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Catena 70 (2007) 443–454
CATENA
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Spatial and temporal variation of muddy floods in central Belgium, off-site impacts and potential control measures

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Received 28 July 2006; received in revised form 24 November 2006; accepted 29 November 2006

Abstract

Numerous villages in the European loess belt are confronted with floods caused by runoff from agricultural land. Seventy-nine percent of the municipalities in central Belgium experienced at least one muddy flood during the last decade. Of these flooded municipalities, 22% have been affected more than 10 times during this period. Twenty municipalities have been selected for a detailed analysis. A database of 367 locations affected by muddy floods has been compiled, and the connectivity between cultivated areas and inhabited zones could be assessed for 100 flooded locations. Roads and drainage network facilitate runoff transfer between cultivated and inhabited areas in 64% of cases. Three types of areas producing muddy floods have been identified: hillslopes (1–30 ha) without thalweg where runoff is generally dominated by sheet flow; small catchments (10–300 ha) characterised by runoff concentration in the thalweg and medium catchments (100–300 ha) with multiple thalwegs dominated by concentrated runoff. About 90% of muddy floods are generated on hillslopes and in small catchments. A critical area–slope threshold for triggering muddy floods has been computed for hillslopes. A logistic regression shows that muddy floods are generated in small and medium catchments with 99% probability after 43 mm rainfall. Rainfall depths required to trigger muddy floods are lower in May and June (25 ± 12 mm) than between July and September (46 ± 20 mm), because of different surface conditions (crusting, roughness and crop cover). Each year, muddy floods lead to a total societal cost of 16×10^6–172×10^6 € in central Belgium, depending on the extent and intensity of thunderstorms and monetary values damaged. Recent datasets suggest that the phenomenon is becoming more frequent in central Belgium, because of land consolidation, urban sprawl and expansion of row crops, sown in spring, at the expense of winter cereals. The huge costs induced by muddy floods justify the installation of erosion control measures. It is suggested to install a grassed buffer strip at the downslope edge of cultivated hillslopes to protect houses and roads. In small and medium catchments, it is preferred to install a grassed waterway and earthen dams in the thalweg.
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Keywords: Muddy floods; Runoff control; Cost analysis; Belgium

1. Introduction

Numerous villages in central Belgium are confronted with floods caused directly by runoff from agricultural land (Boardman et al., 1994; Verstraeten and Poesen, 1999; Bielders et al., 2003). This type of process is now commonly referred to as a 'muddy flood', and has recently been defined as water flowing from agricultural fields carrying large quantities of soil as suspended sediment or bedload (Boardman et al., 2006). Therefore, it is a fluvial process rather than a mass movement one, originating in valleys without permanent water courses (so called 'thalwegs'). Muddy floods are reported from most European loess areas, e.g. from the Belgium loess belt, the South Downs in the UK, from South Limburg in the Netherlands, from Northern France and Slovakia (Boardman et al., 1994, 2006).

According to Verstraeten and Poesen (1999), the risk to be affected by such a flood can be considered as a combination of property vulnerability and muddy flood hazard. On the one hand, Varnes (1984) defines a hazard as the probability of occurrence within a specific period of time and within a given

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doi:10.1016/j.catena.2006.11.011

Table 1
Main literature contributions about 'muddy floods' in the European loess belt

Study area	Main contribution	Reference
Northwestern Europe	First European overview of the phenomenon	Boardman et al. (1994)
	Updated European overview	Boardman et al. (2006)
Northern France	General description of the phenomenon	Auzet (1987)
	Influence of soil surface state on runoff	Papy and Douyer (1991), Auzet et al. (1995)
	Effect of land use change on runoff	Souchère et al. (2003)
	Use of farming techniques to reduce runoff	Martin (1999)
	Farmer's leeway to reduce runoff	Joannon et al. (2005)
	Design of runoff models	Cerdan et al. (2001), King et al. (2005)
South Downs, UK	First specific study on the problem	Stammers and Boardman (1984)
	Property damage	Boardman (1995)
	Risk assessment	Boardman et al. (2003)
	Types of responses to the phenomenon	Boardman et al. (2003)
Central Belgium	General causes; retention ponds as a symptom	Verstraeten and Poesen (1999)
	Farmer perception of erosion; extent of flooding	Bielders et al. (2003)
	Ephemeral gully development	Poesen et al. (2003), Vanwalleghem et al. (2005)
	Effect of farming practices on runoff	Takken et al. (2001), Gyssels et al. (2002)
South Limbourg, The Netherlands	Description of the phenomenon	Schouten et al. (1985)
	Design of LISEM model	De Roo et al. (1996)
Germany	On-site and off-site damage due to erosion	Auerswald (1991)
	Efficiency of grassed waterways to reduce runoff	Fiener and Auerswald (2003)

area of a potentially damaging phenomenon. On the other hand, vulnerability expresses the level of damage incurred by a target for a given hazard (Blaikie et al., 1994). The muddy flood hazard itself depends on the occurrence of a meteorological hazard on a vulnerable landscape. Major factors influencing landscape vulnerability (e.g. geomorphology, land use, cropping practices) as well as climatic conditions leading to muddy floods in the European loess belt were first synthesised by Boardman et al. (1994). Meanwhile, further research has been carried out (Table 1) and a new overview of muddy floods throughout Europe has been provided (Boardman et al., 2006).

In the continental, western-European loess belt, landscape vulnerability is strongly related to the areal extent of cropland and cropping practices, and in particular by the presence of summer crops, which occupy up to 50% of the cropland area in some regions (e.g. the loess belt of central Belgium; Bielders et al., 2003). These summer crops provide a low soil cover during the intense storms of May and June (see references in Table 1). Furthermore, they require a fine seedbed that promotes surface seal development and reduces surface roughness, thereby increasing runoff volume and velocity; and enhancing peak discharge (Schröder and Auerswald, 2000; Le Bissonnais et al., 2005). These sources of vulnerability have increased during the last thirty years as a result of an increase in farm size, farm mechanisation, the conversion of grassland into cropland, and the expansion of summer crops at the expense of winter cereals.

Whereas the land use factors and cropping practices that favour the occurrence of muddy floods have been studied in some detail, much less is known regarding the morphology of the sites draining to flooded locations (physical landscape vulnerability) and the rainfall depth leading to muddy floods (meteorological hazard). Such information is crucial to implement strategies to cope with the phenomenon and to prevent the frequent flooding of houses and villages. So far, the literature on landscape configurations where muddy floods are generated only describes the general landscape context. Boardman et al. (1994) mention 'dry valley systems'. Verstraeten and Poesen (1999) refer to 'concentration of runoff in thalwegs' and state that runoff starts in 'small agricultural drainage basins'. They list all relevant topographic conditions (e.g. catchment morphology, slope gradient, slope morphology), but they do not quantify thresholds for the occurrence of muddy floods. Boardman et al. (2003) create logistic regression models to determine the probability of occurrence of muddy floods and their magnitude from geomorphic and land use parameters, as well as combined criteria. However, these were based on data available for southern England. Their applicability to central Belgian conditions remains to be proven. Regarding rainfall conditions leading to muddy floods, the literature mentions 'heavy thunderstorms' (Boardman et al., 1994; Van Dijk et al., 2005) or 'heavy convective rainshowers' (Verstraeten and Poesen, 1999). When rainfall depths or intensities are given, they usually refer to single extreme events from which a rainfall threshold can hardly be derived (Table 2).

The aim of this paper is to refine previous conceptual models of muddy flood triggering by determining rainfall and topographic

Table 2
Rainfall conditions leading to muddy floods in the literature

Specific information	Study area	Reference
General conditions		
Rainfall intensity >10 mm h^{-1}	Pays de Caux, France	Boardman et al. (1994)
35 mm h^{-1} for 15 min	Belgian catchment (50 ha)	Boardman et al. (1994)
30 mm in two days for rilling	South Downs, UK	Boardman et al. (2003)
Extreme events		
60 mm in 2 h (May 8, 1988)	Dué catchment, France	Larue (2001)
45 mm in 30 min (May 8, 1990)	Dué catchment, France	Larue (2001)
60 mm in 1 h (June 8, 1996)	Heks, Flanders, Belgium	Verstraeten et al. (2001)
70 mm in 1 h (May 30, 1999)	Hoegaarden, Flanders, Belgium	Boardman et al. (2006)
70–75 mm in 1 h (May 8, 2000)	Velm, Flanders, Belgium	Verstraeten et al. (2001)
32 mm in 20 min (May 24, 2001)	Landser, Alsace, France	Van Dijk et al. (2005)

thresholds for the Belgian loess belt as well as to quantify off-site impacts of muddy floods. Based on the evidence, the most suitable control measures to be applied in different landscape configurations are then reviewed. Indeed, both the connectivity between the areas producing runoff and the flooded locations as well as the probability of flooding of specific sites should be taken into account in order to design the most appropriate control measures. In addition, information regarding costs induced by muddy floods is needed to assess the financial feasibility of the proposed control measures.

2. Materials and methods

2.1. Study area

Belgium (32,545 km^2) can be divided into 14 agro-pedological regions (i.e. zones of similar geology, soil type, relief and climate; Ministère de l'Agriculture, 1958). The loess belt (8867 km^2), regroups both the silt–loam and sandy–loam agro-pedological regions and consists of a plateau in central Belgium (Fig. 1). This plateau, gently sloping to the North, has a mean altitude of 115 m. Valleys having a north–south orientation dissect the plateau. Mean annual temperature ranges from 9 to 10 °C, while mean annual precipitation in central Belgium varies between 700 and 900 mm (Hufty, 2001; Verstraeten et al., 2006). Rainfall is evenly distributed throughout the year, but rainfall erosivity shows a peak between May and September (Verstraeten et al., 2006). Mean monthly potential evapotranspiration reaches 75 mm (Mitchell et al., 2004). Arable land is by far the most important land use in the loess belt, covering c. 65% of the total surface (FPS Economy, 2006). The most important crops are cereals, industrial and fodder crops (oilseed rape, maize, sugar beet), as well as potatoes. Sowing of cover crops (e.g. mustard, phacelia) is encouraged among the farmers during the dormant period (Bielders et al., 2003). The study area includes 204 municipalities (104 in Wallonia and 100 in Flanders). The administrative entities of Flanders and Wallonia are responsible for agriculture and environment, but these entities do not correspond to a homogeneous physical region. Brussels is excluded, since agricultural land is virtually absent from the capital city.

The Sint–Truiden catchment (c. 200 km^2) is a pilot area in the Belgian loess belt (Fig. 1). The area has been affected by numerous muddy floods during the last decades. The local water agency specifically addresses the problems of flooding and water quality. Therefore, 120 grassed strips and grassed waterways combined with earthen dams have been installed in the catchment between 2002 and 2005.

2.2. Data sources on muddy floods in the Belgian loess belt

A survey on muddy floods was previously carried out for the municipalities of Wallonia (Bielders et al., 2003) and Flanders (Verstraeten and Poesen, 1999). However, these studies can hardly be compared, due to the differences in the set-up of the questionnaires. Therefore, a questionnaire similar to the one used in Wallonia was sent to the Flemish municipalities of the loess belt (n=100) in order to obtain comparable data for the entire Belgian loess belt. In both questionnaires, the local authorities were asked: (1) if they were confronted with muddy

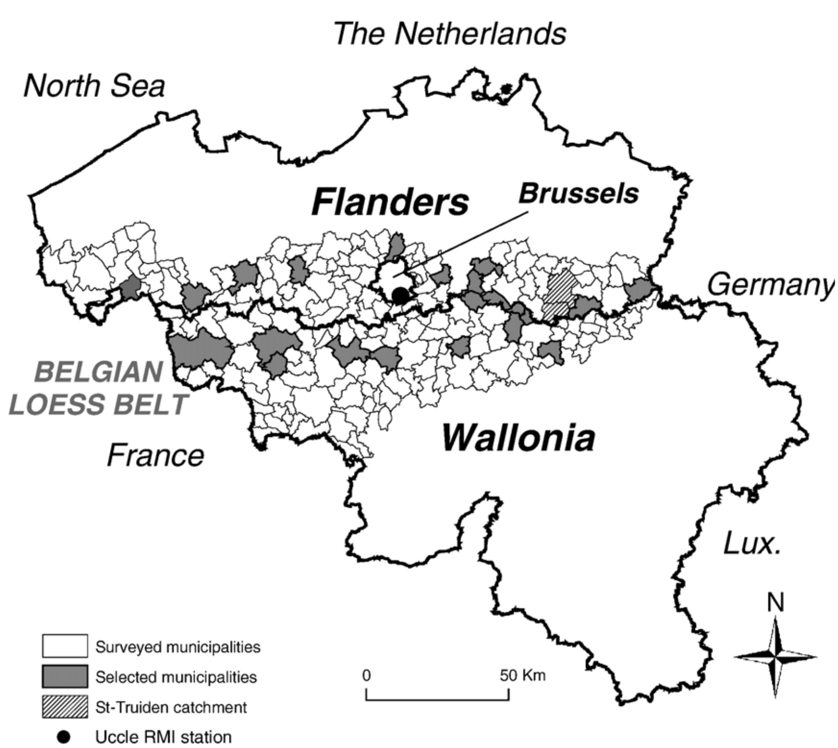

Fig. 1. Location of the loess belt, the 20 selected municipalities (regional database), the Sint–Truiden pilot catchment (Sint–Truiden database) and the Uccle RMI station (rainfall reference station) in Belgium.

floods during the previous decade; (2) how many floods occurred during this period; (3) on which dates important muddy floods occurred. Both surveys concern different time intervals (1991–2000 in Wallonia vs. 1995–2004 in Flanders). The 4-year difference between the two surveys was not considered a problem given that climate and land use did not change significantly over such a short period (SPF Economy, 2006; Verstraeten et al., 2006). Rainfall erosivity is considered to be homogeneous in the Belgian loess belt and Uccle (Fig. 1) is generally taken as the reference station (Laurant and Bollinne, 1976; Bollinne et al., 1979; Verstraeten, 2006). The annual rainfall erosivity (R-factor in the RUSLE model of Renard et al., 1997; MJ.mm.ha^{-1}.yr^{-1} h^{-1}) can be expressed as a function of the mean annual rainfall depth (P in mm; Bollinne et al., 1979; Eq. (1)).

$$R = 115.4 \times e^{0.00215 \times P} \tag{1}$$

Mean rainfall erosivity in Uccle, calculated according to Eq. (1), differed by less than 10% for both survey periods compared to the 1995–2004 period (725 MJ mm ha^{-1} yr^{-1} h^{-1} for 1991–2000 vs. 791 MJ.mm.ha^{-1}.yr^{-1} h^{-1} for 1995–2004; Royal Meteorological Institute — RMI). Furthermore, the total agricultural area remained stable at 60–65% of the Belgian loess belt surface during this period (SPF Economy, 2006).

The records of the Disaster Fund (Belgian Ministry of Home Affairs) provided a second source of data on muddy floods. The records are available for the 204 municipalities of the Belgian loess belt for the 1993–2002 period, and constitute the ‘Disaster Fund database’. Four conditions need to be fulfilled for an event to be recognised as a natural disaster : (1) total damage has to reach 1,250,000 €; (2) each affected household must incur at least 5000 € damage; (3) the event must have a 20-year return period or more according to the RMI; (4) the event must be exceptional at the national scale. The Belgian official journal ‘Moniteur belge’ cites the cause of the event recognised as a natural disaster and lists the affected municipalities. In order to restrict our research as much as possible to muddy floods and avoid accounting for river flooding, we excluded the disasters due to ‘overbank flow of watercourses’ and focused on the categories ‘heavy rainfall’, ‘intense rainfall’ and ‘violent thunderstorms’.

Data on fire brigade interventions related to muddy floods are available for the Sint–Truiden catchment during the 1977–2001 period. The local fire brigade classifies its interventions according to their nature (fire, road accident, riverine flood, muddy flood). These data will subsequently be referred to as ‘Sint–Truiden database’.

2.3. Analysis of physical landscape vulnerability

Based on the Walloon survey (Bielders et al., 2003) and the updated Flemish survey, 20 municipalities (10 in each administrative entity, covering a total area of 870 km^2) were selected on the basis of muddy flood frequency (more than 5 muddy floods in 10 years) and the presence of a RMI rain gauge. Note that the Sint–Truiden catchment has not been selected as one of the 20 municipalities, because the installation of mitigation measures could introduce a bias in the location of the flooded sites and the assessment of flood frequency.

The selected municipalities are fairly evenly distributed over the entire study area (Fig. 1). In the Walloon municipalities, locations affected by muddy floods were visited in the field and located on a 1:10,000 topographic map. In Flanders, this fieldwork was not necessary given the existence of municipal erosion mitigation schemes pointing out the affected areas. Reports corresponding to the selected municipalities were therefore consulted at the Flemish Ministry of Environment. In total, a database of 367 flooded sites, which will be subsequently referred to as ‘regional database’, has been obtained for the 20 selected municipalities. Information on connectivity between the locations affected by muddy floods and the upslope draining area was available for 100 flooded sites that were visited in the field or well documented in the municipal erosion mitigation schemes.

According to the threshold concept (Patton and Schumm, 1975), there exists for a given slope gradient of the soil surface a critical drainage area necessary to produce sufficient runoff which will cause valley instability. Based on this concept applied by Vandaele et al. (1996) and Poesen et al. (2003) to the triggering for gully incision, we hypothesise that, for a given slope gradient (mean slope gradient of the drainage area), a critical drainage area is needed to trigger muddy floods. Such a threshold line can be described by a power function (Eq. (2)).

$$S_{cr} = a \times A^{-b} \tag{2}$$

where S_{cr} is the critical slope gradient (m/m); A is the drainage area (ha); a is a coefficient and b is an exponent. Slope length was measured between the higher and lower extremities of the drainage area, perpendicular to the contour lines. Slope gradient was calculated as the ratio of the elevation difference measured between the higher and lower extremities of the drainage area, perpendicular to the contour lines and the slope length. Drainage area was derived by catchment delineation. Slope length, slope gradient and drainage area were determined for (i) the 100 flooded sites for which information on connectivity between the cultivated area and the flooded sites was available from the regional database as well as for (ii) 50 comparable locations where no muddy flood has been reported. Critical slope gradient was then plotted versus drainage area for the flooded and non-flooded sites to derive the a and b parameters of Eq. (2).

2.4. Analysis of rainfall hazard

In order to refine the rainfall threshold conditions leading to muddy floods, we identified from (1) the Disaster Fund database and (2) the list of flood dates given by the local authorities who filled in the questionnaire 132 muddy floods that occurred in the 20 selected municipalities (between 1993 and 2005) for which daily rainfall was available from rain gauges of the RMI.

For the Sint–Truiden catchment, daily precipitation depths for the 1977–2001 period were obtained from the local RMI rain gauge station in Gorsem (1.5 km from the town centre of Sint–Truiden). According to the Sint–Truiden database, most rainfall events leading to muddy floods are thunderstorms lasting less than 1 h. However, rainfall data were not available at a temporal resolution finer than one day over such a long period. Consequently, estimation of rainfall return periods is probably underestimated.

2.5. Probability of muddy flood generation

A linear logistic regression has been used to generate probabilities (p) of muddy flood occurrence as a function of daily precipitation and the topographic variables (slope length, slope gradient and drainage area; Boardman et al., 2003) using the 100 muddy flood locations available from the regional database and the 50 comparable sites which were not flooded. Daily rainfall is available from the RMI stations for muddy flood events identified from (1) the Disaster Fund database and (2) the list of flood dates given by the local authorities in the questionnaire. The lower number of non-flooded locations ($n=50$) compared to flooded locations ($n=100$) is not considered a problem, given that the number of observations per variable (50/4 = 12.5) is greater than 10 (Peduzzi et al., 1996). A logistic model is used to predict a binary dependant variable from one or several independent variables (Wrigley, 1985). The linear logistic model has the form (Eq. (3)):

$$\mathrm{log}it(p) = \log\left(\frac{p}{1-p}\right) = \alpha + \beta_n X_n \tag{3}$$

where α is the intercept; β_n are slope parameters and X_n are the three topographic variables and the daily precipitation.

The probability values can thus be expressed as (Eq. (4)):

$$p = \frac{\exp(\alpha + \beta_n X_n)}{1 + \exp(\alpha + \beta_n X_n)} \tag{4}$$

2.6. Cost of muddy floods

Data about damage costs were available from the Disaster Fund database (1601 records for the 20 selected municipalities). The authorities of 10 municipalities also had their own damage data for a total of 16 muddy floods. This information has been exploited to (i) associate a rough damage cost to rainfall events of different intensities as well as to (ii) provide a global figure of costs induced by muddy floods in the Belgian loess belt.

Data on damage costs induced by muddy floods and on costs due to the installation of pilot measures were also available for the Sint–Truiden catchment (and particularly for the Velm village) from the Disaster Fund and the local water agency. These data were used to assess the economic feasibility of the installation of the control measures.

3. Results and discussion

3.1. Extent and frequency of muddy floods in the Belgian loess belt

Only three municipalities did not respond to the questionnaire (response rate of 98.5%). Muddy floods are a very widespread phenomenon in central Belgium (Fig. 2; Table 3). Seventy-nine percent of the municipalities ($n=201$) were confronted with at least one muddy flood over a ten year period. Of these 160 flooded municipalities, 22% experienced more than 10 floods in 10 years. The muddy flood problem is more acute in Flanders where 90% (1995–2004) of the municipalities have to deal with the problem as opposed to 67% (1991–2000) in Wallonia. For intense events requiring an intervention of the Belgian Disaster Fund, the situation is also very different in Flanders and Wallonia (Table 3). More than one disaster occurred in c. 75% of the Flemish municipalities, and in only 50% of the Walloon municipalities. Given the similar physical, climatic and agricultural context in both entities, such differences must be explained by other factors, e.g. the difference in population density (500 inhabitants km^{-2} in Flanders, and 370 inhabitants km^{-2} in Wallonia). These differences are attributed to a different socio-economic evolution and an earlier urban sprawl in the Flemish countryside (Denis, 1992). Muddy floods are more likely to go unnoticed in less populated areas as long as there is no damage to public or private infrastructure. The higher cost of muddy flood damage in more populated areas will also lead to more frequent recognition of flood events as natural disasters (see criteria in Section 2.2). The adoption of specific policies to combat erosion in Flanders can also explain the higher number of muddy floods reported. The Flemish regional government adopted an erosion decree in December, 2001 (Verstraeten et al., 2003). These policies lead to an increased consciousness raising and encourage local managers to better identify the problem. Undoubtedly, awareness of local agents about muddy floods has increased during the last years. In a previous survey carried out by Verstraeten and Poesen (1999) in Flanders for the period 1987–1997, only 43% of the municipalities reported muddy floods (vs. 90% in 2005, according to our updated survey).

The analysis of the Disaster Fund database indicates that muddy floods affect more municipalities than reported by the respondents of the municipality survey. This is rather surprising as only floods with serious damage are recorded in the Disaster Fund database, whereas no such restriction applies to the survey data. It is possible that the flood events derived from the Disaster Fund database were not all ‘muddy’ and therefore not reported by the survey respondents.

The number of muddy floods can be expressed per 100 km^2 to enable a comparison with the literature (e.g. Boardman et al., 2006). According to the analysis of the regional database covering a total area of 870 km^2, mud deposits on roads are quite widespread (42 flooded sites/100 km^2). Muddy floods lead to problems to houses in 50% of the cases, representing 21 flooded sites/100 km^2. The sites indicated by local authorities were flooded at least once between 2000 and 2005. The annual figure would then be 8.2 floods per 100 km^2 yr^{-1} (or 4.2 floods if we only consider those that led to problems to houses). On average, each municipality of the Belgian loess belt (mean area of 43.5 km^2) is therefore confronted with 3.6 muddy floods per year. Although probably underestimated by the local authorities, we observed a higher number of floods than reported by Boardman et al., 2006 (1–3 muddy floods per 100 km^2 yr^{-1} for the loess belt of Flanders).

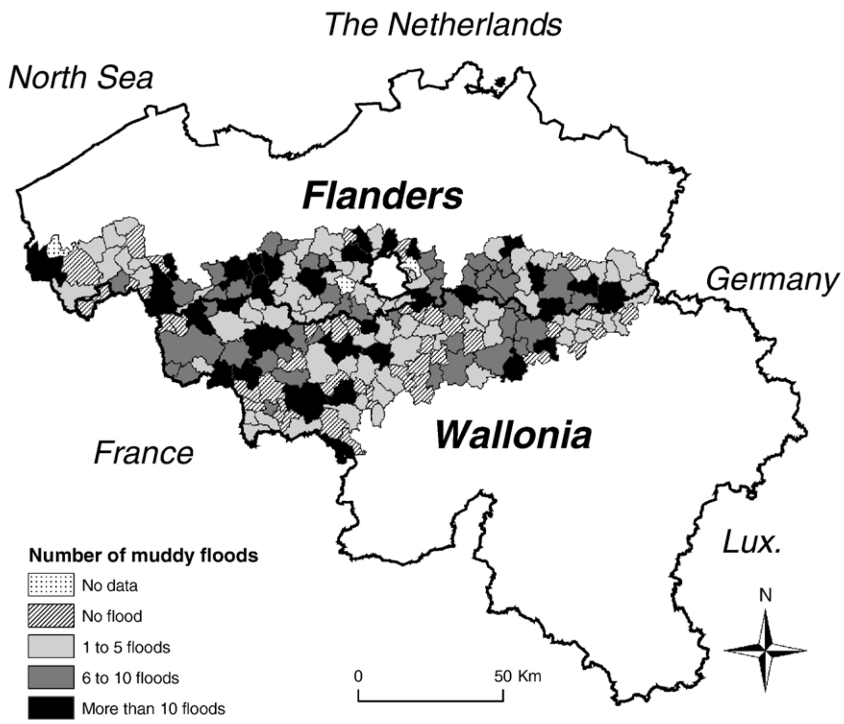

Fig. 2. Frequency of muddy floods over a 10-year period in all municipalities of the study area; data for Wallonia (1991–2000) taken from Bielders et al. (2003), data for Flanders (1995–2004) derived from a questionnaire sent to all municipalities in 2005.

The increase of muddy flood frequency is confirmed by the Sint–Truiden database (Fig. 3). This increase is neither due to a significant increase of rainfall erosivity (Fig. 4), nor to the occurrence of land consolidation in the catchment, which had already been consolidated before 1977. The most important factor explaining this increase of muddy floods is the expansion of row crops, vegetables and orchards at the expense of cereals in the area (Fig. 5).

At the regional scale, local press reports regarding muddy floods have increased over the years (Verstraeten and Poesen, 1999), but no systematic records are kept by local authorities. Besides a greater awareness and the expansion of vegetable and row crops, as observed in Sint–Truiden, two additional explanations can be put forward regarding this increase. First, land consolidation schemes were carried out in central Belgium since 1956. The main objectives were to increase productivity by increasing field size and improving field accessibility by constructing new concrete roads. It has been shown that such roads lead to runoff concentration and to an increase of runoff velocity, endangering the downstream villages (Evrard et al., 2007). According to the regional database, 45% of the flooded sites are situated downstream of consolidated areas for a region where only 15% of the area has been consolidated (Ministère de la Région Wallonne, Direction Générale de l'Agriculture).

Table 3
Frequency of muddy floods in the municipalities of central Belgium over a 10-year period as derived from 1) a municipal questionnaire in Wallonia (1991–2000; adapted from Bielders et al., 2003) and Flanders (1995–2004; updated questionnaire, this study); and 2) Disaster Fund database (1993–2002 Belgian Ministry of Home Affairs)

Number of floods in ten years	% of municipalities		
	Central Belgium	Wallonia	Flanders
Municipal questionnaire	$n=202$	$n=103$	$n=99$
No muddy flood	21.6	32.4	10.1
1 to 5 muddy floods	39.7	34.3	45.4
6 to 10 muddy floods	21.6	20.0	23.2
More than 10 muddy floods	17.1	13.3	21.2
Disaster Fund database	$n=205$	$n=103$	$n=102$
No disaster	9.7	14.3	4.9
1 disaster	27.5	34.3	20.6
2 to 4 disasters	45.9	40.0	52.1
5 disasters and more	16.9	11.4	22.5

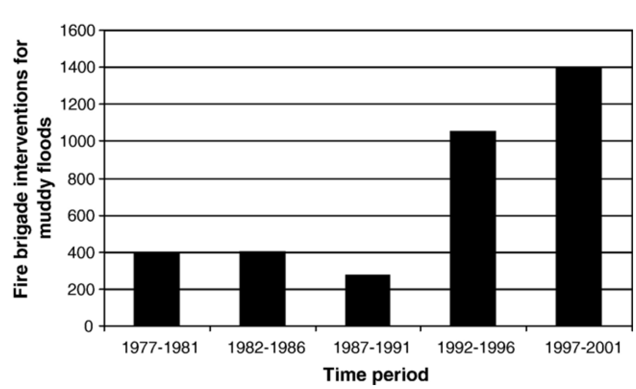

Fig. 3. Evolution of fire brigade interventions in relation to muddy floods in Sint–Truiden district, central Belgium; period 1977–2001.

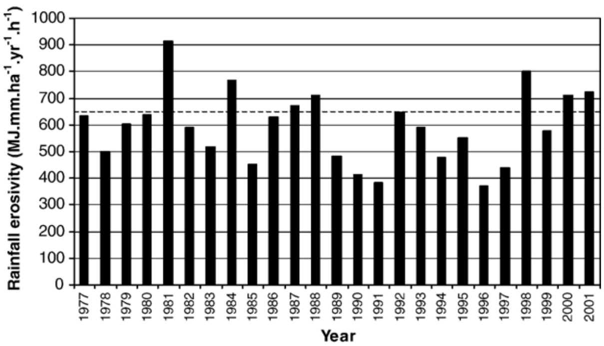

Fig. 4. Annual rainfall erosivity in Gorsem (Sint–Truiden) for the period 1977–2001 (RMI, 2006). Dotted line represents mean annual rainfall erosivity for the period 1977–2001 (667 MJ mm ha^{-1} yr^{-1} h^{-1}).

Second, urban sprawl is increasing in central Belgium. According to the regional database, we observed that c. 30% of flooded sites concerned new houses, even though only 7.5% of the houses have been built since 1991 (Ministère de la Région Wallonne, Direction Générale des Ressources Naturelles et de l'Environnement). This would indicate the particular sensitivity of new building sites in rural areas.

3.2. Analysis of physical landscape vulnerability

We could assess the connectivity between cultivated land and the affected human infrastructures for the sites in the regional database (Table 4). In 36% of the cases, erosion phenomena (e.g. interrill and rill erosion, ephemeral gullies) were observed. A road network acts as connector in 31% of the cases, while the existing drainage network (e.g. watercourses, ditches or culverts) ensures connectivity in 33% of the cases.

A slope versus drainage area diagram has been plotted for (i) the cultivated areas connected to inhabited zones by roads and ditches (Fig. 6A) and for (ii) the cultivated areas where erosion phenomena have been observed up to the inhabited zones (Fig. 6B). In the first case, muddy floods are always reported, stressing the important role played by roads and ditches in muddy flood triggering. The three types of drainage areas identified in the field are represented in the slope–drainage area diagrams (Fig. 6 A–B). The first type consists of hillslopes (1–30 ha) without thalweg where runoff is generally dominated by sheet flow. They are subsequently referred to as 'hillslopes'. A critical slope–area threshold for muddy flood triggering could only be plotted for hillslopes connected to the flooded site by erosion phenomena (Eq. (5)):

$$S_{cr} = 0.0035 \times A^{-0.659} \quad (5)$$

About 15% of the hillslopes where no muddy flood has been reported have similar characteristics to those where floods have been observed (Fig. 6 B). However, on average, the latter are steeper (5.7% vs. 2.5%) and larger (13 ha vs. 11 ha; Table 5).

The second type of drainage area, referred to as 'small catchments', occurs when a thalweg is clearly recognisable on the 1:10,000 topographical map. These are generally larger (10–300 ha) than the hillslopes and are characterised by concentrated runoff in the valley bottom. Slope gradient has no influence on the triggering of muddy floods from small catchments (Fig. 6 A–B). However, muddy floods are triggered in such a landscape configuration when they drain an upslope area of at least 20 ha and when they are not connected to the flooded site by a road or a ditch (Fig. 6 B). When such a connection is observed, muddy floods are systematically reported from the downstream inhabited zones (Fig. 6 A). The third type of drainage area consists of medium catchments with multiple thalwegs dominated by concentrated runoff (100–300 ha). Connecting roads or ditches have always been observed in medium catchments and muddy floods have systematically been reported in the downstream inhabited zones (Fig. 6 A). Muddy floods from hillslopes and small catchments (92%) are the most frequent (Table 5). They generally cause damage to limited sections of roads (leaving a 'mud blanket'), isolated houses or hamlets. Runoff generated on more complex terrain such as medium catchments is observed less frequently (8%) but it systematically leads to larger-scale muddy floods. Hillslopes have gentle to moderate slope gradients (2.5–5.7% on average) and drain to wide outlets, the width of the junction between the cultivated hillslope and the connector (contour length) reaching 170–241 m on average (Table 5). Small and medium catchments have a gentler slope

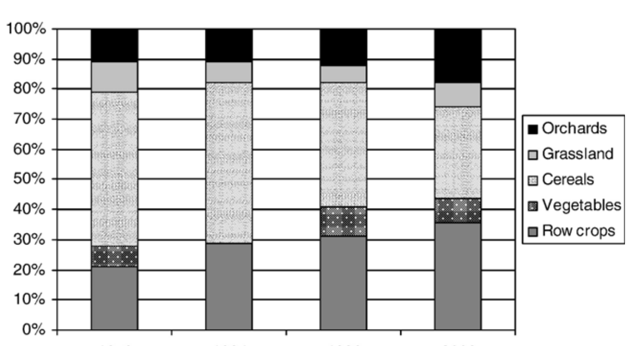

Fig. 5. Evolution of the relative agricultural land cover in the Sint–Truiden catchment between 1973 and 2000 (Data for Gingelom; SPF Economy, 2006).

Table 4
Runoff connectivity between cultivated areas and inhabited areas in central Belgium

Connector	Number of observations
Erosion phenomena	36
Interrill and rill erosion	28
Ephemeral gully	6
Bank gully	2
Drainage network	33
Watercourse	16
Ditch	13
Culvert	4
Road network	31
Road	24
Sunken lane	7

Dataset: 100 flooded locations visited in the field or well-documented in the Flemish erosion mitigation schemes.

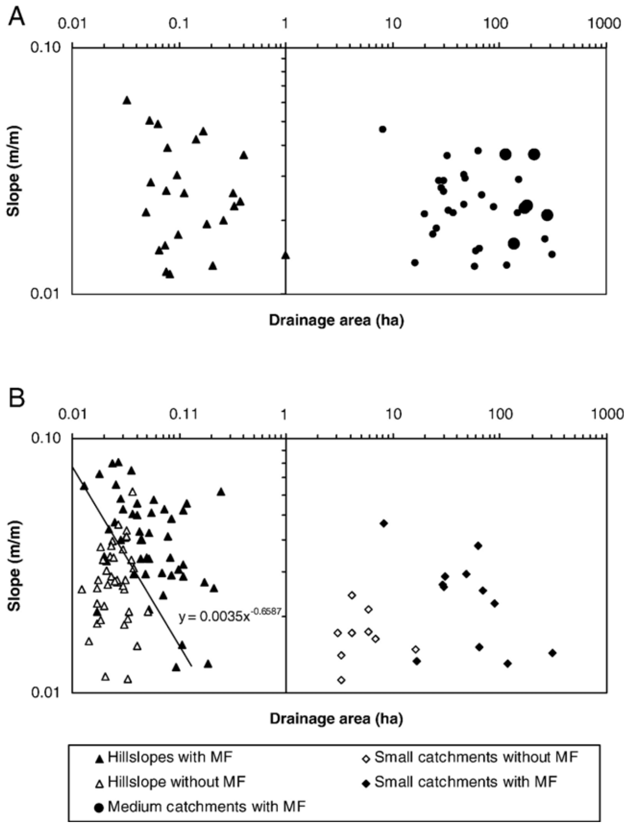

Fig. 6. Slope gradient versus drainage area for 100 areas draining to flooded locations in central Belgium and 50 non-flooded sites. (A) Runoff connectivity achieved by road or drainage network; (B) runoff connectivity achieved by erosion phenomena. Solid line represents critical threshold conditions for muddy flood triggering on hillslopes (Eq. (5)).

(mean value of 1.2–2.3%) but, since runoff concentrates in the valley bottom, it drains through a narrower section (108–152 m on average; Table 5).

3.3. Analysis of rainfall hazard

According to the Sint–Truiden database, 85% of fire brigade interventions in relation to runoff from cultivated areas occur from May to September (Fig. 7). This is consistent with the findings of Vandaele and Poesen (1995) who reported that muddy floods in central Belgium mainly occur between May and September, after local convective storms. Rainy days with less than 10 mm account for 90% of all rainfall events, but they lead to muddy floods in only 1% of the cases. In contrast, 100% of rainfall events with more than 45 mm lead to floods (Fig. 8). Mean rainfall which produced the floods is lower in May and June (25 ± 12 mm) than between July and September (46 ± 20 mm). In central Belgium, potatoes, maize and sugar beets protect the soil surface very poorly (less than 20% cover) in May and June at a time when rainfall erosivity is at its highest. Fields planted with these summer crops are hence particularly sensitive to surface sealing by rainfall. At the beginning of May, after a fine seedbed preparation, soil roughness is low and crusting may rapidly occur. With such a surface crust,

Table 5
Mean topographic characteristics of areas producing muddy floods (MF); in total 100 sites where muddy floods occurred (1995–2004) are taken into account, as well as 50 sites where no muddy flood has been reported

Type of drainage area	Frequency	Area (SD) (ha)	Slope (SD) (%)	Contour length (SD) (m)
Connection achieved by erosion phenomena				
Hillslopes				
With MF	36	13 (13)	5.7 (4)	192 (113)
Without MF	41	11 (8)	2.5 (0.9)	241 (146)
Small catchments				
With MF	12	45 (80)	2.3 (0.8)	108 (25)
Without MF	9	73 (81)	1.2 (0.6)	124 (17)
Connection achieved by roads and ditches				
Hillslopes				
With MF	22	21 (25)	3.9 (1.9)	170 (106)
Small catchments				
With MF	23	71 (62)	2.3 (0.5)	106 (19)
Medium catchments				
With MF	8	187 (75)	2.2 (0.4)	152 (51)

Standard deviation (SD) is indicated for each characteristic.

infiltration capacity is very low (less than 5 mm h^{-1}; e.g. Le Bissonnais, 1996). In summer (July to September), the soil crust is disturbed by earthworm activity and desiccation (e.g. Schröder and Auerswald, 2000). Soils are also well protected by the vegetation. This can explain the higher rainfall required to trigger a muddy flood.

3.4. Probability of muddy flood generation

Two separate regression analyses have been performed on the regional database: (a) for hillslopes and (b) for small and medium catchments (Table 6). We focused on topographic and rainfall conditions to explain muddy flood triggering, since the influence of individual crops is averaged out by crop rotation and soils are quite homogenous in the loess belt. A stepwise selection of the criteria (with a 0.05 significance level to enter the model) was chosen. For a muddy flood to be generated on a hillslope, the most important explanatory variables are the upslope area, the slope gradient as well as a combination of slope and rainfall. In contrast, the only significant explanatory variable for small and medium catchments is the rainfall

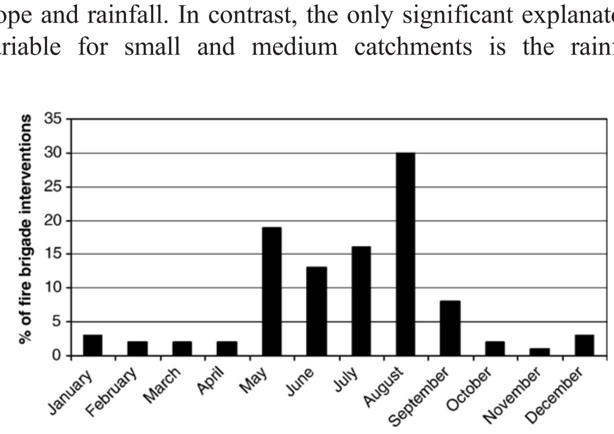

Fig. 7. Monthly distribution of fire brigade interventions in relation to muddy flood events from the Sint–Truiden database between 1977 and 2001.

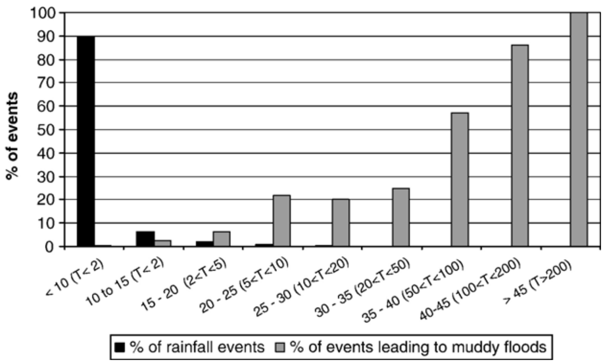

Fig. 8. Frequency distribution of daily rainfall and percentage of rainfall events leading to muddy floods for different classes of daily rainfall from the Sint–Truiden database. Rainfall data from the Gorsem station of the RMI; muddy flood data according to fire brigade interventions. Rainfall return period (*T*) in years for 24 hours-rain (after Delbeke, 2001).

amount. Small catchments hence generate muddy floods as soon as a rainfall threshold is reached if no control measure is taken. Upon 25 mm of daily rainfall, the probability to observe a muddy flood at the outlet of small and medium catchments is 7%, whereas it reaches 99% after 43 mm precipitation. The spatial distribution of the different types of crops within the catchment would hence be more important to trigger muddy floods than the catchment topographic characteristics. The larger the catchment area, the higher the probability to observe crops sensitive to runoff generation (e.g. row crops) in the catchment. Both regressions have a quite good explanatory power (ρ^2-values of 0.39 and 0.45). In empirical studies, goodness-of-fit values between 0.2–0.4 generally represent a very good fit of the logistic model (Wrigley, 1985). Similar models developed by Boardman et al. (2003) with greatest predictive power contained the variables of mean relief, catchment area and absolute runoff contributing area on slopes in excess of 10% gradient. The inclusion of additional topographic variables in the Boardman et al. (2003) study can be explained by a more complex geomorphology compared to central Belgium. The South Downs (UK) are a range of low rolling hills rising to more than 200 m and are dissected by deep dry valleys (Boardman et al., 2003).

Table 6
Linear logistic regressions relating rainfall and topographic factors to the probability of occurrence of muddy floods: (a) on hillslopes, $\rho^2=0.39$; (b) in small and medium catchments, $\rho^2=0.45$

Variable	Parameter estimate	Standard error	Wald χ^2	$p>\chi^2$
(a) Hillslopes				
Intercept	2.1929	3.1903	0.4725	0.4918
Rainfall	−0.1508	0.0896	2.8356	0.0922
Upslope area	0.1543	0.0411	14.0961	0.0002
Slope	−3.9381	1.3805	8.1383	0.0043
Rainfall * Slope	0.1256	0.0385	10.6558	0.0011
(b) Small and medium catchments				
Intercept	−12.6655	4.2481	8.8889	0.0029
Rainfall	0.4014	0.1315	9.3164	0.0023

Only statistically significant ($p<0.05$) parameters have been retained. In model (a), rainfall is included in the model despite a $p=0.0922$ given it is also contained in a significant interaction variable (Rainfall * Slope; $p=0.0011$).

3.5. Cost of muddy floods

After a flood, the fire brigade and municipal workers clean up public infrastructure and private property (Table 7). Fire brigade interventions cost between 2250 € and 25,000 € per event, while cleaning operations lead to an estimated cost that ranges between 500 € for a single road segment and 11,000 € for a whole village. Several additional repairs to infrastructure may be required, such as unclogging of sewers, local replacement of tarmac or pavements. These works are very costly, ranging between 14,000 € and 300,000 € per event and per municipality. In total, damage to public infrastructure and cleaning induce a global cost of $12.5–122\times10^6$ € yr^{-1} for the entire Belgian loess belt. It must be underlined that the highest costs are only reached after widespread extreme thunderstorms (e.g. August 26–28, 2002, with rainfall depths of more than 100 mm in 24 h in some areas).

Damage to houses is also very important, affecting gardens, garages or even the ground floor of the houses. According to the analysis of the Disaster Fund database, mean damage costs reach 4436 € ± 3406 per house. The number of flooded sites with affected houses obtained from the analysis of the regional database (4.2 floods per 100 km^2 yr^{-1}) can be extrapolated to the entire Belgian loess belt (8867 km^2). Assuming 1 and 10 affected houses per flooded site, damage to private property varies between 1.6×10^6 and 16.5×10^6 € yr^{-1}, respectively.

Table 7
Data on damage costs induced by muddy floods collected in the visited municipalities

Municipality	Date of event	Type of intervention	Cost (€)
Beauvechain	August 2002	Cleaning of roads	10,125
	September 2005	Cleaning of roads	16,350
Chaumont-Gistoux	May 5, 2006	Cleaning of roads and cellars	80,000
Ellezelles	2–3 floods yr^{-1}	Cleaning of roads	500–1000
Fernelmont	August 27, 2002	Damage to bridges and roads	143,000
Flobecq	1999	Cleaning of streets, help to population	11,000
	June 4–5, 2002	Cleaning of streets	4720
Frasnes-lez-Anvaing	September 8–10, 2005	Cleaning of roads	1512
		Repair to roads	14,000
Herzele	1999	Cleaning and repairs	327,640
		Fire brigade interventions	9000
	2001	Cleaning and repairs	83,475
		Fire brigade interventions	2250
	2002	Cleaning and repairs	83,275
		Fire brigade interventions	2250
Riemst	July 1999	Repairs to public infrastructure	150,000
		Repairs to public buildings	70,000
		Mud storage	32,000
		Staff and material costs	48,000
Walhain	August 2002	Repair to infrastructures	164,620

Data available from the 'public work' services of the municipalities, except for Herzele and Riemst (data available from the municipal erosion mitigation schemes).

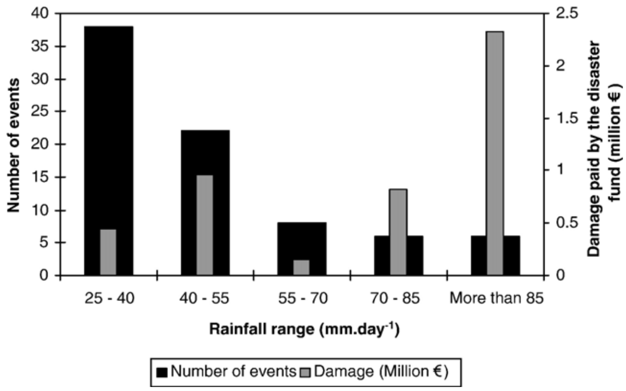

Fig. 9. Frequency of daily rainfall and total damage paid by the Disaster Fund for muddy floods in 20 municipalities of central Belgium between 1993 and 2002; rainfall data from the Royal Meteorological Institute of Belgium; damage data from the Belgian Ministry of Home Affairs, Disaster Fund.

These estimates do not take all the off-site impacts of muddy floods into account, such as the dredging of rivers. For instance, the Belgian Hainaut Province spends c. 18,000 € to dredge 1 km of a 2-m wide watercourse (total length c. 10 km). On average, such works are carried out every four years (Mr. Personne, Hainaut Province, personal communication). Besides the cost induced by the technical operation, biodiversity is subjected to several disturbances because of dredging. Still riparian habitats contribute to maintenance of biodiversity in agro-ecosystems (e.g. Deschênes et al., 2003; Jobin et al., 2004).

The costs associated to muddy floods generated by rainfall events of different magnitude was assessed using the Disaster Fund database (Fig. 9). Although very intense storms are not frequent, they lead to huge costs. More frequent events lead to much lower costs, but they induce psychological damage due to repeated flooding of certain houses (Boardman et al., 2006).

3.6. Control strategies to curtail muddy floods

The best long-term solution would be the adoption of alternative farming practices that reduce soil loss, such as reduced tillage or no-tillage (e.g., Holland, 2004). Gillijns et al. (2004) have shown that conservation farming practices significantly reduce soil erosion and runoff in the Belgian loess belt. Although such a conversion has been encouraged among farmers for several years in Flanders, very few have adopted these practices. For instance, for the entire Flemish Region (where agricultural land covers a total area of 633,769 ha), no-till has been subsidised on 985 ha and direct drilling on only 58 ha (Flemish Ministry of Environment, 2006). However, mitigation measures can relatively easily be installed along field borders or in small and medium catchments (Fig. 10).

Grass buffer strips reduce runoff and erosion by sediment filtration and runoff infiltration. This infiltration leads to a decrease of runoff volume. Combined with the reduction of runoff velocity, it leads to a decrease of runoff transport capacity and hence to an increase of sedimentation (e.g., Mersie et al., 2003; Le Bissonnais et al., 2004; Vianello et al., 2005). A grass buffer strip can be installed at the downslope end of fields in order to slow runoff down and hence allow re-infiltration and sediment deposition. In Belgium, grass buffer strips along field borders are subsidised. Hillslopes with topographic conditions exceeding threshold conditions mentioned in the Section 3.2 should be equipped as a priority. The sowing and maintenance of grass buffer strips is currently subsidised in Flanders (0.13–0.16 € m^{-2} yr^{-1}) and Wallonia (0.15 € m^{-2} yr^{-1}). The grass strip width recommended by the regional authorities varies between 3 and 30 m, with a mean of 12 m. For a 12 m-wide grass strip installed at the downslope end of a field running 100 m along the contour line (area of 1200 m^2), the cost will be relatively low (180 € yr^{-1} in Wallonia or 156–192 € yr^{-1} in

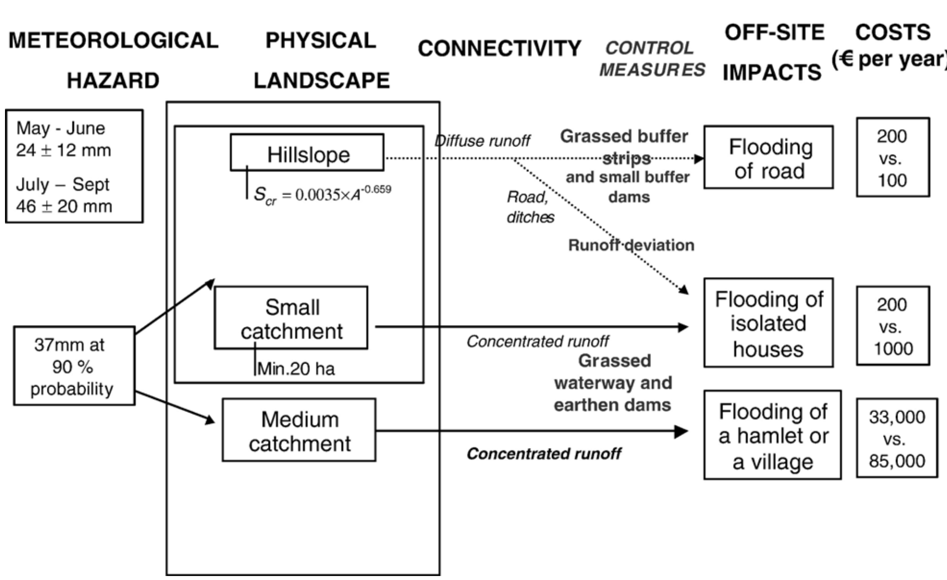

Fig. 10. Conceptual model of muddy flood triggering mechanisms and possible control measures in central Belgium. Two situations are compared regarding costs: cleaning and damage costs induced by a muddy flood (after data collected in the visited municipalities of the Belgian loess belt) vs. cost to install control measures (after data obtained for the catchment of Sint–Truiden). We assume that a muddy flood occurs on a given site every 5 years.

Flanders) in comparison with the damage due to the flooding of a house (4436 € on average) or the cleaning of a road (at least 500 €). Since consolidation roads collect runoff and facilitate its transfer to villages located downstream (see Section 3.2), ditches can help to drain water from the road and redirect runoff to nearby grassed waterways or grassed buffer strips. Runoff from roads should be redirected to a grass buffer strip by grids across the roads or by lowering its shoulders (Fig. 10).

Greater attention should be paid to control floods from small and medium catchments, since they are characterised by concentrated runoff. It is suggested to install a grassed waterway in the thalweg in order to slow down runoff and prevent gullying, as shown by previous studies (e.g. Fiener and Auerswald, 2003; Evrard et al., 2007). To further buffer runoff, small-scale earthen dams can be installed across the waterway (Fiener et al., 2005; Evrard et al., 2007). Straw-bale dams can also be set up, in order to filter runoff and reduce runoff velocity. In a pilot thalweg draining to Velm village located in the Sint–Truiden catchment, a 12 ha grassed waterway as well as three earthen retention dams have been installed in 2002–2003 for a 20-year period. Total cost of the works amount to 351,528 € (17,567 € yr^{-1}), and subsidies given to farmers for the maintenance of the grassed waterway equal 16,000 € per year. Available data about damage induced by muddy floods in the village suggest that it would cost c. 1,700,000 € if the village was affected by 4 floods in the next twenty years (85,000 € yr^{-1}). On a yearly basis, the installation of the mitigation measures is hence worthwhile (33,500 vs. 85,000 € yr^{-1}). Overall, the financial feasibility of the installation of these control measures has been proven for the Belgian loess belt.

4. Conclusions

Muddy floods are a widespread phenomenon in central Belgium, affecting 79% of the municipalities at least once in 10 years. One fifth of the municipalities were confronted with more than five floods during the last decade. Floods are mainly generated on hillslopes (1–30 ha) or in small (10–300 ha) and medium (100–300 ha) catchments. Upslope area, slope gradient and rainfall are relevant factors for triggering a muddy flood on a hillslope. In contrast, all small and medium catchments generate floods whenever heavy rainfall occurs if no mitigation measure is taken. The probability of flooding generated in small and medium catchments reaches 99% for 43 mm daily rainfall (5 year-return period). Roads and ditches facilitate runoff transfer between cultivated and inhabited areas in 64% of the observed cases. On average, each municipality is affected by 3.6 muddy floods each year. A detailed dataset for a 200 km^2-catchment suggests that the phenomenon becomes more frequent in central Belgium, mainly as a result of increasing acreage of row crops and orchards at the expense of cereals. The high costs induced by muddy floods ($16–172 \times 10^6$ € yr^{-1} for the entire Belgian loess belt) strengthen the necessity to take immediate measures to alleviate the phenomenon. At the downslope end of small hillslopes, grassed buffer strips can help mitigate floods at a low cost compared to potential damage to property, while in small and medium catchments, it is recommended to install a grassed waterway as well as earthen dams. Pilot measures have been installed in the 200 km^2-catchment of Sint–Truiden. Their efficiency is being quantified in a long-term study in order to optimise their design for future application.

Acknowledgements

The remarks of two anonymous referees greatly improved the manuscript. We are also grateful to the following administrations for providing data: Belgian Ministry of Home Affairs, Disaster Fund; Royal Meteorological Institute of Belgium; Ministerie van de Vlaamse Gemeenschap, AMINAL, Afdeling Land; Ministère Wallon de l'Equipement et des Transports; Ministère de la Région Wallonne, Direction Générale de l'Agriculture–Direction Générale des Ressources Naturelles et de l'Environnement; the staff in all visited municipalities.

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