Effectiveness of erosion mitigation measures to prevent muddy floods: A case study in the Belgian loam belt

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Abstract

During the previous decade, 68 per cent of the municipalities in the Belgian loam belt have been confronted with muddy floods from agricultural catchments after intense rainfall. Runoff concentrates in dry valleys and causes damage to infrastructure and housing property downstream. A typical problem area is the village of Velm where a permanent river is constrained by a culvert designed to accommodate its peak discharge. However, the design of the culvert does not take the local flooding from seven dry valleys just upstream into account. This study focuses peak discharge from one of these agricultural catchments (c. 300 ha). The Meshed Hydrological Model (MHM) is used to evaluate the effectiveness of mitigation measures to reduce flooding under seasonal variation of soil cover in cropland and difference in land use patterns i.e. before and after land consolidation. The land cover spatial pattern was mapped at regular intervals during 2003. The largest potential of runoff generation occurs in December, and therefore represents a worst-case scenario. Mitigation measures implemented after the extreme event of August, 2002 (a 12 ha grassed waterway and a retention dam in the thalweg) alleviate the flooding risk in Velm. The model simulates a peak discharge and a runoff volume reduction of more than 40%. The retention pond would buffer all the generated runoff volume for the selected worst-case scenario. Land consolidation carried out in the 1970s has led to a 33 per cent rise of peak discharge and to a 19 per cent increase of runoff volume. The major role played by a new consolidation road built in the thalweg on runoff concentration is highlighted. Implementation of additional soil conservation measures is therefore needed to limit runoff generation within the catchment.

Keywords : muddy floods; agricultural catchment; grassed waterway (GWW); modelling; Belgian loam belt

1. Introduction

Many villages of the Belgian loam belt (Fig. 1) are confronted with muddy floods from small agricultural catchments (c. 100 ha – 1000 ha). These floods occur after intense rainfall, mainly at the end of spring or early in the summer, and cause important damage to infrastructure and housing property in the villages located downstream (Verstraeten and Poesen, 1999; Verstraeten et al., 2003). A survey undertaken in the Walloon Region (Fig. 1a) shows that muddy floods have affected 68 % of the municipalities of the loam belt from 1990 to 2000. Furthermore, 80 % of these municipalities were flooded at least twice during this period (Bielders et al., 2003). Other regions in the north-western European loam belt experience similar flooding : the South Downs, UK (Boardman et al., 2003); and northern France (Souchère et al., 2003). Previous studies focused on erosion phenomena at the small catchment scale (Vandaele and Poesen, 1995; Beuselinck et al., 2000; Chaplot and Le Bissonnais, 2000; Steegen et al., 2000; Cerdan et al., 2002), but nearly none investigated the flood risk issue and the effectiveness of erosion control measures for villages located downstream of one or several small cultivated catchments (< 500 ha). Since discharges are not normally measured in the thalweg of these small catchments, expert-based models can offer a solution (Cerdan et al., 2001).

The impact of muddy floods on infrastructure has increased in the last 30 years for several reasons (Boardman et al., 1994; Boardman et al., 2003). Grassland has progressively been converted into cropland while summer crops (maize, sugar beets, potatoes, oilseed rape) increased at the expense of winter cereals. These summer crops provide a low soil cover during the intense storms of May and June. Furthermore, they require a fine seedbed that is very sensitive to surface sealing. Moreover, increase in farm size, agricultural intensification as well as inefficiency of land planning that led to housing construction in critical zones are frequently mentioned as causes for increased flooding (Poiret, 1999; Bielders et al., 2003; Souchère et al., 2003).

Several types of measures can be implemented to mitigate muddy floods. A first type of actions aims at preventing runoff generation. Cover crops during the dormant period and alternative agricultural practices, such as “no-till”, aim to prevent the generation of runoff. Grassed buffer strips or grassed waterways (GWW) slow runoff down and in some cases enhance reinfiltration. Grassed buffer strips along field borders are up to 6m-wide and 200m-long. They increase infiltration and decrease net soil loss (Le Bissonnais et al., 2004). In contrast, GWW are larger (min. 10m-wide) and installed in the thalweg (Fiener and Auerswald, 2003). They have a potential to reduce runoff volume and peak discharge rate, especially in small watersheds, up to 15 ha (Fiener and Auerswald, 2005). Finally, water retention structures can be built in order to buffer runoff and reduce peak discharges in the villages downstream.

Although mitigation measures are currently being installed in several catchments in Flanders (Fig.1), there is no consistent monitoring of the effects of these measures on reducing flood risk. Such assessment is urgently needed, given the farmers’ and the local inhabitants’ confidence would be durably damaged if the measures were revealed inefficient during heavy rainfall.

This study aims to assess the effectiveness of erosion control measures to reduce the downstream impacts of muddy floods from a catchment without permanent stream (hereafter referred to as a “dry valley”). A spatially-distributed hydrological model designed to simulate heavy rainfall events and based on expert-judgement is used to assess flooding under different patterns of seasonal crop cover. Furthermore, the influence of the land consolidation operation carried out in 1977 on runoff will also be addressed.

2. Materials and methods

2.1. Study area

During the last decade, the village of Velm, located South of Sint-Truiden (Flanders, Belgium), has been confronted at least 10 times with muddy floods from agricultural catchments. In total, seven agricultural catchments with a “dry valley” morphology and covering all together an area of 930 ha drain into the Molenbeek river directly upstream of its passage through Velm village (Fig. 1a). In the 1980s, a culvert with a capacity of 4 $m^3.s^{-1}$ was built to canalize the river across the village. This culvert was designed on bankfull discharge of the Molenbeek draining the large catchment upstream of Gingelom (Fig. 1). However, the additional runoff from the seven dry valleys was not taken into account, and consequently the village is flooded when an additional large amount of muddy water from these dry valleys drains into the river.

This study focuses on one of these dry valley systems with an altitude between 67 and 106 meters and an area of 300 ha (Fig. 1). The soils within the catchment are loess-derived luvisols. A topsoil sample typically contains 100 g. kg^{-1} clay, 800 g. kg^{-1} silt and 100 g. kg^{-1} sand (Baeyens, 1958). Central Belgium has a temperate climate with evenly distributed rainfall and a mean annual temperature of 9.9 °C. Mean annual precipitation reaches 817 mm (Hufty, 2001). After repeated floods, it was finally decided in 2002 to construct an earthen retention dam with a capacity of 2000 m^3 and a grassed buffer strip of 12 ha in the lower part of the thalweg.

2.2. Field surveys

Several land cover classes are permanent throughout the year in the study area (Fig. 1). However, for cropland, four field surveys were carried out in 2003 to document the seasonal variability of the soil cover by vegetation (Fig. 2). The April and December surveys followed the spring and fall sowings, respectively. The June survey corresponds to the situation before the harvest of both winter and summer crops, when the crop cover is well developed. Finally, the September survey outlines the intermediary situation occurring just between the harvest of winter wheat (*Triticum aestivum L.*) and flax (*Linum usitatissimum L.*)when fields are not yet ploughed, and potatoes (*Solanum tuberosum L.*) and sugar beets (*Beta vulgaris L.*) are not yet harvested.

2.3. The hydrological model

The "Meshed Hydrological Model" (MHM) is used in this study (Randriamaherisoa, 1993; El Idrissi and Persoons, 1997; Hang, 2002). This model, coupled with geographical information systems (GIS) functionalities, is able to simulate the discharge at every point in the catchment, from slope, flow direction and land cover. This deterministic spatially-distributed model is based upon several hypotheses that are only valid in the case of a heavy rainfall event. It subdivides the catchment into regular grid cells whose physical properties are supposed to be uniform. For this study, two-meters-cells were used, in order to account for the road network and to obtain a trade-off between precision of the results and computing time. A hydrological class *ij* is assigned to each cell, from its land cover *i* and slope *j*. A runoff coefficient and a runoff velocity are attributed to each hydrological class. The model relies on two different functions. A runoff production function determines the transformation of total rainfall into net runoff (eq. 1).

$$C_{ij} = \frac{R_{ij}}{P} \quad (1)$$

where C_{ij} is the runoff coefficient for hydrological class *ij* [dimensionless]; R_{ij} is the runoff for the class *ij* [mm]; P is the total rainfall [mm].

Runoff coefficients evolve asymptotically towards a constant value during rainfall, while soil saturation is progressively reached. The MHM model, however, is based on linearity and permanence of the production function through an event. This is an acceptable hypothesis in the case of intense rainfall, when rainfall intensity rapidly exceeds the infiltration capacity of the soil. The production function determines the proportion of rainfall that runs off from each cell. A transfer function determines the flow of runoff between the cells to the outlet. This function is based on the runoff velocities given for each hydrological class *ij*. Transfer velocities are considered constant during an event and the transferred volume cannot reinfiltrate in gridcells downstream. This is acceptable in case of heavy rainfall when infiltration capacity is exceeded all over the catchment. In the absence of a hydrographical network, the Linsley method is used to represent the rainfall-runoff relationship (Linsley et al., 1992). This method subdivides the catchment in *n* areas (A_n) of equal transfer time to the outlet. Isochrones represent the contour lines nΔt between such areas, where Δt is the time interval between two isochrones. This subdivision is made on the basis of the velocity matrix, as well as on the flow directions. The hydrograph at the outlet consists of runoff from successive isochrone areas located each a temporal lag Δt further upstream.The transfer function needs to be associated with the production function to determine rainfall that runs off for each isochrone area (eq. 2).

$$Q(t) = \sum_{k=1}^{n} A_k \times C_k \times I(t-k+1) \quad \text{for (t-k+1)} > 0 \qquad (2)$$

where Q(t) is the discharge at the outlet at time *t* [$m^3.s^{-1}$]; A_k is the area of the isochrone k; $C_k = \sum^{ij} C_{ij} \times \frac{A_{ij}}{A_k}$ is the runoff coefficient for each isochrone area *k*; I(t) is the rainfall intensity at time *t*. The final result is a surface runoff hydrograph (Randriamaherisoa, 1993; El Idrissi and Persoons, 1997; Hang, 2002).

2.4. The model input dataset

Five data layers are needed to compute runoff at the catchment outlet. First, a land cover dataset is created assigning a cover class at each field of the catchment field pattern dataset (see section 3.1). Then, the slope and flow direction spatial datasets are calculated from the digital elevation model (DEM), with 2m size grid cells. The DEM is obtained by digitising the contour lines (equidistance 2.50m) of the 1:10,000 topographical map (National Geographical Institute of Belgium). The "inverse distance weighted" (IDW) method is used for interpolation. An intense storm is then simulated, with a 10 year return period. Finally, a configuration dataset containing runoff coefficients and velocities for each hydrological class is built. For grassed areas, road network and woodland, the coefficients were taken from previous studies carried out in the Belgian loam belt (Ministère de l'Equipement et des Transports, 2002; Rapport final de la Convention ADALI, 2002). Unfortunately, croplands were only characterized by a global runoff coefficient and velocity in these studies. In order to study the temporal variability of these parameters for croplands, the field survey method developed by Cerdan et al. (2002) for the STREAM model was combined with the experimental data for other types of land use from the studies mentioned above. The STREAM model takes surface crusting, soil roughness and vegetation cover into account to determine a relative category of runoff sensitivity. These categories were determined by field surveys (Table 1). Runoff coefficients and velocities were then attributed to these relative categories, in such a way that cropland values fall within the range of values for the other types of land use from previous experimental studies carried out in the Belgian loam belt (Table 2). The following sequence of increasing probability to generate runoff was used (e.g. Musy and Higy, 2004):

Woodlands < Grassland < Dense crops < Sparse crops < Bare soils < Roads

2.5. Simulations

In order to select a worst-case scenario, four seasons are simulated, to evaluate the most sensitive period for flooding. The land cover spatial datasets for each season are transformed into two-meter gridcells. The model is run with the same rainfall event for the four different land cover datasets. Furthermore, the impact of the land consolidation of 1977 is investigated for this specific catchment. The former field pattern is mapped from digitised aerial photographs of 1957. A visual observation of the photographs allowed the recognition of most types of cover within the catchment. For the remaining 7% of the fields, the land cover from agricultural statistics for the loam belt were used (Institut National de Statistiques, 1957). A land cover class was randomly assigned to each field for which the cover was impossible to distinguish on the photograph, according to these statistics. The impact of the GWW installed in the thalweg in 2002 is analysed. For this purpose, the worst-case scenario is simulated. Finally, the effect of the retention dam is also addressed.

2.6 Strengthening confidence in the model for extreme events

A validation of the MHM model has already been successfully implemented in catchments under temperate and semi-arid climates (El Idrissi, 1996; Ntaguzwa, 1999; Hang, 2002). The model is also used by the hydrological service (SETHY, Service d'ETudes HYdrologiques) of the Walloon Region of Belgium. As the model does not simulate water reinfiltration, the topographic index (eq. 3) has been computed at both extremities of the GWW to check its topographic sensitivity to surface saturation (Beven and Kirkby, 1979; Moore et al., 1988).

$$I = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (3)$$

where I is the topographic index; α is the local catchment area per unit contour length and is expressed in meters ;β is the slope of the ground surface (in degrees). Typically, a large local catchment area and a small slope result in a high value of the index, meaning that the groundwater table is located at a low depth and that wetter soil can be expected (Rodhe and Seibert, 1999).

Furthermore, to increase the confidence in the model for this specific application, several events were used for comparison of simulated discharges with the observed ones at the catchment outlet. Water level measurements behind a dam are used. Water is temporally stored in a retention pond and drains through two pipes of 0.25m and 0.2m diameter in the bottom of the dam. Few runoff events have been recorded since 2003. A crest stage recorder was installed behind the dam to measure water level when runoff to the outlet occurred. Such a recorder consists of a plastic tube with a length of water-sensitive tape which changes colour on contact with water (Hooke and Mant, 2000). Water levels were then converted to outflow discharge of the pipes in the dam by eq. 4 (Ilaco, 1985).

$$Q = m \times A \times \sqrt{2 \times g \times h} \qquad (4)$$

where *Q* is the discharge ($m^3.s^{-1}$); *m* is the discharge coefficient (here equal to 0.62); *A* is the cross-section of the drain (m^2); *g* is the gravity acceleration (9.81 $m^2. s^{-1}$) and *h* is the hydraulic head (m).A tipping bucket raingauge was installed 500 meters north of the outlet.

3. Results and discussion

3.1. Strenghtening confidence in the model

According to the litterature, we obtained very high values of the topographic index at the GWW upstream extremity (I =16.1) and the catchment outlet (I =16.7). By comparison, Beven and Wood (1983) found that the first saturated areas of a catchment had a topographic index value close to 15. Rodhe and Steibert (1999) found maximal I values of ~17 in Swedish catchments. This means that the GWW will be very quickly saturated during a storm.

Reinfiltration is hence highly unlikely in that place, and the hypothesis of the model is hence acceptable.

Runoff occurred three times in 2004 (Table 3). The occurrence of runoff is correctly predicted even if the peak discharge is overestimated by ~50%. It remains hence in the same order of magnitude. Other recorded rainfall events that did not lead to runoff at the outlet were simulated with the model. Simulated runoff during these events was very low and completely buffered by the retention dam.

3.2. Selection of a worst-case scenario

The simulation of the event with a 10 year return period shows that highest peak discharges and runoff volumes are reached in December (1.0 $m^3.s^{-1}$; 4586 m^3), while they are lowest in September (0.3 $m^3.s^{-1}$; 1715 m^3; Fig. 3; Table 4). These results are explained by the higher proportion of bare soil (35 %) and sparsely covered soil (43 %) at the beginning of winter (Fig. 2d). The December situation is hence chosen as a worst-case scenario. June is the second highest risk period, because crop cover is quite low and crusts develop on these sparsely covered soils (Fig.2b; Table 1).

3.3. Potential effect of land consolidation on runoff

After the 1977 consolidation, the mean size of the fields in the study area increased about four-fold from 1.02 ha in 1957 to 4.34 ha in 2003. This is in agreement with Verstraeten and Poesen (1999) and Beuselinck et al. (2000) who studied land consolidation in an area of central Belgium. The land cover before the consolidation in the 1970s (Fig. 4a) is compared to that of April 2003 (Fig. 4b). For an event with a 10 year return period, runoff volume increased by 19 per cent following the land consolidation operation (from 1443 m^3 in 1957 to

1715 m³ in 2003), while peak discharge rose by 33 per cent (Fig. 5), reaching 0.3 $m^3.s^{-1}$ for the 1957 simulation, against 0.4 $m^3.s^{-1}$ in April 2003. The lag time is similar in both situations and is close to 75 minutes (Fig. 5). However, the hydrograph shape is different. The rising limb is more gradual before the land consolidation scheme. After land consolidation, the first peak in the hydrograph, corresponds to the sudden arrival of water that concentrates on the road in the thalweg.

In comparison with other studies, land consolidation does not lead to a sharp rise of runoff volume (e.g. more than 75 % rise according to Souchère et al., 2003). Two reasons can be put forward. First, the Belgian openfield context is different from that of bocage landscapes. In the study area, no grassland or hedgerows were present before 1977. Consequently, there was no ploughing up of grassed areas, which resulted in an important increase of runoff volume in other European regions. Second, the model does not take into account the ditch network of the catchment, where water can be temporally buffered. This impact is hence underestimated in this study, which highlights the major role played by a consolidation road constructed in the thalweg and leading to an increase of the runoff transfer velocity to the outlet (10 minutes-long sharp rising limb in 2003 instead of a more gradual rising limb lasting for 30 minutes in 1977).

3.4. Impact of the mitigation measures

The impact of the GWW (12 ha) installed in 2002 is simulated for the worst-case scenario (Fig. 6). Peak discharge is reduced by 50 % when the GWW is taken into account (0.5 $m^3.s^{-1}$ instead of 1.0 $m^3.s^{-1}$; Fig. 7; Table 4). Runoff volume transferred to the outlet decreased by 40 per cent (2651 m³ instead of 4586 m³; Table 4). Another very interesting effect of GWW is the lag time increase (+ 16%; Table 4). The rising limb is also more gradual when the GWW is considered (Fig. 7). Results are difficult to compare with the ones obtained in other studies, given the much smaller size of the studied catchments (15 ha in Fiener and Auerswald, 2003) or a too different landscape context (GWW and terraces in the USA e.g. Chow et al., 1999). However, these studies observe the same trends (decrease of both peak discharge and total runoff volume).

The decrease in total runoff volume (1935 m³) when the GWW is considered can be explained by two reasons. First, less runoff has been produced in the GWW due to its lower runoff coefficient (680 m³). Second, a reduction in runoff velocity (0.1 $m.s^{-1}$ instead of 0.27$m.s^{-1}$) upon replacing sparsely covered cropland with a GWW has resulted in a long-tail of runoff. Remaining runoff volume at the outlet (1255 m³) is spread over a longer period. The model does not simulate the whole recession limb in this case, given it is limited to a 180-minutes simulation.

In relation to the flood risk in Velm village, the maximal observed outflow peak discharge reached 0.47 $m^3.s^{-1}$ in 2004, which is very close to the one simulated by the model taking the GWW into account (0.50 $m^2.s^{-1}$; Table 4). No flooding of the village resulted in 2004. Given the model overestimates the discharge by ~50% (Table 3), any new flooding of Velm is highly unlikely for the selected worst-case scenario. As the retention pond buffers all the incoming runoff, the diameter of the outflow pipes could be narrowed (with metal plates e.g.) to limit runoff discharge towards the village.

4. Conclusions

This case study in a small agricultural catchment (c. 300 ha) of central Belgium shows that a GWW and a retention dam alleviate the muddy floods risk for Velm village. Peak discharge and total runoff volume are reduced by 50% and 40% respectively, while the lag time increases by 16%. However, land consolidation carried out in the 1970s led to an increase of peak discharge (33%) and total runoff volume (19%). It is explained by a rise in field sizes (from 1.02 ha in 1977 to 4.34 ha in 2003) but also and mainly by the construction of a road in the thalweg of the catchment leading to runoff concentration. Consequently, on-site soil conservation measures are to be installed within the catchment to prevent runoff generation and mitigate its concentration in the catchment thalweg. Furthermore, as generated runoff volume is buffered in the retention pond for the selected worst-case scenario, a reduction of the outflow pipes diameter could be envisaged in order to limit the discharge towards the village.

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Tables

Table 1. Runoff sensitivity relative categories for the different crop cover classes and survey periods (after Cerdan et al., 2002)

Crop cover	April	June	September	December
Dense crops (class 3) ; more than 50 % of soil cover by vegetation				
Roughness	R3 [1]	R3	R3	R3
Surface state	F0 [2]	F0	F0	F0
Runoff sensitivity category	0 [3]	0	0	0
Sparse crops (class 2); less than 50 % of soil cover by vegetation				
Roughness	R3	R2	R2	R1
Surface state	F0	F11	F11	F12
Runoff sensitivity category	0	1	1	2
Bare soils (class 1); no soil cover by vegetation				
Roughness	R2	R1	R2	R1
Surface state	F11	F12	F11	F12
Runoff sensitivity category	1	2	1	2

[1] R : soil surface roughness state (height difference between the deepest part of microdepressions and the lowest point of their divide). R0 : 0-1 cm; R1 : 1-2 cm; R2 : 2-5 cm; R3 : 5-10 cm.

[2] F: soil surface crusting stage. F0 : initial fragmentary structure; F11 : altered fragmentary state with structural crusts; F12 : local appearance of depositional crusts; F2 : continuous crusts.

[3] :The runoff sensitivity category range from 0 to 2. The greater the value of the category, the greatest potential to generate runoff.

Table 2. Runoff coefficients and velocities for different months and different land cover classes in the study area

Land cover	Study area covered (%)	Runoff coefficient	Runoff velocity (m/s)
APRIL			
woods	0.28	0.015	0.06
road network	3.50	0.5	0.4
orchards	13.33	0.02	0.1
grassed areas	4.89	0.02	0.1
dense crops	36.35	0.03	0.1
sparse crops	21.67	0.1	0.5
bare soil	21.48	0.15	0.13
JUNE			
woods	0.28	0.015	0.06
road network	3.50	0.5	0.4
orchards	13.33	0.02	0.1
grassed areas	4.89	0.02	0.1
dense crops	74.20	0.03	0.08
sparse crops	2.45	0.3	0.28
bare soil	0.89	0.3	0.28
SEPTEMBER			
woods	0.28	0.015	0.06
road network	3.50	0.5	0.4
orchards	13.33	0.02	0.1
grassed areas	4.89	0.02	0.1
dense crops	40.89	0.03	0.1
sparse crops	8.98	0.15	0.13
bare soil	11.44	0.15	0.13
DECEMBER			
woods	0.28	0.015	0.06
road network	3.50	0.5	0.4
orchards	13.33	0.02	0.1
grassed areas	4.89	0.02	0.1
dense crops	0	0.03	0.1
sparse crops	42.97	0.3	0.27
bare soil	34.90	0.3	0.27

Table 3. Rainfall and discharge in 2003 and 2004

Event date	Rainfall [1] (mm)	Return period [2] (years)	Q out obs. [3] ($m^3.s^{-1}$)	Q out sim.[4] ($m^3.s^{-1}$)
8/07/2004	14.2	5	0	0
17/07/2004	12.2	2 - 5	0	0
21/07/2004	20 (*)	25	0.47	0.70
23/07/2004	23.2 (*)	10	0.47	0.70
8/08/2004	11	2	0	0
13/08/2004	11.2	2 - 5	0	0
14/08/2004	20.6 (*)	2	0.45	0.70

[1]Discharge at the outlet was recorded for the events with (*).
[2] Return periods after Delbeke (2001). They are computed for the rainfall duration considered.
[3] Q out obs. is the outflow discharge calculated from H obs. with eq. (3).
[4] Q out sim. is the simulated outflow discharge after introduction in the MHM model.

Table 4. Peak discharge, total runoff volume and lag time at the catchment outlet for the different situations simulated with the MHM model

Situation	Peak discharge ($m^3.s^{-1}$)	Total runoff volume (m^3)	Lag time (minutes)
April 2003	0.37	1715	70
June 2003	0.50	2365	73
September 2003	0.29	1326	90
December 2003	1.01	4586	75
Before LC [1]	0.30	1443	73
After LC	0.40	1715	71
Comparison	+ 33 %	+ 19 %	- 3 %
Without GWW [2]	1.01	4586	74
With GWW	0.51	2652	86
Comparison	- 49 %	- 42 %	+ 16 %

[1] LC : land consolidation (April situation)
[2] GWW: grassed waterway

Captions of figures

Figure 1. Location map of Velm village, the upstream agricultural catchments and land use of the study area.

Figure 2. Seasonal evolution of land cover in the study area
(a) April; (b) June; (c) September; (d) December

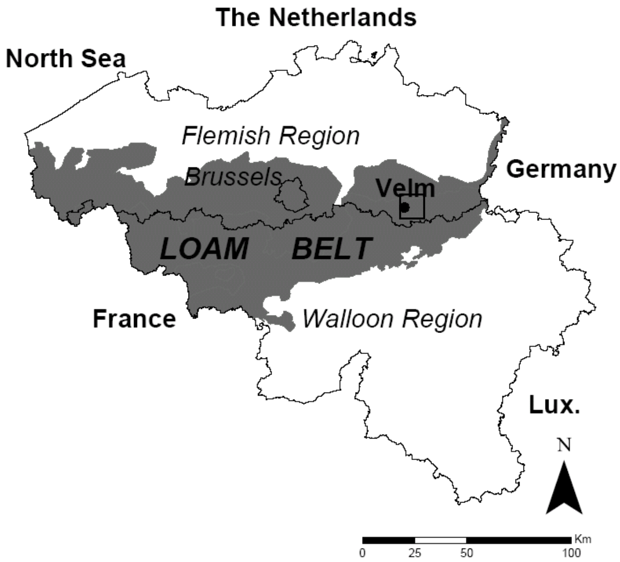
Figure 3. Discharge at the catchment outlet in different seasons according to land cover in 2003 (see the corresponding land cover maps on Fig. 2)

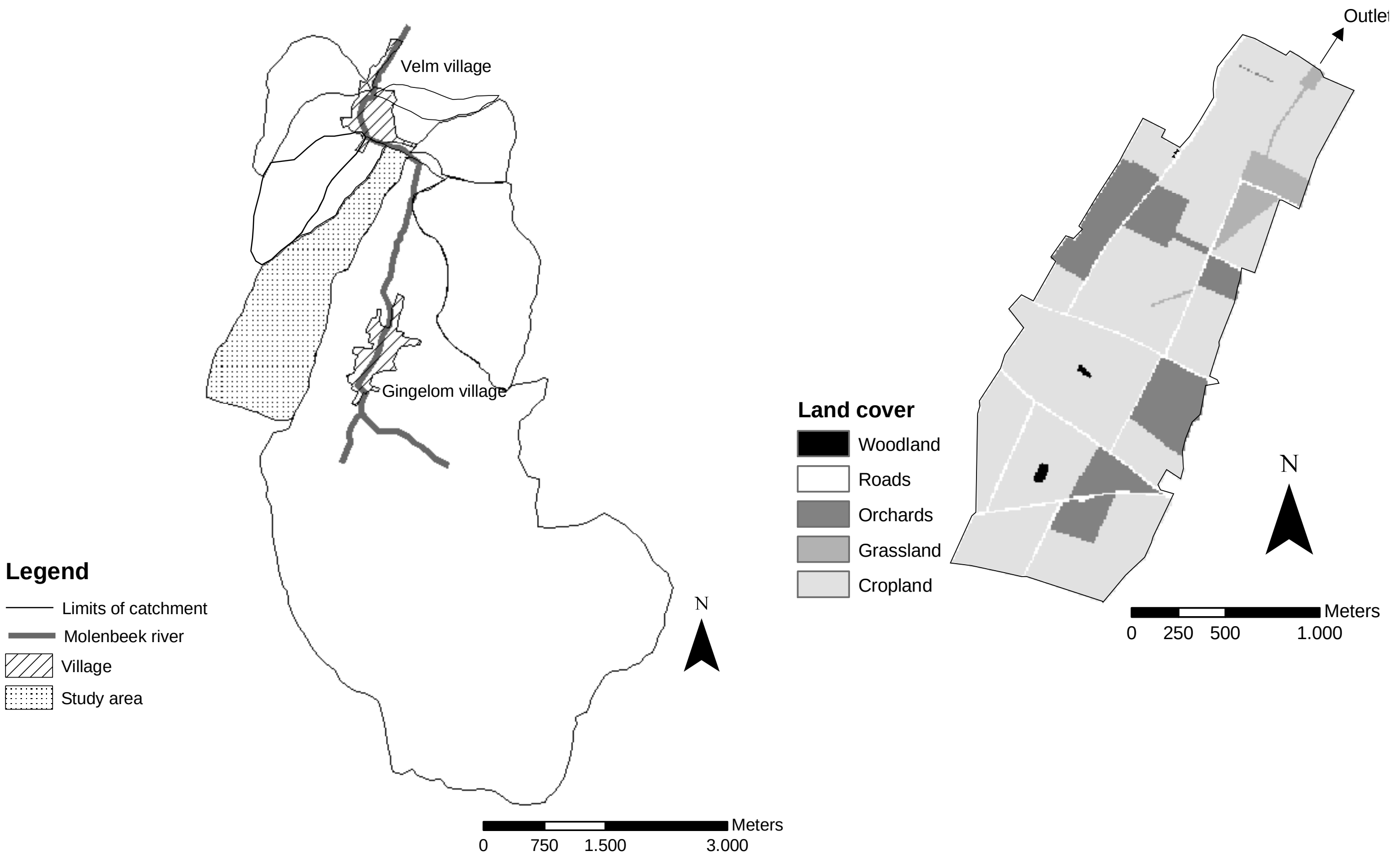
Figure 4. Land use and land cover before (a) and after (b) land consolidation

Figure 5. Simulated hydrographs at the catchment outlet for the situation before and after the land consolidation

Figure 6. Grassed waterway and other land covers in December 2003

Figure 7. Hydrograph at the catchment outlet for the December situation, with and without grassed waterway


The Netherlands
North Sea
Flemish Region
Brussels
Germany
Velm
LOAM BELT
France
Walloon Region
Lux.
N
Km
0 25 50 100


Velm village
Gingelom village
Legend
Limits of catchment
Molenbeek river
Village
Study area
N
Meters
0 750 1.500 3.000
Outlet
Land cover
Woodland
Roads
Orchards
Grassland
Cropland
N
Meters
0 250 500 1.000

(a) (b)

Figure 1

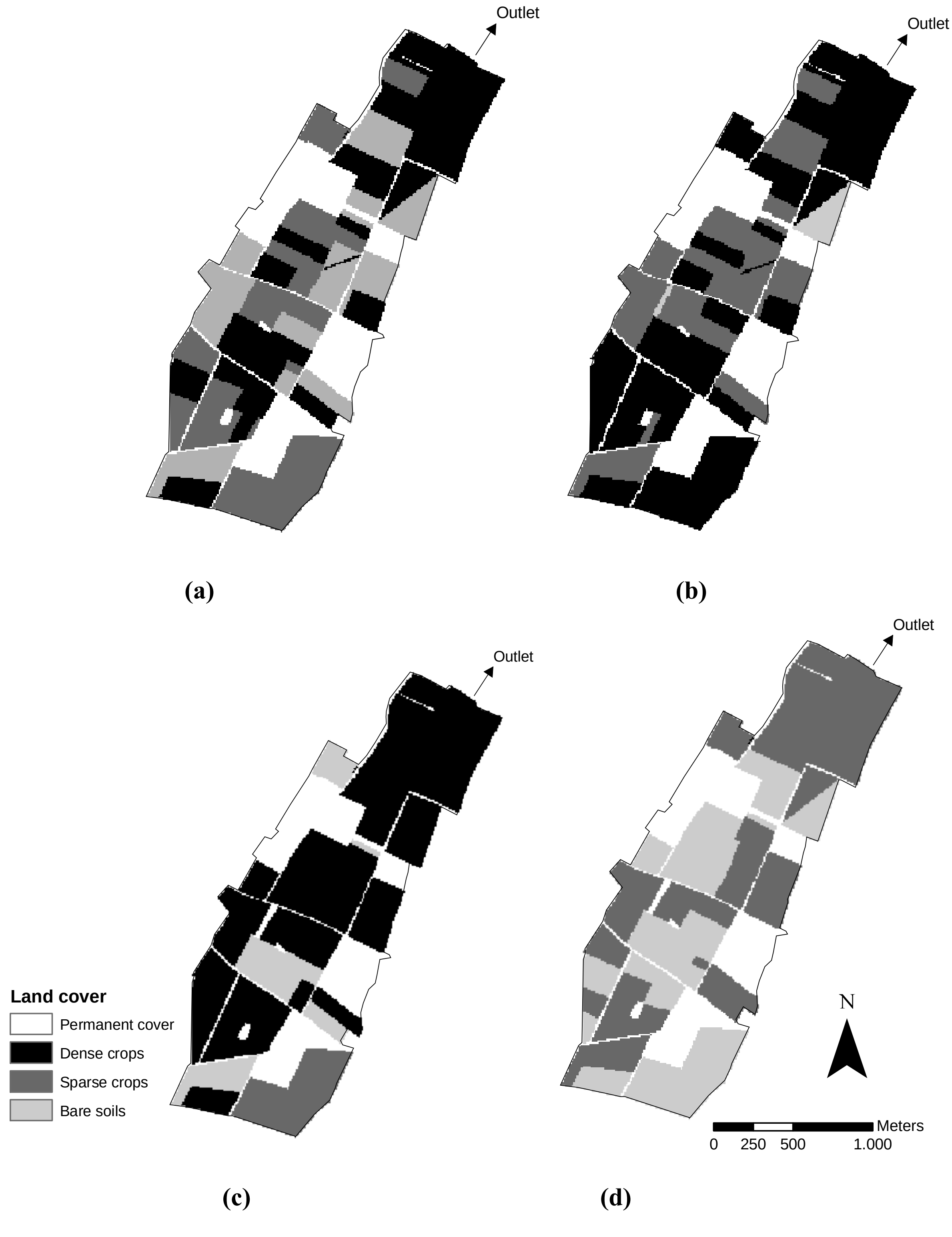
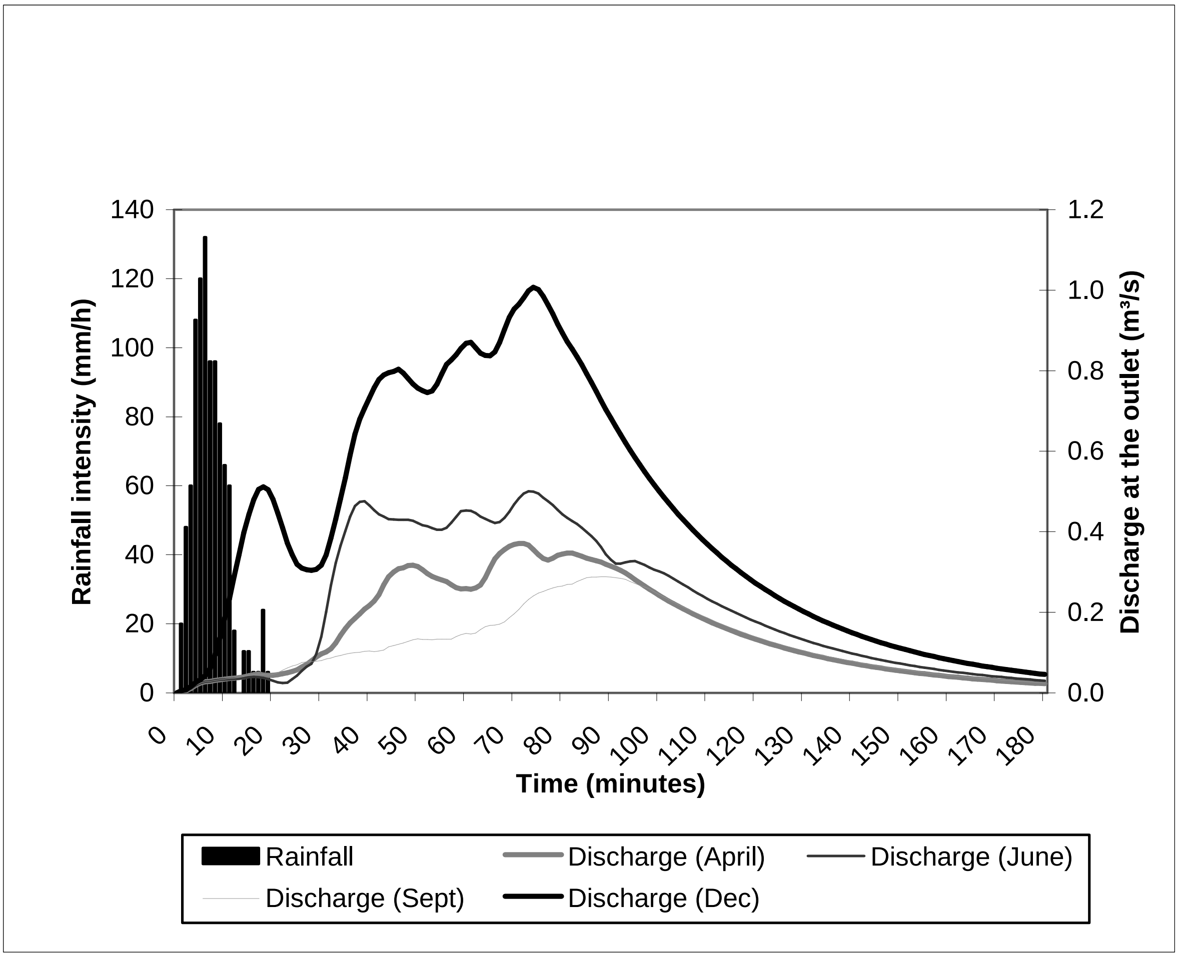

Outlet
Outlet
Outlet
Outlet
(a)
(b)
Land cover
Permanent cover
Dense crops
Sparse crops
Bare soils
N
Meters
0 250 500 1.000
(c)
(d)

Figure 2



140
120
100
80
60
40
20
0
Rainfall intensity (mm/h)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Discharge at the outlet (m³/s)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Time (minutes)
Rainfall
Discharge (April)
Discharge (June)
Discharge (Sept)
Discharge (Dec)

Figure 3


Outlet
Land cover
Permanent cover
Dense crops
Sparse crops
Bare soils
Outlet
N
Meters
0
250
500
1.000

(a) **(b)**

Figure 4

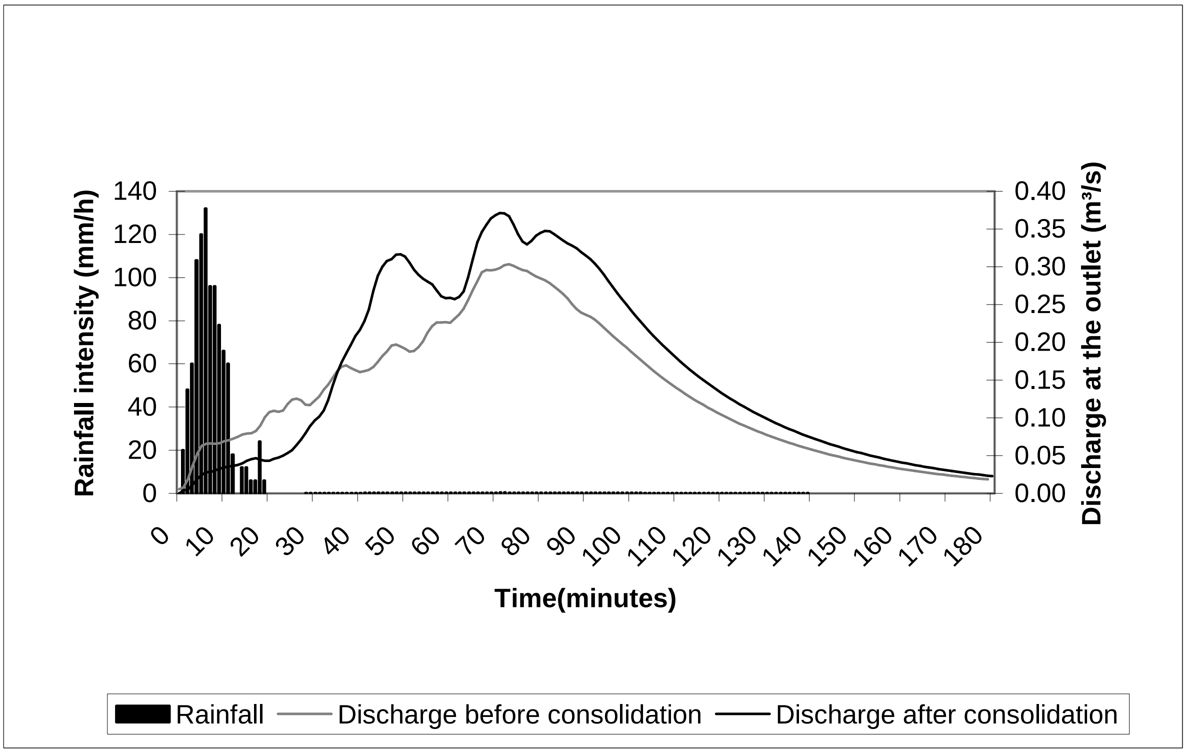

Rainfall intensity (mm/h)
140
120
100
80
60
40
20
0
Discharge at the outlet (m³/s)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Time(minutes)
Rainfall
Discharge before consolidation
Discharge after consolidation

Figure 5

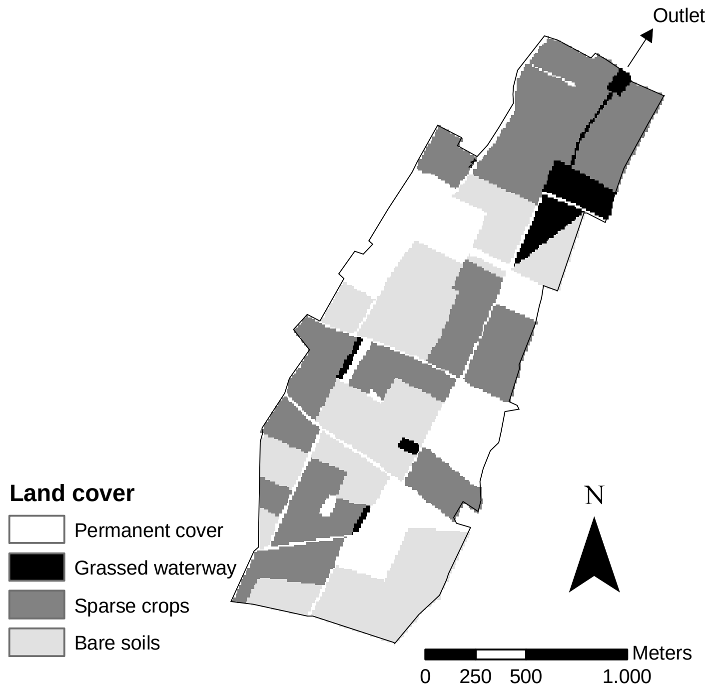
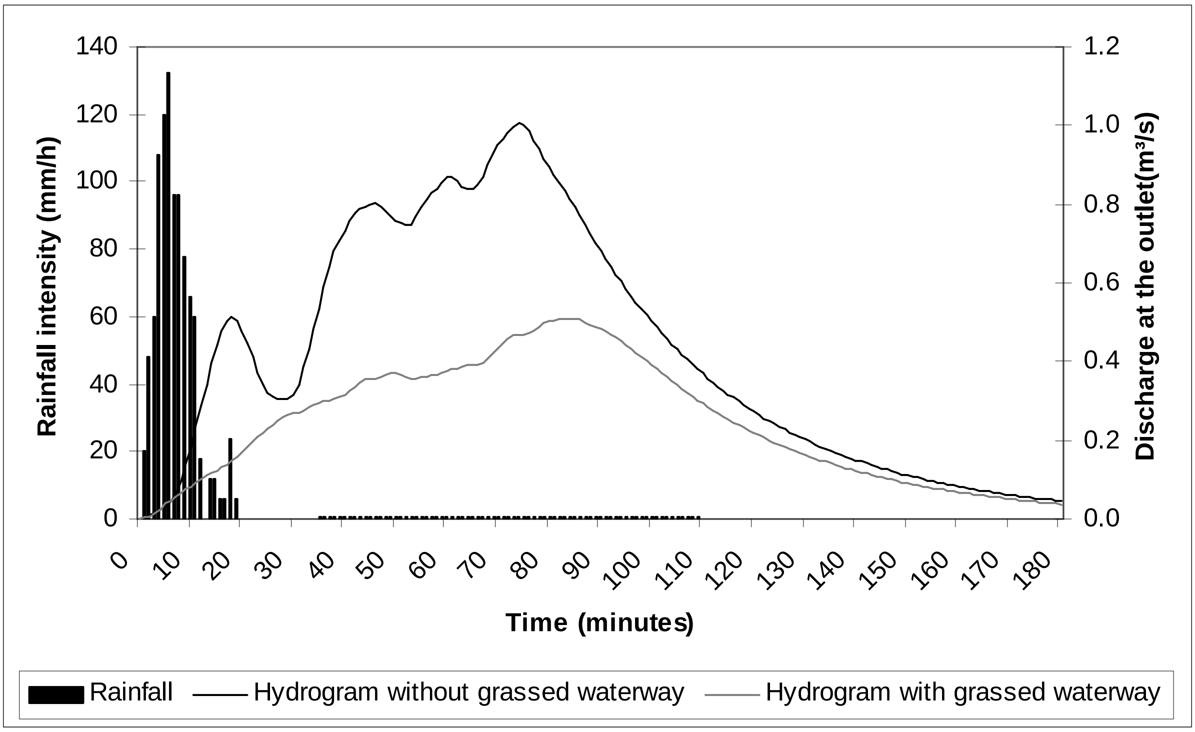

Outlet
Land cover
Permanent cover
Grassed waterway
Sparse crops
Bare soils
N
Meters
0
250
500
1.000

Figure 6



140
120
100
80
60
40
20
0
Rainfall intensity (mm/h)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Discharge at the outlet(m³/s)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Time (minutes)
Rainfall
Hydrogram without grassed waterway
Hydrogram with grassed waterway

Figure 7