subsequent decrease of peak discharge also
14 reduces the flood risk in the downstream villages (Evrard et al., 2007b).

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

22 3.4 Comparison of measured runoff coefficients with other methods

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

1 In the case of sugar beet (Fig. 6b), runoff coefficients obtained with the three
2 methods are in the same order of magnitude and follow a similar evolution
3 throughout the year. Again, the coefficients calculated from the infiltration
4 values proposed by Cerdan et al. (2001) overestimate runoff in summer.

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

11 3.5 *Estimation of runoff risk at the field and catchment scales and implica-* 12 *tions for muddy flood triggering*

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

28 Runoff generation risk has been evaluated for common crops in central Belgium
29 based on the monthly surveys of soil surface characteristics (Table 5a). Risk
30 classes have been defined based on infiltration rates measured at the field scale
31 (Table 5b). For the combinations of soil surface characteristics containing at
32 least one of the three parameters whereby runoff was never observed during the
33 rainfall simulations (F0, R3, R4), an infiltration rate higher than 60 mm.h⁻¹
34 has been attributed. Crops with a high risk are mainly observed between May
35 and September (sugarbeet, maize, potatoes). It coincides with the period when
36 rainfall intensity is at its highest in central Belgium (Verstraeten et al., 2006).

1 Large quantities of runoff can then be generated when a heavy rainfall event
 2 occurs. High risk is also observed on bare and crusted soils in February, but it
 3 is unlikely to observe large quantities of runoff because of low intensity rainfall.

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

$$I_{CATCHMENT} = 1/A \sum_i I_{RUNOFFi} \cdot S_i \quad (5)$$

6 Where $I_{CATCHMENT}$ is the runoff risk at the catchment scale, A is the catch-
 7 ment area (ha), $I_{RUNOFFi}$ is the runoff risk of the crop i given in Table 5b, S_i
 8 is the area of catchment cropland surface (ha) covered by the crop i . Runoff
 9 risk classification at the catchment scale is given in Table 5b.

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

22 Monthly distribution of heavy rainfall and runoff events has been plotted for
 23 the hillslope and catchment databases (Fig. 9). Given these datasets cover 4
 24 and 5 years respectively (Table 1), we assume that the effect of crop rota-
 25 tion is taken into account (Table 7). It appears from Fig. 9 that most runoff
 26 events have been recorded between May and September (60% in Walhain and
 27 68% in Velm). This confirms the runoff risk classification at the field scale
 28 (Table 5c). The rather high number of runoff events recorded during Win-
 29 ter in Walhain is explained by very wet winter months in 2001 and 2002.
 30 This situation caused the generation of saturation overland flow. This finding
 31 is in agreement with former studies carried out in the Netherlands (Kwaad,
 32 1991; Van Dijk and Kwaad, 1996). However, the saturation flow produced by
 33 long-duration rainfall of low intensity was distributed over entire days. Large
 34 quantities of runoff must be generated over a much shorter period to generate
 35 a muddy flood (Boardman et al., 2006). This situation occurs after local con-
 36 vective thunderstorms in spring and summer (Fig. 9). This is illustrated by the
 37 monthly distribution of mean runoff volumes and peak discharges recorded at
 38 the outlet of the 16ha-hillslope (Fig. 10). The largest quantities of runoff and
 39 the highest peak discharges are recorded between May and August. This is

1 consistent with the muddy flood data available for central Belgium, showing
2 that 90% of floods are recorded between May and September (Vandaele and
3 Poesen, 1995; Verstraeten and Poesen, 1999; Evrard et al., 2007a).

4 4 Conclusions

5 The simulation of a heavy rainfall event (60 mm.h^{-1} during 30 minutes) has
6 been carried out on 17 representative combinations of soil surface characteris-
7 tics (crop cover, surface crusting and roughness) throughout the year, as well
8 as on maize lines and on wheel tracks. Runoff has been observed in 10 cases
9 only, rainfall infiltrating completely in the case of (ploughed) bare soils that
10 are not yet crusted and soils with a dense crop cover, a moderate roughness
11 and an incomplete crust. The highest runoff coefficients have been observed for
12 wheel tracks ($95 \pm 3\%$) and fields with maize lines in May and June ($90 \pm 3\%$).
13 In May and June, sugar beet as well as crusted soils with a dense crop cover
14 also generate runoff (mean runoff coefficients of 57 and 58%, respectively).
15 Overall, grassed areas have a higher runoff coefficient (63% for GWWs and
16 72% for GBSs, on average) than cultivated fields (13-58% on average).

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

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23 6 Figure captions

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27 Figure 1. (a) Location of the study sites in Belgium; (b) Louvain-la-Neuve field
28 (6 ha); (c) Walhain catchment (5 fields ; 16 ha); (d) Sint-Truiden catchment
29 (58 fields and a grassed waterway - GWW; 300 ha).

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31
32 Figure 2. Combination of soil surface characteristics for all observed fields
33 (n=65) in 2005. The classification of soil surface characteristics is given in
34 Table 2.

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

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41 Figure 4. Relative importance of soil surface characteristics for runoff genera-
42 tion. Bars represent one standard deviation.

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

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49 Figure 6. Evolution of runoff coefficient calculated after three methods for a
50 30 mm-rainfall event on (a) a winter wheat field and (b) a sugar beet field.

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52
53 Figure 7. Comparison of infiltration rates obtained for monthly soil surface
54 characteristics of fields planted with summer and winter crops based on (i)
55 rainfall simulations and (ii) long-term monitoring of the 6 ha-field. Error bars
56 represent one standard deviation.

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59 Figure 8. Spatial distribution of runoff generation risk in the Sint-Truiden
60 catchment. Risk estimated according to the distribution of crops as observed

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4 in (a) May, 2002 and (b) May, 2006.

5
6 Figure 9. Monthly distribution of the observed rainfall events with more than
7 15mm of cumulative precipitation, and number of recorded runoff events in
8 (a) Walhain hillslope and (b) Sint-Truiden catchment.

9
10 Figure 10. Monthly distribution of (a) mean runoff volumes (m^3) and (b) mean
11 peak discharges (l.s^{-1}) measured at the outlet of the 16ha-hillslope. Error bars
12 represent the maximal range of measurements over the 4 year period.
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Table 1: Characteristics of the rainfall-runoff events recorded in the three monitored sites.

Characteristics	Louvain-la-Neuve (6 ha)	Walhain (16 ha)	St-Truiden (300 ha)
Number of events	71	83	46
Mean rainfall (mm)	11.4	12.4	18.6
Mean runoff volume (mm)	0.3	0.7	NA
Monitoring periods	01/2001 - 12/2002 01/2005 - 12/2006	01/2001 - 08/2002 01/2005 - 12/2006	05/2002 - 12/2006

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.

Grade	Roughness (cm)
R0	0 - 1
R1	1 - 2
R2	2 - 5
R3	5 - 10
R4	> 10

(b) Classes of soil surface crusting.

Notation	Description
F0	Initial fragmentary structure
F11	Altered fragmentary state with structural crusts
F12	Local appearance of depositional crusts
F2	Continuous state with depositional crusts

(c) Classes of crop cover.

Notation	Area covered by canopy or litter (%)
C 1	From 0 to 20%
C 2	From 21 to 60%
C 3	From 61 to 100%

Table 3: Soil surface combinations selected for rainfall simulation, typical agricultural situations and observation of runoff during the simulations.

Combinations	Period(s) of observation	Typical agricultural situations	Runoff
C1-F0-R4	January April	bare and ploughed fields bare field with ridges	No
C1-F0-R3	March-April December	bare and ploughed field bare field	No
C1-F0-R2	April-June August-December	bare field with fine seedbed bare field with crop residues	No
C1-F0-R1	April June October-November	bare field with fine seedbed growing maize bare field with mulch	No
C1-F11-R3	December-February April	bare field bare and ploughed field	No
C1-F11-R2	From November to June	bare field	Yes
C1-F11-R1	May-June November-December	row crops bare field or field with growing crop	Yes
C1-F12-R2	January-March	growing winter cereals	Yes
C1-F12-R1	January-March May	winter cereals growing peas or sugar beets	Yes
C2-F11-R2	April November	growing crops cover crops	No
C2-F12-R2	April November	growing crops cover crops	Yes
C3-F11-R2	February October-December	winter cereals cover crops	No
C3-F11-R1	June-July November-December	sugar beets, maize, chicory maize residues, cover crops	No
C3-F12-R2	February October	winter cereals cover crops	No
C3-F12-R1	January-March July-October	winter cereals row crops and cover crops	Yes
C3-F12-R0	April-October	winter cereals (April-May); row crops and flax (June-October)	Yes
C3-F2-R0	April-October	winter cereals (April-May); row crops and flax (June-October)	Yes

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.

Soil surface Combination	Runoff coefficient (%)		Infiltration rate (mm.h^{-1})	
	Mean value	SD	Mean value	SD
C1-F11-R1	35 ^b	5	39 ^d	3
C1-F12-R1	58 ^c	8	25 ^c	7
C1-F11-R2	42 ^b	6	35 ^d	4
C1-F12-R2	33 ^b	8	40 ^d	8
C2-F12-R2	25 ^b	2	45 ^d	2
C3-F12-R0	45 ^b	3	33 ^d	2
C3-F2-R0	57 ^c	3	26 ^c	3
C3-F12-R1	13 ^a	5	52 ^e	3
Wheel track	95 ^e	3	3 ^a	3
Maize line	90 ^e	3	6 ^a	2
Grassed buffer strip	62 ^c	5	23 ^c	3
Grassed waterway	73 ^d	3	16 ^b	3
Orchard (wheel track)	78 ^d	5	13 ^b	3
Orchard (grass)	33 ^b	9	40 ^d	8

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.

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

(b) Classification of runoff risk

Runoff risk	Infiltration rate (mm.h ⁻¹)	I _{RUNOFF}	I _{CATCHMENT}
No risk	> 60	0	NA
Low risk	40 - 60	1	0 - 0.9
Medium risk	20 - 39	2	1 - 1.9
High risk	< 20	3	2 - 3

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

Crop	January	February	March	April	May	June	July	August	September	October	November	December
Wheat									Intercrop	Intercrop		
Flax								Intercrop	Intercrop	Intercrop	Intercrop	Intercrop
Sugarbeet	Intercrop	Intercrop										
Maize	Intercrop	Intercrop										
Potatoes	Intercrop	Intercrop	Intercrop						Intercrop	Intercrop	Intercrop	Intercrop

Table 6: Surface (%) covered by the different crops in the Walhain and Sint-Truiden study sites.

	Walhain (16 ha)				Sint-Truiden (300 ha)				
	2001	2002	2005	2006	2002	2003	2004	2005	2006
Wheat	26	74	55	37	11	44	38	38	37
Flax	0	0	0	0	0	16	6	4	14
Sugarbeet	0	26	34	35	46	16	20	34	32
Maize	74	0	11	8	21	1	10	2	0
Potatoes	0	0	0	20	16	12	8	14	7
Other crops	0	0	0	0	6	11	18	8	10

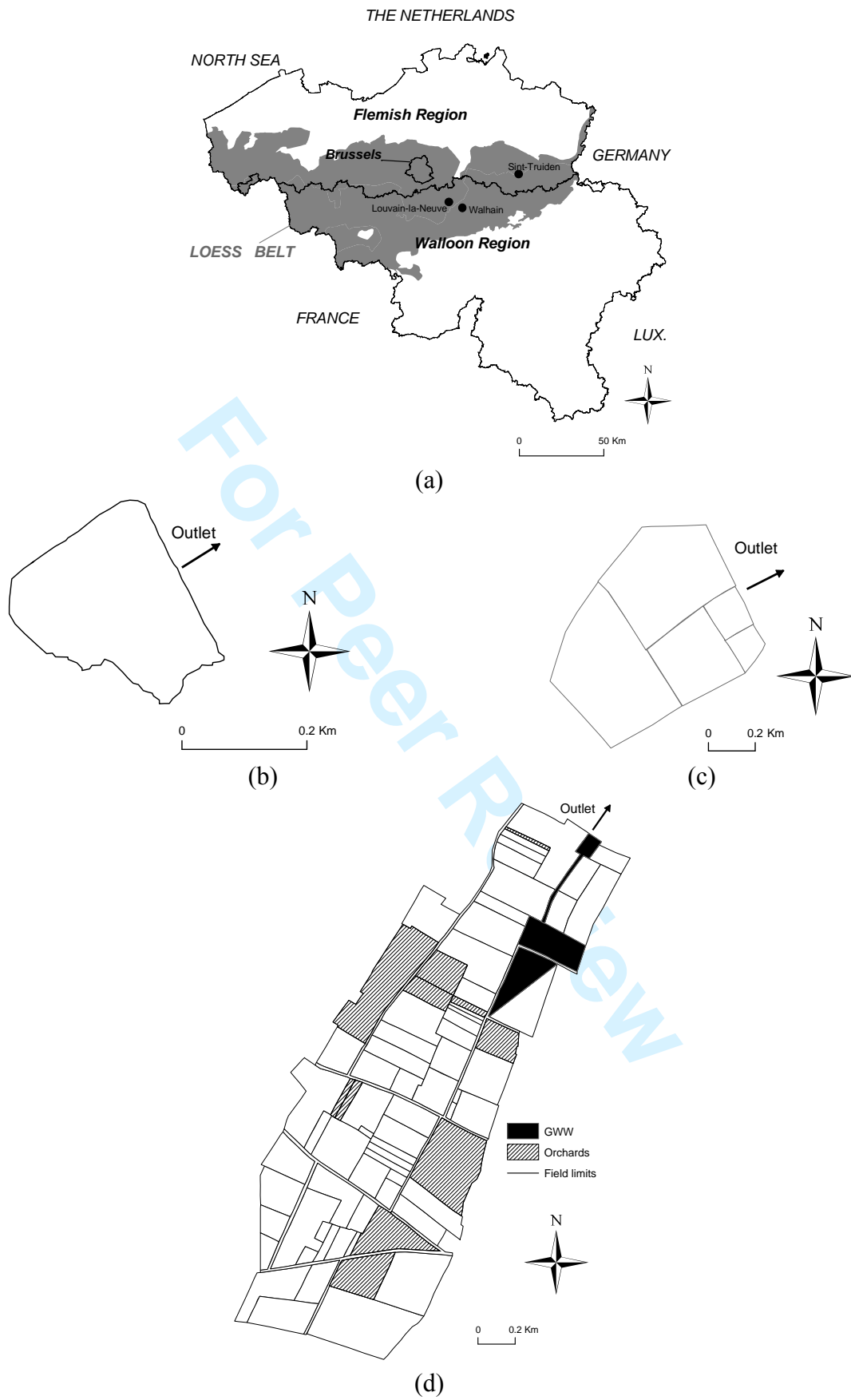


Figure 1

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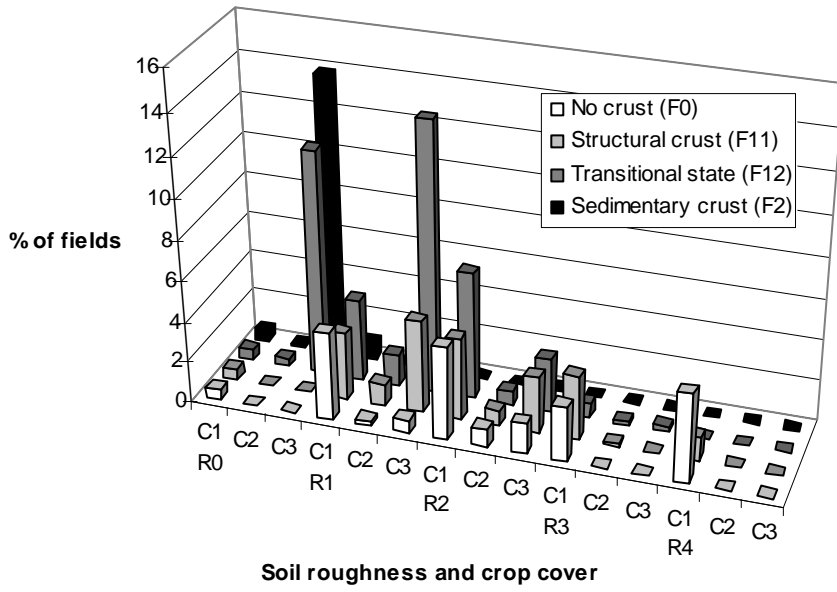


Figure 2

Peer Review

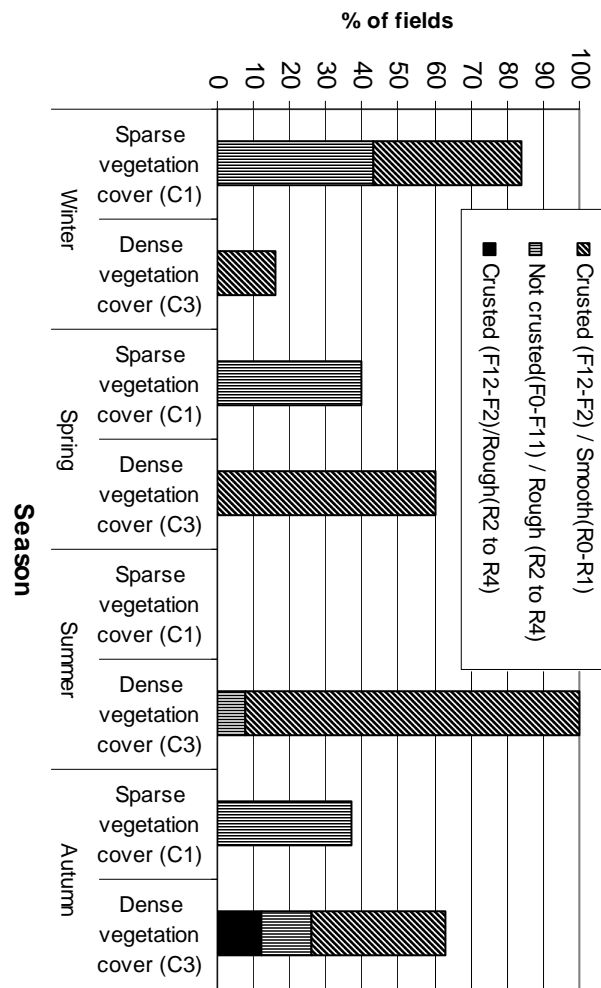


Figure 3

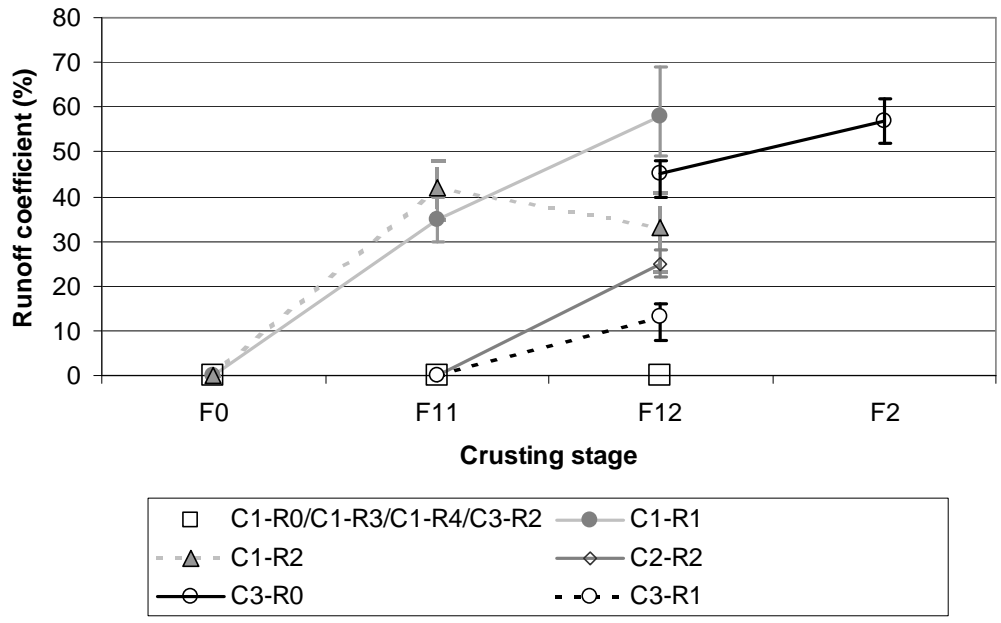
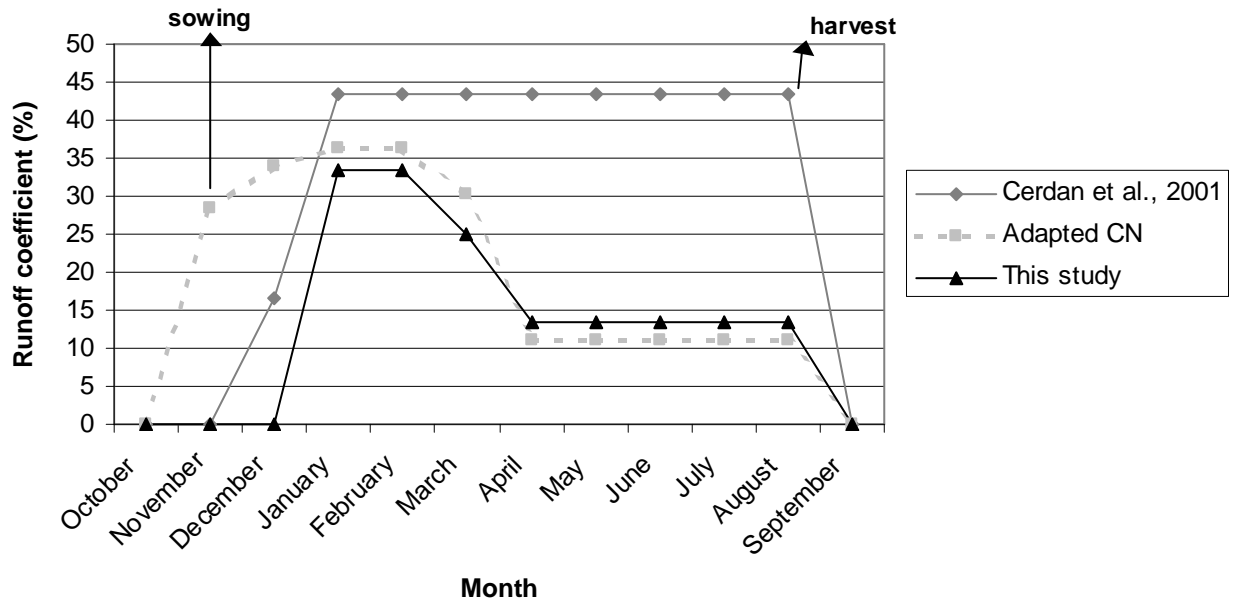


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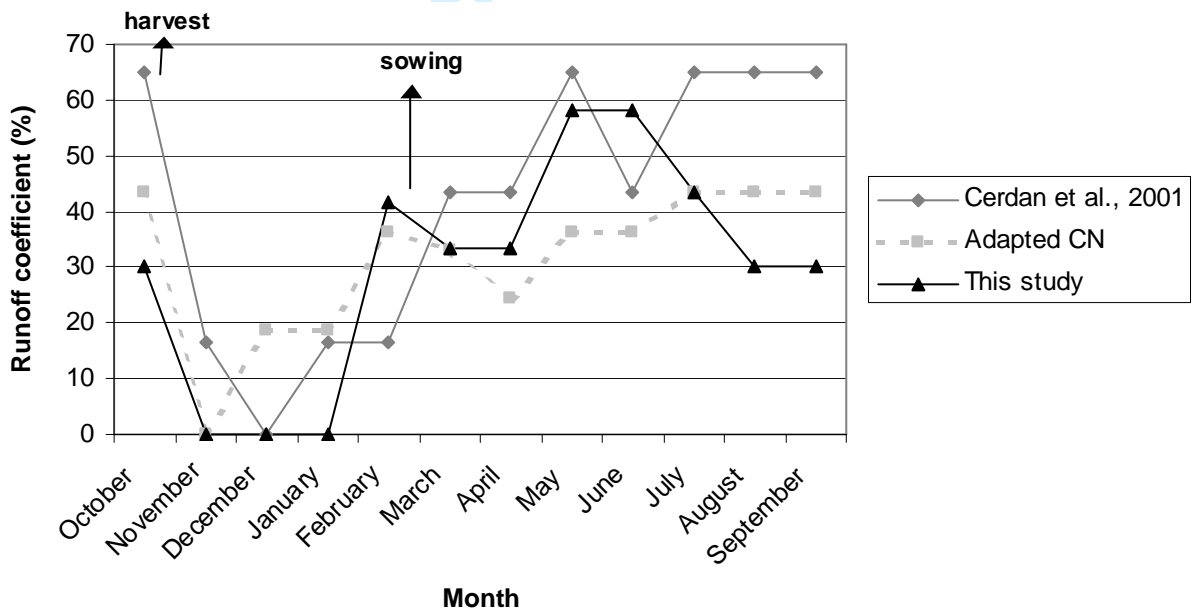
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Figure 5



(a)



(b)

Figure 6

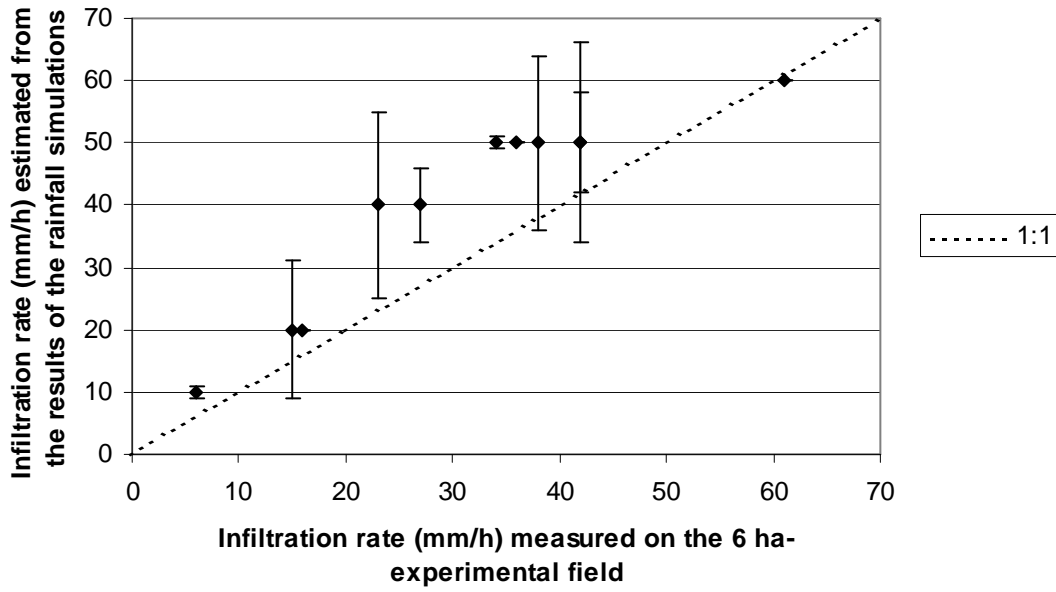


Figure 7

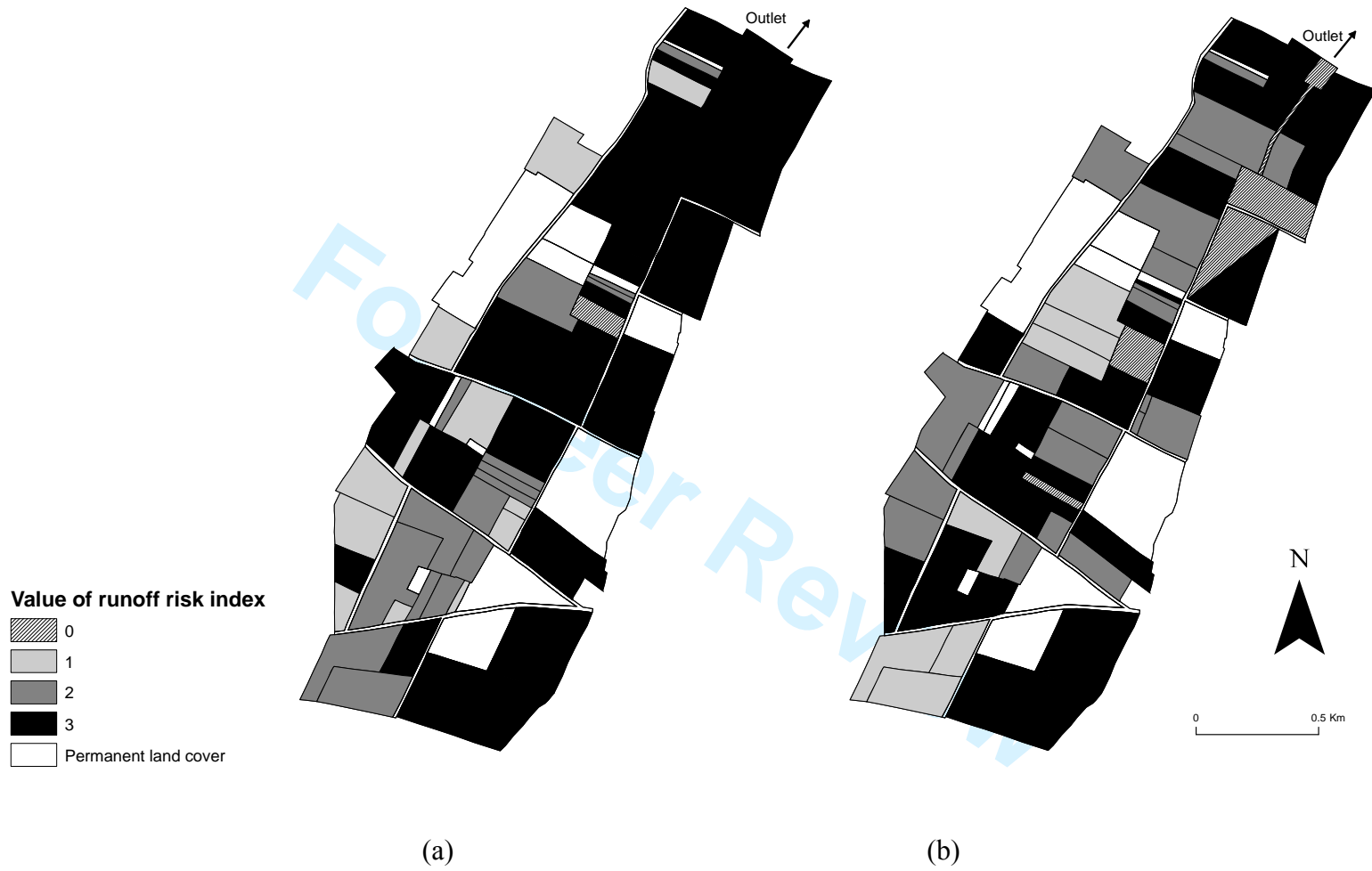
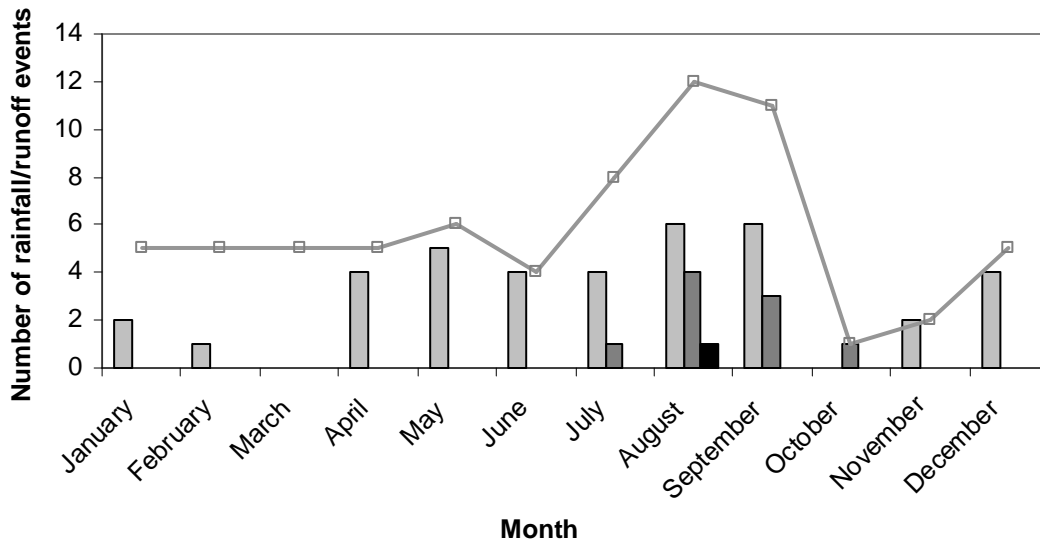
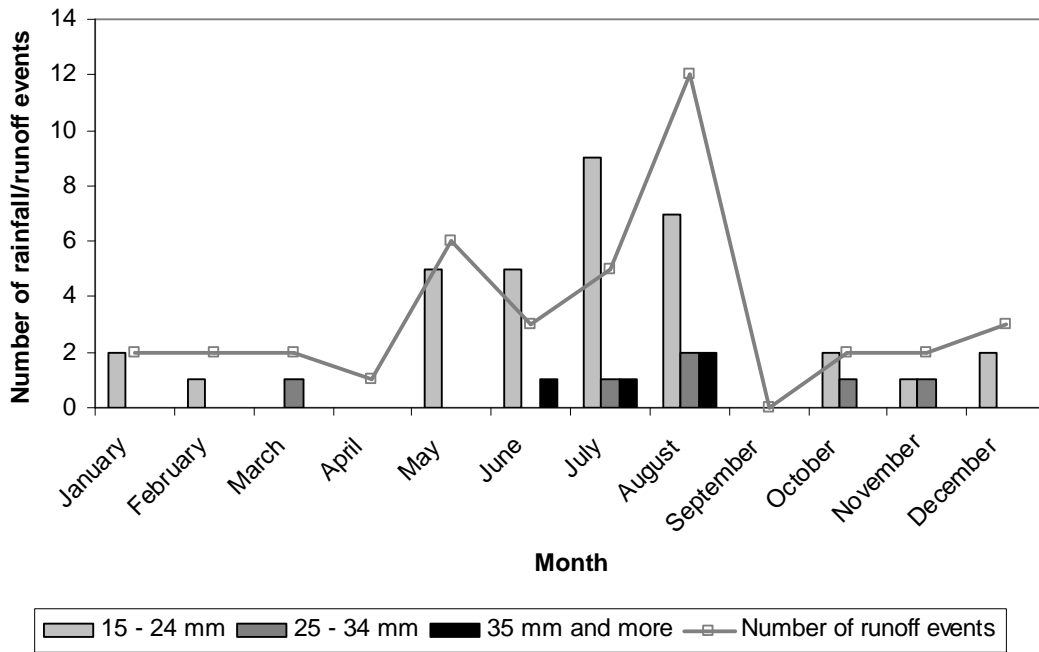


Figure 8

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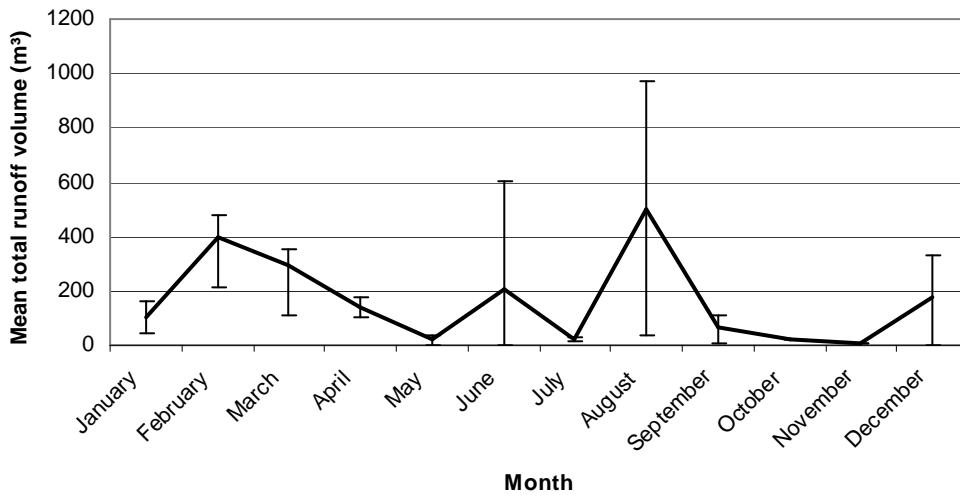


(a)

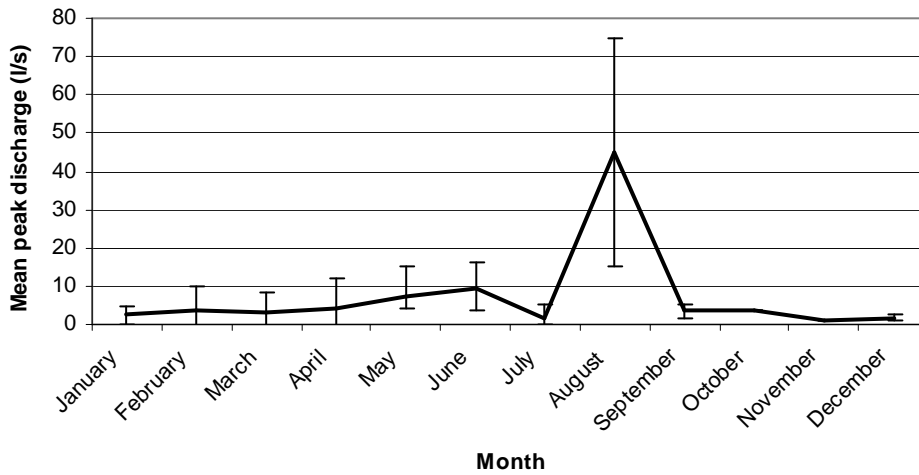


(b)

Figure 9



(a)



(b)

Figure 10