Available online at www.sciencedirect.com
ScienceDirect
Agriculture, Ecosystems and Environment 118 (2007) 149–158
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

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

Olivier Evrard [a,1,*], Etienne Persoons [b], Karel Vandaele [c], Bas van Wesemael [a]

[a] Département de Géographie, Université catholique de Louvain, Place Louis Pasteur, 3, B-1348 Louvain-la-Neuve, Belgium
[b] Département des Sciences du Milieu et de l'Aménagement du Territoire, Université catholique de Louvain, Croix du Sud, 2, Bte 2, B-1348 Louvain-la-Neuve, Belgium
[c] Watering van Sint-Truiden, Interbestuurlijke samenwerking Land en Water, Minderbroedersstraat, 16, B-3800 Sint-Truiden, Belgium

Received 10 June 2005; received in revised form 21 February 2006; accepted 28 February 2006
Available online 21 June 2006

## Abstract

During the previous decade, 68% of the municipalities in the Belgian loam belt have been confronted with muddy floods from agricultural catchments after intense rainfall. A muddy flood means that runoff concentrates in a dry valley causing 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 on peak discharge from one of these agricultural catchments (ca. 300 ha). The Meshed Hydrological Model (MHM) is used to evaluate the effectiveness of mitigation measures to reduce flooding. Seasonal variation of soil cover in cropland and difference in land use patterns, i.e. before and after land consolidation is explicitly taken into account. 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 (i.e. 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 the generated runoff volume entirely for the worst-case scenario. Land consolidation carried out in the 1970s has led to an increase in peak discharge by 33% and in runoff volume by 19%. 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 (ca. 100–1000 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. 1) 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 northwestern 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

* Corresponding author. Tel.: +32 10 47 29 91; fax: +32 10 47 28 77.
*E-mail address:* evrard@geog.ucl.ac.be (O. Evrard).
[1] Fonds pour la formation à la Recherche dans l'Industrie et l'Agriculture (FRIA), Belgium.

0167-8809/$ – see front matter 
doi:10.1016/j.agee.2006.02.019

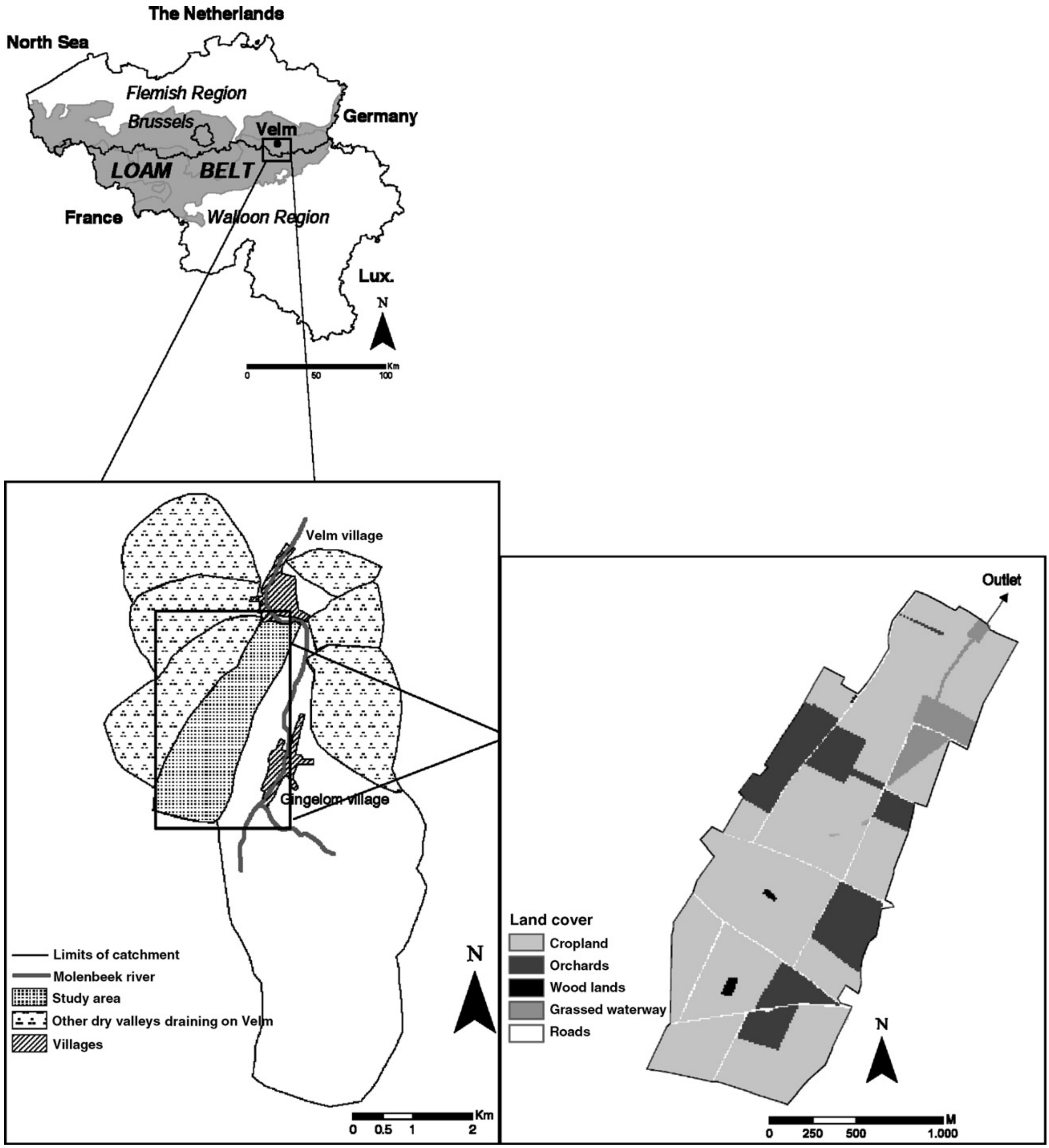


Fig. 1. Location map of Velm village, the upstream agricultural catchments and land use of the study area.

Bissonnais, 2000; Steegen et al., 2000; Cerdan et al., 2002), but very few investigated the flood risk issue and the effectiveness of erosion control measures for villages located downstream of one or several small cultivated catchments (e.g. Souchère et al., 2005). 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, 2003). Grassland has progressively been converted into cropland while summer crops such as maize (*Zea Mays* L.), sugar beets (*Beta vulgaris* L.), potatoes (*Solanum tuberosum* L.) and oilseed rape (*Brassica napus* L.) 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 6 m wide and 200 m long. They increase infiltration and decrease net soil loss (Le Bissonnais et al., 2004). In contrast, GWW are wider (min. 10 m 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 catchments, 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. 1). 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 m 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 after the harvest of winter wheat (*Triticum aestivum* L.) and flax (*Linum usitatissimum* L.) when fields are not yet ploughed, and before that of potatoes and sugar beets.

### 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 heavy rainfall. It subdivides the catchment into regular grid cells whose physical properties are supposed to be uniform. For this study, 2-m-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)).

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

where $C_{ij}$ is the runoff coefficient for hydrological class *ij*, $R_{ij}$ 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

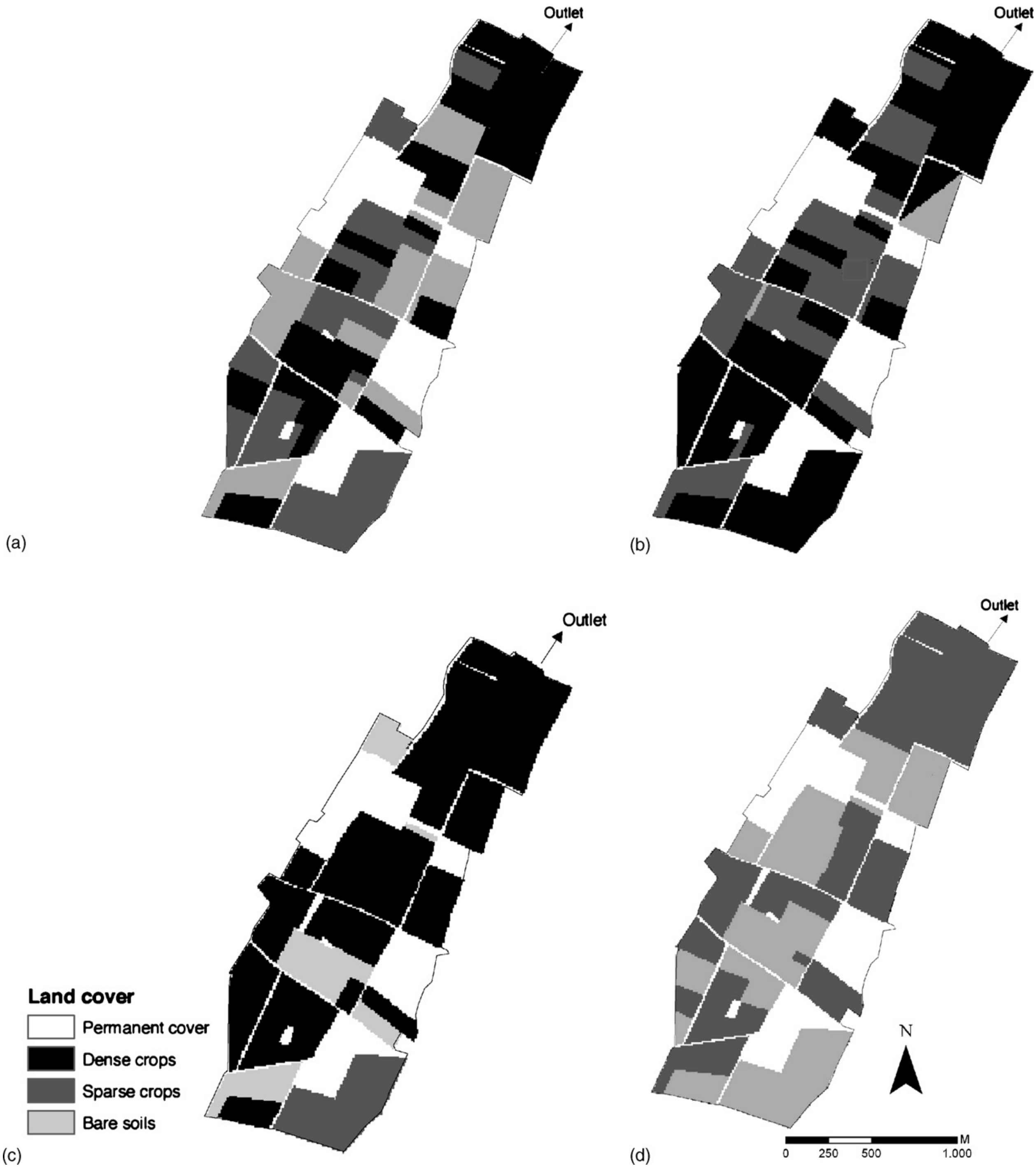


Fig. 2. Seasonal evolution of land cover in the study area. (a) April; (b) June; (c) September; (d) December.

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 drainage 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 $n\Delta t$ between such areas, where $\Delta t$ 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 $\Delta t$ 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)).

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

where $Q(t)$ is the discharge at the outlet at time $t$ ($m^3\,s^{-1}$), $A_k$ the area of the isochrone $k$, $C_k = \sum^{ij} c_{ij} \times \frac{A_{ij}}{A_k}$ 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. Then, the slope and flow direction spatial datasets are calculated from the digital elevation model (DEM), with 2 m size grid cells. The DEM is obtained by digitising the contour lines (equidistance 2.50 m) 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 < Grasslands < 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 2-m gridcells. The model is run at a 1-min time step 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 April 1957. A visual observation of the photographs allowed the recognition of

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[a] | R3 | R3 | R3 | R3 |
| Surface state[b] | F0 | F0 | F0 | F0 |
| Runoff sensitivity category[c] | 0 | 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 |

[a] Soil surface roughness state (height difference between the deepest part of microdepressions and the lowest point of their divide). R0: 0–1 cm; R1: 1–2 cm; R2: 2–5 cm; R3: 5–10 cm.
[b] Soil surface crusting stage. F0: initial fragmentary structure; F11: altered fragmentary state with structural crusts; F12: local appearance of depositional crusts
[c] The runoff sensitivity category ranges 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 |

most types of cover within the catchment. For the remaining 7% of the fields, the land cover obtained 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. Since 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).

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

where $I$ is the topographic index, $\alpha$ the local catchment area per unit contour length (m), $\beta$ is the slope gradient. Typically, a large local catchment area and a small slope result in a high value of the index, meaning that the groundwater table is close to the surface and that soils can be expected to be wet (Rodhe and Seibert, 1999).

Furthermore, to increase the confidence in the model for this specific application, simulated discharges were compared to observed ones during a number of events, for which the return period was estimated. Water level measurements behind a dam are used. 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 is temporally stored in a retention pond and drains through two pipes of 0.25 and 0.2 m diameter in the bottom of the dam. Water levels were then converted to outflow discharge using Eq. (4) (Ilaco, 1985).

$$Q = mA\sqrt{2gh} \tag{4}$$

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

## 3. Results and discussion

### *3.1. Strenghtening confidence in the model for extreme events*

The values of the topographic index are very high at the GWW upstream extremity ($I = 16.1$) and the catchment outlet ($I = 16.7$) compared to the ones cited in the literature. Beven et al. (1983) found that the areas likely to quickly become saturated during rainfall had a topographic index value close to 15. Rodhe and Seibert (1999) found maximum $I$ values of ca. 17 in Swedish catchments. The high $I$ values indicate that the GWW will become very quickly saturated during a storm. Reinfiltration is hence highly unlikely, and the basic assumption of the model is hence acceptable. The occurrence of runoff (three events in 2004) is correctly predicted even if the peak discharge is overestimated by ca. 50% (Table 3). It remains hence in the same order of magnitude. Other recorded rainfall events that did not produce runoff at the outlet were also simulated with the

Table 3
Rainfall and discharge in 2003 and 2004

| Event date | Rainfall[a] (mm) | Return period[b] (years) | $Q$ out obs.[c] ($m^3 s^{-1}$) | $Q$ out sim.[d] ($m^3 s^{-1}$) |
|---|---|---|---|---|
| 8/07/2004 | 14.2 | 5 | 0 | 0 |
| 17/07/2004 | 12.2 | 2–5 | 0 | 0 |
| 21/07/2004 | 20 (*) | 25 | 0.47 | 0.7 |
| 23/07/2004 | 23.2 (*) | 10 | 0.47 | 0.7 |
| 8/08/2004 | 11 | 2 | 0 | 0 |
| 13/08/2004 | 11.2 | 2–5 | 0 | 0 |
| 14/08/2004 | 20.6 (*) | 2 | 0.45 | 0.7 |

[a] Discharge at the outlet was recorded for the events with (*).
[b] Return periods after Delbeke (2001) computed for the rainfall duration considered.
[c] $Q$ out obs. is the peak discharge of the outflow calculated from observed water height using Eq. (4).
[d] $Q$ out sim. is the simulated outflow discharge after introduction in the MHM model.

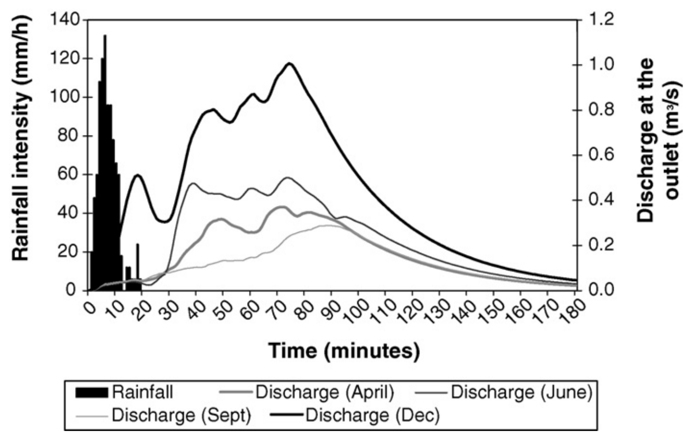


Fig. 3. Discharge at the catchment outlet in different seasons according to land cover in 2003 (see the corresponding land cover maps in Fig. 2).

model. The model correctly simulated very low runoff during these events.

### 3.2. Selection of a worst-case scenario

The simulation of an 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 and 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, based on aerial photos of April 1957 (Fig. 4a) is compared to that of April 2003 (Fig. 4b). For an event with a 10-year return period, runoff volume increases by 19% (from 1443 $m^3$ in 1957 to 1715 $m^3$ in 2003). Peak discharge rises by 33% (from 0.3 $m^3 s^{-1}$ in 1957 to 0.4 $m^3 s^{-1}$ in 2003). The lag time is similar in both situations and is close to 70 min (Fig. 5). However, the hydrograph shape is

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 (min) |
|---|---|---|---|
| April 2003 | 0.4 | 1715 | 70 |
| June 2003 | 0.5 | 2365 | 73 |
| September 2003 | 0.3 | 1326 | 90 |
| December 2003 | 1.0 | 4586 | 75 |
| Before LC[a] | 0.3 | 1443 | 73 |
| After LC | 0.4 | 1715 | 71 |
| Comparison | +33% | +19% | −3% |
| Without GWW[b] | 1.0 | 4586 | 74 |
| With GWW | 0.5 | 2652 | 86 |
| Comparison | −49% | −42% | +16% |

[a] LC: land consolidation (April situation).
[b] GWW: grassed waterway.


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

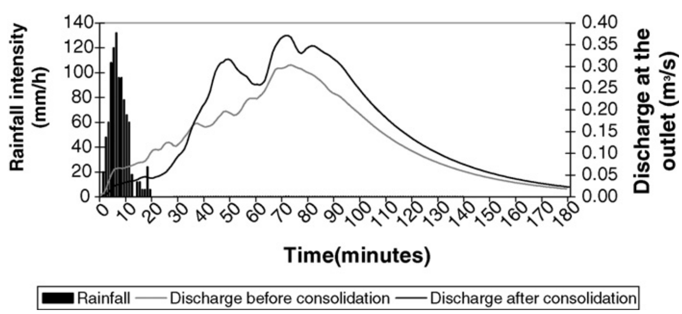


Fig. 5. Simulated hydrographs at the catchment outlet for the situation before and after the land consolidation.

different. The rising limb is more gradual before land consolidation. After land consolidation, the first peak in the hydrograph corresponds to the sudden arrival of water that concentrates on the road in the thalweg.

Land consolidation does not lead to the sharp rise of runoff volume reported by other authors (e.g. more than 75% rise according to Souchère et al., 2003). Two reasons can be put forward. First, the Belgian open field context is different from that of boscage 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 (sharp rising limb in 2003 instead of a more gradual rising limb in 1957).

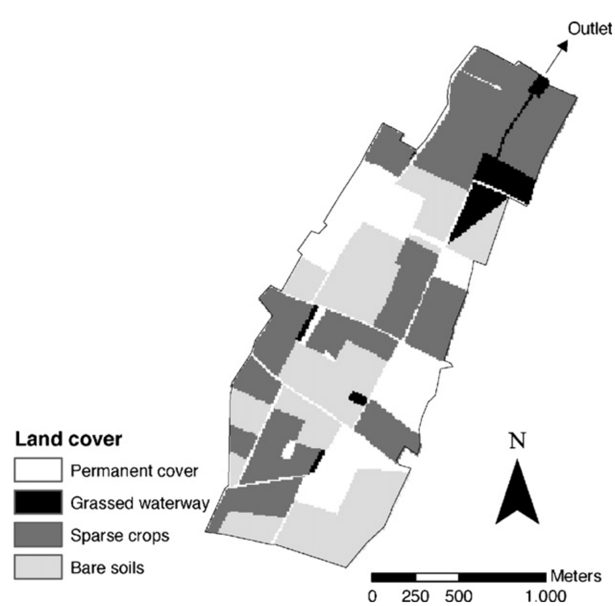


Fig. 6. Grassed waterway and other land covers in December 2003.

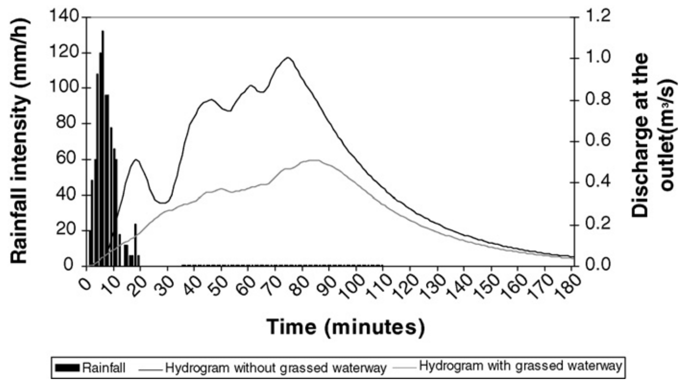


Fig. 7. Hydrograph at the catchment outlet for the December situation, with and without grassed waterway.

### 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 decreases 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 and Table 4). Runoff volume transferred to the outlet decreases by 40% (2651 $m^3$ instead of 4586 $m^3$; Table 4). Furthermore, the lag time increases with 16% and the rising limb becomes more gradual. The decrease of peak discharge and reduction of total runoff volume are often reported after the installation of a GWW (Chow et al., 1999; Fiener and Auerswald, 2003). Still the current catchment is much larger than the one studied by Fiener and Auerswald (2003) and slopes are much more gradual than in the terraced catchment of Chow et al. (1999). There are two factors explaining the decrease in total runoff volume (1935 $m^3$) when the GWW is considered. First of all, less runoff has been produced in the GWW itself due to its lower runoff coefficient. This accounts for a decrease of 680 $m^3$. Then the remaining decrease in runoff volume of 1255 $m^3$ can be explained by the reduction in runoff velocity in the GWW (0.1 $m s^{-1}$ in a GWW instead of 0.3 $m s^{-1}$ on sparsely covered cropland). Such a reduction appears realistic since the mean water depth in the GWW (8 mm) is small compared to the height of the vegetation (ca. 5 cm). This leads to a long tail in the hydrograph. Since the MHM model is limited to simulations of 180 min, this long tail is not taken into account. However, the spreading of runoff over more than 180 min decreases the flood risk for the village situated 500 m downstream.

The maximum observed peak discharge at the outflow of the dam reaches 0.5 $m^3 s^{-1}$ for a 10-year return period. This peak discharge of the outflow is similar to the peak discharge of the inflow simulated by the model taking the GWW into account (0.5 $m^3 s^{-1}$; Table 4). Hence, flooding of Velm is unlikely for a 10-year event occurring under the worst-case scenario. Since the inflow and the outflow of such an event are of the same order of magnitude, the retention pond does not serve its purpose. It is suggested to narrow the drain pipes and hence reduce the outflow.

## 4. Conclusions

This case study in a small agricultural catchment (ca. 300 ha) of central Belgium shows that a 12 ha GWW (4% of total surface) and a retention dam (with a capacity of 2000 $m^3$, i.e. 75% of total runoff during an event with a 10-year return period) alleviate the risk of muddy floods for a village downstream. Peak discharge and total runoff volume were reduced by 50% and 40%, respectively, while the lag time increased by 16%. However, land consolidation carried out in the 1970s led to an increase of peak discharge (33%) and total runoff volume (19%). This can be explained by an increase in field size (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. Since the runoff volume was 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.

## Acknowledgements

We are grateful to Matthieu Kervyn for his helpful comments on an earlier draft of this paper. Furthermore, the remarks of two anonymous referees greatly improved the manuscript.

## References

Baeyens, L., 1958. Carte des sols de la Belgique. Texte explicatif de la planchette de Sint-Truiden 105 E. Institut pour l'encouragement de la Recherche Scientifique dans l'Industrie et l'Agriculture, Brussels (In Dutch and French).

Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Poesen, J., 2000. Characteristic of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. Geomorphology 32, 69–82.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Hydrol. Sci.: Bull. Sci. Hydrol. 24, 43–69.

Beven, K., Wood, E.F., 1983. Catchment geomorphology and the dynamics of runoff contributing areas. J. Hydrol. 65, 139–158.

Bielders, C.L., Ramelot, C., Persoons, E., 2003. Farmer perception of runoff and erosion and extent of flooding in the silt-loam belt of the Belgian Walloon Region. Environ. Sci. Policy 6, 85–93.

Boardman, J., Ligneau, L., De Roo, A., Vandaele, K., 1994. Flooding of property by runoff from agricultural land in northwestern Europe. Geomorphology 10, 183–196.

Boardman, J., Evans, R., Ford, J., 2003. Muddy floods on the South downs, southern England: problem and responses. Environ. Sci. Policy 6, 69–83.

Cerdan, O., Couturier, A., Le Bissonnais, Y., Lecomte, V., Souchère, V., 2001. Incorporating soil surface crusting processes in an expert-based runoff model: sealing and transfer by runoff and erosion related to agricultural management. Catena 46, 189–205.

Cerdan, O., Le Bissonnais, Y., Souchère, V., Martin, P., Lecomte, V., 2002. Sediment concentration in interrill flow: interactions between soil surface conditions, vegetation and rainfall. Earth Surf. Proc. Land. 27, 193–205.

Chaplot, V., Le Bissonnais, Y., 2000. Field measurements of interrill erosion under different slopes and plot sizes. Earth Surf. Proc. Land. 25, 145–153.

Chow, T.L., Rees, H.W., Daigle, J.L., 1999. Effectiveness of terraces/grassed waterway systems for soil and water conservation: a field evaluation. J. Soil Water Conserv. 3, 577–583.

Delbeke, L., 2001. Extreme neerslag in Vlaanderen. AMINAL, Afdeling Water. Ministèrie van de Vlaamse Gemeenschap (In Dutch).

El Idrissi, A., 1996. Effet de l'humidité initiale du sol sur le processus de ruissellement à l'échelle de la parcelle et du bassin versant. Unpublished Ph.D. Thesis. Agricultural Engineering Unit, Université Catholique de Louvain (In French).

El Idrissi, A., Persoons, E., 1997. MHM: le Modèle Hydrologique Maillé. In: FAO: Remote Sensing and Water Resources. Proceedings of the International Workshop, Montpellier (France). World Wide Web Address http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/W7320B/w7320b37.htm (In French)

Fiener, P., Auerswald, K., 2003. Concepts and effects of a multi-purpose grassed waterway. Soil Use Manage. 19, 65–72.

Fiener, P., Auerswald, K., 2005. Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. Soil Till. Res. 87 (1), 48–58.

Hang, P., 2002. Conception et développement du modèle OGIVE et application à des micro-bassins versants belges. Unpublished Ph.D. Thesis. Faculty of Biological, Agronomical and Environmental Engineering, Université Catholique de Louvain (In French).

Hooke, J.M., Mant, J.M., 2000. Geomorphological impacts of a flood event on ephemeral channels in SE Spain. Geomorphology 34, 163–180.

Hufty, A., 2001. Introduction à la climatologie. De Boeck Université, Brussels, 542 pp. (In French).

Ilaco, 1985. Agricultural Compendium for Rural Development. Elsevier, Amsterdam, 738 pp.

Institut National de Statistiques, 1957. Recensement agricole et horticole au 15 mai 1957. Brussels, Ministère des Affaires économiques (In French).

Le Bissonnais, Y., Lecomte, V., Cerdan, O., 2004. Grass strip effects on runoff and soil loss. Agronomie 24, 129–136.

Linsley, R.K., Franzini, J.B., Freyberg, D.L., Tchobanoglous, G., 1992. Water Resources Engineering, 4th ed. MacGraw-Hill, 841 pp.

Ministère de l'Equipement et des Transports. Direction des Routes de Liège, 2002. Bilan de fonctionnement hydraulique et écologique des bassins d'orage de l'autoroute E40. Rapport final. Groupe Interuniversitaire de Recherches en Ecologie Appliquée (GIREA) and Agricultural Engineering Unit, Faculty of Biological, Agronomical and Environmental Engineering, Université Catholique de Louvain (In French).

Moore, I.D., Burch, G.J., Mackenzie, D.H., 1988. Topographic effects on the distribution of surface soil water and the location of ephemeral gullies. Trans. ASAE 31 (4), 1098–1107.

Musy, A., Higy, C., 2004. Hydrologie. Une science de la nature. Presses Polytechniques et Universitaires Romandes, Lausanne, 314 pp. (In French).

Ntaguzwa, D., 1999. La relation pluie-débit et l'incertitude en modélisation hydrologique. Application aux bassins versants du complexe des barrages de l'Eau d'Heure (Belgique). Unpublished Ph.D. Thesis. Agricultural Engineering Unit, Université Catholique de Louvain (In French).

Poiret, M., 1999. Crop trends and environmental impacts. European Commission. Directorate General for Agriculture, In: http://ec.europa.eu/comm/agriculture/envir/report/en/evo_cu_en/report.htm).

Randriamaherisoa, A., 1993. Modèle Hydrologique Maillé et Système d'Information Géographique. L'impact de la déforestation sur le régime hydrologique de la Lokoho (Madagascar). Unpublished Ph.D. Thesis. Agricultural Engineering Unit, Université Catholique de Louvain (In French).

Rapport final de la Convention ADALI (Adaptation des Aménagements hydrauliques à la Lutte contre les Inondations), 2002. Agricultural Engineering Unit, Faculty of Biological, Agronomical and Environmental Engineering, Université Catholique de Louvain (In French).

Rodhe, A., Seibert, J., 1999. Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators. Agric. For. Meteorol. 98–99, 325–340.

Souchère, V., King, C., Dubreuil, N., Lecomte-Morel, V., Le Bissonnais, Y., Chalat, M., 2003. Grassland and crop trends: role of the European Union Common Agricultural Policy and consequences for runoff and soil erosion. Environ. Sci. Policy 6, 7–16.

Souchère, V., Cerdan, O., Dubreuil, N., Le Bissonnais, Y., King, C., 2005. Modelling the impact of agri-environmental scenarios on runoff in a cultivated catchment (Normandy France). Catena 61, 229–240.

Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Beuselinck, L., Poesen, J., 2000. Sediment export by water from an agricultural catchment in the Loam Belt of central Belgium. Geomorphology 33, 25–36.

Vandaele, K., Poesen, J., 1995. Spatial and temporal patterns of soil erosion rates in an agricultural catchment, central Belgium. Catena 25, 213–226.

Verstraeten, G., Poesen, J., 1999. The nature of small-scale flooding, muddy floods and retention pond sedimentation in central Belgium. Geomorphology 29, 275–292.

Verstraeten, G., Poesen, J., Govers, G., Gillijns, K., Van Rompaey, A., Van Oost, K., 2003. Integrating science, policy and farmers to reduce soil loss and sediment delivery in Flanders, Belgium. Environ. Sci. Policy 6, 95–103.