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2 Spatial and temporal variation of muddy floods in central Belgium,  
3 off-site impacts and potential control measures  
4

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1 **Abstract**

2  
3 Numerous villages in the European loess belt are confronted with floods caused by runoff  
4 from agricultural land. Seventy-nine percent of the municipalities in central Belgium  
5 experienced at least one muddy flood during the last decade. Of these flooded municipalities,  
6 22% have been affected more than 10 times during this period. Twenty municipalities have  
7 been selected for a detailed analysis. A database of 367 locations affected by muddy floods  
8 has been compiled, and the connectivity between cultivated areas and inhabited zones could  
9 be assessed for 100 flooded locations. Roads and drainage network facilitate runoff transfer  
10 between cultivated and inhabited areas in 64% of cases. Three types of areas producing  
11 muddy floods have been identified: hillslopes (1 – 30 ha) without thalweg where runoff is  
12 generally dominated by sheet flow; small catchments (10 – 300 ha) characterised by runoff  
13 concentration in the thalweg and medium catchments (100 – 300 ha) with multiple thalwegs  
14 dominated by concentrated runoff. About 90% of muddy floods are generated on hillslopes  
15 and in small catchments. A critical area – slope threshold for triggering muddy floods has  
16 been computed for hillslopes. A logistic regression shows that muddy floods are generated in  
17 small and medium catchments with 99% probability after 43 mm rainfall. Rainfall depths  
18 required to trigger muddy floods are lower in May and June ( $25 \pm 12$  mm) than between July  
19 and September ( $46 \pm 20$  mm), because of different surface conditions (crusting, roughness and  
20 crop cover). Each year, muddy floods lead to a total societal cost of  $16 \times 10^6 - 172 \times 10^6$  € in  
21 central Belgium, depending on the extent and intensity of thunderstorms and monetary values  
22 damaged. Recent datasets suggest that the phenomenon is becoming more frequent in central  
23 Belgium, because of land consolidation, urban sprawl and expansion of row crops, sown in  
24 spring, at the expense of winter cereals. The huge costs induced by muddy floods justify the  
25 installation of erosion control measures. It is suggested to install a grassed buffer strip at the

1 downslope edge of cultivated hillslopes to protect houses and roads. In small and medium  
2 catchments, it is preferred to install a grassed waterway and earthen dams in the thalweg.

3 **Keywords** : muddy floods; runoff control; cost analysis; Belgium  
4  
5

## 6 **1. Introduction**

7  
8 Numerous villages in central Belgium are confronted with floods caused directly by  
9 runoff from agricultural land (Boardman et al., 1994; Verstraeten and Poesen, 1999; Bielders  
10 et al., 2003). This type of process is now commonly referred to as a ‘muddy flood’, and has  
11 recently been defined as water flowing from agricultural fields carrying large quantities of soil  
12 as suspended sediment or bedload (Boardman et al., 2006). Therefore, it is a fluvial process  
13 rather than a mass movement one, originating in valleys without permanent water courses (so  
14 called ‘thalwegs’). Muddy floods are reported from most European loess areas, e.g. from the  
15 Belgium loess belt, the South Downs in the UK, from South Limburg in the Netherlands,  
16 from Northern France and Slovakia (Boardman et al., 1994; Boardman et al., 2006).

17 According to Verstraeten and Poesen (1999), the risk to be affected by such a flood  
18 can be considered as a combination of property vulnerability and muddy flood hazard. On the  
19 one hand, Varnes (1984) defines a hazard as the probability of occurrence within a specific  
20 period of time and within a given area of a potentially damaging phenomenon. On the other  
21 hand, vulnerability expresses the level of damage incurred by a target for a given hazard  
22 (Blaikie et al., 1994). The muddy flood hazard itself depends on the occurrence of a  
23 meteorological hazard on a vulnerable landscape. Major factors influencing landscape  
24 vulnerability (e.g. geomorphology, land use, cropping practices) as well as climatic conditions  
25 leading to muddy floods in the European loess belt were first synthesised by Boardman et al.  
26 (1994). Meanwhile, further research has been carried out (Table 1) and a new overview of  
27 muddy floods throughout Europe has been provided (Boardman et al., 2006).

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

12           Whereas the land use factors and cropping practices that favour the occurrence of  
13 muddy floods have been studied in some detail, much less is known regarding the  
14 morphology of the sites draining to flooded locations (physical landscape vulnerability) and  
15 the rainfall depth leading to muddy floods (meteorological hazard). Such information is  
16 crucial to implement strategies to cope with the phenomenon and to prevent the frequent  
17 flooding of houses and villages. So far, the literature on landscape configurations where  
18 muddy floods are generated only describes the general landscape context. Boardman et al.  
19 (1994) mention ‘dry valley systems’. Verstraeten and Poesen (1999) refer to ‘concentration of  
20 runoff in thalwegs’ and state that runoff starts in ‘small agricultural drainage basins’. They list  
21 all relevant topographic conditions (e.g. catchment morphology, slope gradient, slope  
22 morphology), but they do not quantify thresholds for the occurrence of muddy floods.  
23 Boardman et al. (2003) create logistic regression models to determine the probability of  
24 occurrence of muddy floods and their magnitude from geomorphic and land use parameters,  
25 as well as combined criteria. However, these were based on data available for southern

1 England. Their applicability to central Belgian conditions remains to be proven. Regarding  
2 rainfall conditions leading to muddy floods, the literature mentions ‘heavy thunderstorms’  
3 (Boardman et al., 1994; Van Dijk et al., 2005) or ‘heavy convective rainshowers’ (Verstraeten  
4 and Poesen, 1999). When rainfall depths or intensities are given, they usually refer to single  
5 extreme events from which a rainfall threshold can hardly be derived (Table 2).

6 The aim of this paper is to refine previous conceptual models of muddy flood  
7 triggering by determining rainfall and topographic thresholds for the Belgian loess belt as  
8 well as to quantify off-site impacts of muddy floods. Based on the evidence, the most suitable  
9 control measures to be applied in different landscape configurations are then reviewed.  
10 Indeed, both the connectivity between the areas producing runoff and the flooded locations as  
11 well as the probability of flooding of specific sites should be taken into account in order to  
12 design the most appropriate control measures. In addition, information regarding costs  
13 induced by muddy floods is needed to assess the financial feasibility of the proposed control  
14 measures.

15

## 16 **2. Materials and methods**

### 17 *2.1. Study area*

18 Belgium (32,545 km<sup>2</sup>) can be divided into 14 agro-pedological regions (i.e. zones of  
19 similar geology, soil type, relief and climate; Ministère de l’Agriculture, 1958). The loess  
20 belt (8867 km<sup>2</sup>), regroups both the silt-loam and sandy-loam agro-pedological regions and  
21 consists of a plateau in central Belgium (Fig. 1). This plateau, gently sloping to the North, has  
22 a mean altitude of 115 m. Valleys having a north-south orientation dissect the plateau. Mean  
23 annual temperature ranges from 9 to 10°C, while mean annual precipitation in central  
24 Belgium varies between 700 and 900 mm (Hufty, 2001; Verstraeten et al., 2006). Rainfall is  
25 evenly distributed throughout the year, but rainfall erosivity shows a peak between May and

1 September (Verstraeten et al., 2006). Mean monthly potential evapotranspiration reaches 75  
2 mm (Mitchell et al., 2004). Arable land is by far the most important land use in the loess belt,  
3 covering c. 65 % of the total surface (FPS Economy, 2006). The most important crops are  
4 cereals, industrial and fodder crops (oilseed rape, maize, sugar beet), as well as potatoes.  
5 Sowing of cover crops (e.g. mustard, phacelia) is encouraged among the farmers during the  
6 dormant period (Biielders et al., 2003). The study area includes 204 municipalities (104 in  
7 Wallonia and 100 in Flanders). The administrative entities of Flanders and Wallonia are  
8 responsible for agriculture and environment, but these entities do not correspond to a  
9 homogeneous physical region. Brussels is excluded, since agricultural land is virtually absent  
10 from the capital city.

11         The Sint-Truiden catchment (c. 200 km<sup>2</sup>) is a pilot area in the Belgian loess belt (Fig.  
12 1). The area has been affected by numerous muddy floods during the last decades. The local  
13 water agency specifically addresses the problems of flooding and water quality. Therefore,  
14 120 grassed strips and grassed waterways combined with earthen dams have been installed in  
15 the catchment between 2002 and 2005.

16

## 17 *2.2. Data sources on muddy floods in the Belgian loess belt*

18         A **survey** on muddy floods was previously carried out for the municipalities of  
19 Wallonia (Biielders et al., 2003) and Flanders (Verstraeten and Poesen, 1999). However, these  
20 studies can hardly be compared, due to the differences in the set-up of the questionnaires.  
21 Therefore, a questionnaire similar to the one used in Wallonia was sent to the Flemish  
22 municipalities of the loess belt (n=100) in order to obtain comparable data for the entire  
23 Belgian loess belt. In both questionnaires, the local authorities were asked: (1) if they were  
24 confronted with muddy floods during the previous decade; (2) how many floods occurred  
25 during this period; (3) on which dates important muddy floods occurred. Both surveys

1 concern different time intervals (1991-2000 in Wallonia vs. 1995-2004 in Flanders). The 4-  
2 year difference between the two surveys was not considered a problem given that climate and  
3 land use did not change significantly over such a short period (SPF Economy, 2006;  
4 Verstraeten et al., 2006). Rainfall erosivity is considered to be homogeneous in the Belgian  
5 loess belt and Uccle (Fig. 1) is generally taken as the reference station (Laurant and Bollinne,  
6 1978; Bollinne et al., 1979; Verstraeten, 2006). The annual rainfall erosivity (R-factor in the  
7 RUSLE model of Renard et al., 1997; MJ.mm.ha<sup>-1</sup>.yr<sup>-1</sup> h<sup>-1</sup>) can be expressed as a function of  
8 the mean annual rainfall depth (P in mm; Bollinne et al., 1979; Eq. 1).

$$9 \quad R = 115.4 \times e^{0.00215 \times P} \quad (1)$$

10 Mean rainfall erosivity in Uccle, calculated according to Eq. (1), differed by less than  
11 10% for both survey periods compared to the 1995-2004 period (725 MJ.mm.ha<sup>-1</sup>.yr<sup>-1</sup> h<sup>-1</sup> for  
12 1991-2000 vs. 791 MJ.mm.ha<sup>-1</sup>.yr<sup>-1</sup> h<sup>-1</sup> for 1995-2004; Royal Meteorological Institute – RMI).  
13 Furthermore, the total agricultural area remained stable at 60 – 65 % of the Belgian loess belt  
14 surface during this period (SPF Economy, 2006).

15 The **records of the Disaster Fund** (Belgian Ministry of Home Affairs) provided a  
16 second source of data on muddy floods. The records are available for the 204 municipalities  
17 of the Belgian loess belt for the 1993 – 2002 period, and constitute the ‘Disaster Fund  
18 database’. Four conditions need to be fulfilled for an event to be recognised as a natural  
19 disaster : (1) total damage has to reach 1,250,000 €; (2) each affected household must incur at  
20 least 5,000 € damage; (3) the event must have a 20-year return period or more according to  
21 the RMI; (4) the event must be exceptional at the national scale. The Belgian official journal  
22 ‘Moniteur belge’ cites the cause of the event recognised as a natural disaster and lists the  
23 affected municipalities. In order to restrict our research as much as possible to muddy floods  
24 and avoid accounting for river flooding, we excluded the disasters due to ‘overbank flow of



1 watercourses' and focused on the categories 'heavy rainfall', 'intense rainfall' and 'violent  
2 thunderstorms'.

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

7

### 8 *2.3. Analysis of physical landscape vulnerability*

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

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

1 According to the threshold concept (Patton and Schumm, 1975), there exists for a  
2 given slope gradient of the soil surface a critical drainage area necessary to produce sufficient  
3 runoff which will cause valley instability. Based on this concept applied by Vandaele et al.  
4 (1996) and Poesen et al. (2003) to the triggering for gully incision, we hypothesise that, for a  
5 given slope gradient (mean slope gradient of the drainage area), a critical drainage area is  
6 needed to trigger muddy floods. Such a threshold line can be described by a power function  
7 (Eq. 2).

$$8 \quad S_{cr} = a \times A^{-b} \quad (2)$$

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

20

#### 21 *2.4 Analysis of rainfall hazard*

22 In order to refine the rainfall threshold conditions leading to muddy floods, we  
23 identified from (1) the Disaster Fund database and (2) the list of flood dates given by the local  
24 authorities who filled in the questionnaire 132 muddy floods that occurred in the 20 selected

1 municipalities (between 1993 and 2005) for which daily rainfall was available from rain  
2 gauges of the RMI.

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

9

### 10 *2.5 Probability of muddy flood generation*

11 A linear logistic regression has been used to generate probabilities ( $p$ ) of muddy flood  
12 occurrence as a function of daily precipitation and the topographic variables (slope length,  
13 slope gradient and drainage area; Boardman et al., 2003) using the 100 muddy flood locations  
14 available from the regional database and the 50 comparable sites which were not flooded.  
15 Daily rainfall is available from the RMI stations for muddy flood events identified from (1)  
16 the Disaster Fund database and (2) the list of flood dates given by the local authorities in the  
17 questionnaire. The lower number of non-flooded locations ( $n=50$ ) compared to flooded  
18 locations ( $n=100$ ) is not considered a problem, given that the number of observations per  
19 variable ( $50/4=12.5$ ) is greater than 10 (Peduzzi et al., 1996). A logistic model is used to  
20 predict a binary dependant variable from one or several independent variables (Wrigley,  
21 1985). The linear logistic model has the form (Eq. 3) :

$$22 \quad \log it(p) = \log\left(\frac{p}{1-p}\right) = \alpha + \beta_n X_n \quad (3)$$

23 where  $\alpha$  is the intercept;  $\beta_n$  are slope parameters and  $X_n$  are the three topographic variables  
24 and the daily precipitation.

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

$$2 \quad p = \frac{\exp(\alpha + \beta_n X_n)}{1 + \exp(\alpha + \beta_n X_n)} \quad (4)$$

3

## 4 *2.6 Cost of muddy floods*

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

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

14

## 15 **3. Results and discussion**

### 16 *3.1. Extent and frequency of muddy floods in the Belgian loess belt*

17 Only three municipalities did not respond to the questionnaire (response rate of 98.5%).  
18 Muddy floods are a very widespread phenomenon in central Belgium (Fig. 2; Table 3).  
19 Seventy-nine percent of the municipalities (n=201) were confronted with at least one muddy  
20 flood over a ten year period. Of these 160 flooded municipalities, 22 % experienced more  
21 than 10 floods in 10 years. The muddy flood problem is more acute in Flanders where 90 %  
22 (1995-2004) of the municipalities have to deal with the problem as opposed to 67 % (1991-  
23 2000) in Wallonia. For intense events requiring an intervention of the Belgian Disaster Fund,  
24 the situation is also very different in Flanders and Wallonia (Table 3). More than one disaster  
25 occurred in c. 75 % of the Flemish municipalities, and in only 50 % of the Walloon

1 municipalities. Given the similar physical, climatic and agricultural context in both entities,  
2 such differences must be explained by other factors, e.g. the difference in population density  
3 (500 inhabitants km<sup>-2</sup> in Flanders, and 370 inhabitants km<sup>-2</sup> in Wallonia). These differences  
4 are attributed to a different socio-economic evolution and an earlier urban sprawl in the  
5 Flemish countryside (Denis, 1992). Muddy floods are more likely to go unnoticed in less  
6 populated areas as long as there is no damage to public or private infrastructure. The higher  
7 cost of muddy flood damage in more populated areas will also lead to more frequent  
8 recognition of flood events as natural disasters (see criteria in section 2.2). The adoption of  
9 specific policies to combat erosion in Flanders can also explain the higher number of muddy  
10 floods reported. The Flemish regional government adopted an erosion decree in December,  
11 2001 (Verstraeten et al., 2003). These policies lead to an increased consciousness raising and  
12 encourage local managers to better identify the problem. Undoubtedly, awareness of local  
13 agents about muddy floods has increased during the last years. In a previous survey carried  
14 out by Verstraeten and Poesen (1999) in Flanders for the period 1987 –1997, only 43 % of the  
15 municipalities reported muddy floods (vs. 90 % in 2005, according to our updated survey).

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

22         The number of muddy floods can be expressed per 100 km<sup>2</sup> to enable a comparison  
23 with the literature (e.g. Boardman et al., 2006). According to the analysis of the regional  
24 database covering a total area of 870 km<sup>2</sup>, mud deposits on roads are quite widespread (42  
25 flooded sites/100 km<sup>2</sup>). Muddy floods lead to problems to houses in 50% of the cases,

1 representing 21 flooded sites/100 km<sup>2</sup>. The sites indicated by local authorities were flooded at  
2 least once between 2000 and 2005. The annual figure would then be 8.2 floods per 100 km<sup>2</sup>  
3 yr<sup>-1</sup> (or 4.2 floods if we only consider those that led to problems to houses). On average, each  
4 municipality of the Belgian loess belt (mean area of 43.5 km<sup>2</sup>) is therefore confronted with 3.6  
5 muddy floods per year. Although probably underestimated by the local authorities, we  
6 observed a higher number of floods than reported by Boardman et al., 2006 (1 – 3 muddy  
7 floods per 100 km<sup>2</sup> yr<sup>-1</sup> for the loess belt of Flanders).

8         The increase of muddy flood frequency is confirmed by the Sint-Truiden database  
9 (Fig. 3). This increase is neither due to a significant increase of rainfall erosivity (Fig. 4), nor  
10 to the occurrence of land consolidation in the catchment, which had already been consolidated  
11 before 1977. The most important factor explaining this increase of muddy floods is the  
12 expansion of row crops, vegetables and orchards at the expense of cereals in the area (Fig. 5).  
13 At the regional scale, local press reports regarding muddy floods have increased over the  
14 years (Verstraeten and Poesen, 1999), but no systematic records are kept by local authorities.  
15 Besides a greater awareness and the expansion of vegetable and row crops, as observed in  
16 Sint-Truiden, two additional explanations can be put forward regarding this increase. First,  
17 land consolidation schemes were carried out in central Belgium since 1956. The main  
18 objectives were to increase productivity by increasing field size and improving field  
19 accessibility by constructing new concrete roads. It has been shown that such roads lead to  
20 runoff concentration and to an increase of runoff velocity, endangering the downstream  
21 villages (Evrard et al., in press). According to the regional database, 45% of the flooded sites  
22 are situated downstream of consolidated areas for a region where only 15% of the area has  
23 been consolidated (Ministère de la Région Wallonne, Direction Générale de l'Agriculture).  
24 Second, urban sprawl is increasing in central Belgium. According to the regional database, we  
25 observed that c. 30% of flooded sites concerned new houses, even though only 7.5% of the

1 houses have been built since 1991 (Ministère de la Région Wallonne, Direction Générale des  
2 Ressources Naturelles et de l'Environnement). This would indicate the particular sensitivity  
3 of new building sites in rural areas.

4

### 5 *3.2. Analysis of physical landscape vulnerability*

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

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

$$21 \quad S_{cr} = 0.0035 \times A^{-0.659} \quad (5)$$

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

1 The second type of drainage area, referred to as ‘small catchments’, occurs when a thalweg is  
2 clearly recognisable on the 1:10,000 topographical map. These are generally larger (10 – 300  
3 ha) than the hillslopes and are characterised by concentrated runoff in the valley bottom.  
4 Slope gradient has no influence on the triggering of muddy floods from small catchments  
5 (Fig. 6 a-b). However, muddy floods are triggered in such a landscape configuration when  
6 they drain an upslope area of at least 20 ha and when they are not connected to the flooded  
7 site by a road or a ditch (Fig. 6 b). When such a connection is observed, muddy floods are  
8 systematically reported from the downstream inhabited zones (Fig. 6 a). The third type of  
9 drainage area consists of medium catchments with multiple thalwegs dominated by  
10 concentrated runoff (100 – 300 ha). Connecting roads or ditches have always been observed  
11 in medium catchments and muddy floods have systematically been reported in the  
12 downstream inhabited zones (Fig. 6 a). Muddy floods from hillslopes and small catchments  
13 (92 %) are the most frequent (Table 5). They generally cause damage to limited sections of  
14 roads (leaving a ‘mud blanket’), isolated houses or hamlets. Runoff generated on more  
15 complex terrain such as medium catchments is observed less frequently (8 %) but it  
16 systematically leads to larger-scale muddy floods. Hillslopes have gentle to moderate slope  
17 gradients (2.5 – 5.7 % on average) and drain to wide outlets, the width of the junction  
18 between the cultivated hillslope and the connector (contour length) reaching 170 – 241 m on  
19 average (Table 5). Small and medium catchments have a gentler slope (mean value of 1.2 –  
20 2.3 %) but, since runoff concentrates in the valley bottom, it drains through a narrower section  
21 (108 – 152 m on average; Table 5).

22

### 23 *3.3. Analysis of rainfall hazard*

24 According to the Sint-Truiden database, 85% of fire brigade interventions in relation  
25 to runoff from cultivated areas occur from May to September (Fig. 7). This is consistent with



1 the findings of Vandaele and Poesen (1995) who reported that muddy floods in central  
2 Belgium mainly occur between May and September, after local convective storms. Rainy  
3 days with less than 10 mm account for 90% of all rainfall events, but they lead to muddy  
4 floods in only 1% of the cases. In contrast, 100% of rainfall events with more than 45 mm  
5 lead to floods (Fig. 8). Mean rainfall which produced the floods is lower in May and June  
6 ( $25\pm 12$ mm) than between July and September ( $46\pm 20$ mm). In central Belgium, potatoes,  
7 maize and sugar beets protect the soil surface very poorly (less than 20% cover) in May and  
8 June at a time when rainfall erosivity is at its highest. Fields planted with these summer crops  
9 are hence particularly sensitive to surface sealing by rainfall. At the beginning of May, after a  
10 fine seedbed preparation, soil roughness is low and crusting may rapidly occur. With such a  
11 surface crust, infiltration capacity is very low (less than  $5 \text{ mm}\cdot\text{h}^{-1}$ ; e.g. Le Bissonnais, 1996).  
12 In summer (July to September), the soil crust is disturbed by earthworm activity and  
13 desiccation (e.g. Schröder and Auerswald, 2000). Soils are also well protected by the  
14 vegetation. This can explain the higher rainfall required to trigger a muddy flood.

15

#### 16 *3.4. Probability of muddy flood generation*

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

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

16

### 17 *3.5. Cost of muddy floods*

18 After a flood, the fire brigade and municipal workers clean up public infrastructure  
19 and private property (Table 7). Fire brigade interventions cost between 2,250 € and 25,000 €  
20 per event, while cleaning operations lead to an estimated cost that ranges between 500 € for a  
21 single road segment and 11,000 € for a whole village. Several additional repairs to  
22 infrastructure may be required, such as unclogging of sewers, local replacement of tarmac or  
23 pavements. These works are very costly, ranging between 14,000 € and 300,000 € per event  
24 and per municipality. In total, damage to public infrastructure and cleaning induce a global  
25 cost of  $12.5 - 122 \times 10^6 \text{ € yr}^{-1}$  for the entire Belgian loess belt. It must be underlined that the

1 highest costs are only reached after widespread extreme thunderstorms (e.g. August 26-28,  
2 2002, with rainfall depths of more than 100 mm in 24 hours in some areas).

3 Damage to houses is also very important, affecting gardens, garages or even the  
4 ground floor of the houses. According to the analysis of the Disaster Fund database, mean  
5 damage costs reach 4,436 € ± 3,406 per house. The number of flooded sites with affected  
6 houses obtained from the analysis of the regional database (4.2 floods per 100 km<sup>2</sup> yr<sup>-1</sup>) can  
7 be extrapolated to the entire Belgian loess belt (8867 km<sup>2</sup>). Assuming 1 and 10 affected  
8 houses per flooded site, damage to private property varies between  $1.6 \times 10^6$  and  $16.5 \times 10^6$  €  
9 yr<sup>-1</sup>, respectively.

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

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

22

### 23 *3.6 Control strategies to curtail muddy floods*

24 The best long-term solution would be the adoption of alternative farming practices that  
25 reduce soil loss, such as reduced tillage or no-tillage (e.g., Holland, 2004). Gillijns et al.

1 (2004) have shown that conservation farming practices significantly reduce soil erosion and  
2 runoff in the Belgian loess belt. Although such a conversion has been encouraged among  
3 farmers for several years in Flanders, very few have adopted these practices. For instance, for  
4 the entire Flemish Region (where agricultural land covers a total area of 633,769 ha), no-till  
5 has been subsidised on 985 ha and direct drilling on only 58 ha (Flemish Ministry of  
6 Environment, 2006). However, mitigation measures can relatively easily be installed along  
7 field borders or in small and medium catchments (Fig. 10).

8         Grass buffer strips reduce runoff and erosion by sediment filtration and runoff  
9 infiltration. This infiltration leads to a decrease of runoff volume. Combined with the  
10 reduction of runoff velocity, it leads to a decrease of runoff transport capacity and hence to an  
11 increase of sedimentation (e.g., Mersie et al., 2003; Le Bissonnais et al., 2004; Vianello et al.,  
12 2005). A grass buffer strip can be installed at the downslope end of fields in order to slow  
13 runoff down and hence allow re-infiltration and sediment deposition. In Belgium, grass buffer  
14 strips along field borders are subsidised. Hillslopes with topographic conditions exceeding  
15 threshold conditions mentioned in the section 3.2 should be equipped as a priority. The  
16 sowing and maintenance of grass buffer strips is currently subsidised in Flanders (0.13 – 0.16  
17 €·m<sup>-2</sup>·yr<sup>-1</sup>) and Wallonia (0.15 €·m<sup>-2</sup>·yr<sup>-1</sup>). The grass strip width recommended by the regional  
18 authorities varies between 3 and 30 m, with a mean of 12 m. For a 12 m-wide grass strip  
19 installed at the downslope end of a field running 100 m along the contour line (area of 1200  
20 m<sup>2</sup>), the cost will be relatively low (180 € yr<sup>-1</sup> in Wallonia or 156 – 192 € yr<sup>-1</sup> in Flanders) in  
21 comparison with the damage due to the flooding of a house (4,436 € on average) or the  
22 cleaning of a road (at least 500 €). Since consolidation roads collect runoff and facilitate its  
23 transfer to villages located downstream (see section 3.2), ditches can help to drain water from  
24 the road and redirect runoff to nearby grassed waterways or grassed buffer strips. Runoff from

1 roads should be redirected to a grass buffer strip by grids across the roads or by lowering its  
2 shoulders (Fig. 10).

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

18

#### 19 **4. Conclusions**

20

21 Muddy floods are a widespread phenomenon in central Belgium, affecting 79% of the  
22 municipalities at least once in 10 years. One fifth of the municipalities were confronted with  
23 more than five floods during the last decade. Floods are mainly generated on hillslopes (1 –  
24 30 ha) or in small (10 – 300 ha) and medium (100 – 300 ha) catchments. Upslope area, slope  
25 gradient and rainfall are relevant factors for triggering a muddy flood on a hillslope. In

1 contrast, all small and medium catchments generate floods whenever heavy rainfall occurs if  
2 no mitigation measure is taken. The probability of flooding generated in small and medium  
3 catchments reaches 99% for 43 mm daily rainfall (5 year-return period). Roads and ditches  
4 facilitate runoff transfer between cultivated and inhabited areas in 64% of the observed cases.  
5 On average, each municipality is affected by 3.6 muddy floods each year. A detailed dataset  
6 for a 200 km<sup>2</sup>-catchment suggests that the phenomenon becomes more frequent in central  
7 Belgium, mainly as a result of increasing acreage of row crops and orchards at the expense of  
8 cereals. The high costs induced by muddy floods ( $16 - 172 \times 10^6 \text{ € yr}^{-1}$  for the entire Belgian  
9 loess belt) strengthen the necessity to take immediate measures to alleviate the phenomenon.  
10 At the downslope end of small hillslopes, grassed buffer strips can help mitigate floods at a  
11 low cost compared to potential damage to property, while in small and medium catchments, it  
12 is recommended to install a grassed waterway as well as earthen dams. Pilot measures have  
13 been installed in the 200 km<sup>2</sup>-catchment of Sint-Truiden. Their efficiency is being quantified  
14 in a long-term study in order to optimise their design for future application.

15

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17

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22 Transports; Ministère de la Région Wallonne, Direction Générale de l'Agriculture – Direction  
23 Générale des Ressources Naturelles et de l'Environnement; the staff in all visited  
24 municipalities.

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1 **Figure captions**

2

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

6

7 Fig. 2. Frequency of muddy floods over a 10-year period in all municipalities of the study  
8 area; data for Wallonia (1991-2000) taken from Bielders et al. (2003), data for Flanders  
9 (1995-2004) derived from a questionnaire sent to all municipalities in 2005.

10

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

13

14 Fig. 4. Annual rainfall erosivity in Gorseme (Sint-Truiden) for the period 1977 – 2001 (RMI,  
15 2006). Dotted line represents mean annual rainfall erosivity for the period 1977-2001 (667  
16 MJ.mm.ha<sup>-1</sup>.yr<sup>-1</sup> h<sup>-1</sup>).

17

18 Fig. 5. Evolution of the relative agricultural land cover in the Sint-Truiden catchment between  
19 1973 and 2000 (Data for Gingelom; SPF Economy, 2006).

20

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

25

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

1

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

6

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

11

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



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



**Table 2.** Rainfall conditions leading to muddy floods in the literature

Specific information	Study area	Reference
General conditions		
Rainfall intensity > 10 mm.h <sup>-1</sup>	Pays de Caux, France	Boardman et al., 1994
35 mm.h <sup>-1</sup> 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)	Du� catchment, France	Larue, 2001
45 mm in 30 min. (May 8, 1990)	Du� 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
70-75mm 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

**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 (1995-2004; Belgium 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



**Table 4.** Runoff connectivity between cultivated areas and inhabited areas in central Belgium. Dataset: 100 flooded locations visited in the field or well-documented in the Flemish erosion mitigation schemes.

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



**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. Standard deviation (SD) is indicated for each characteristic.

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

**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,  $\rho^2 = 0.45$ . 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;  $p = 0.0011$ ).

Variable	Parameter estimate	Standard error	Wald $\chi^2$	$p > \chi^2$
<b>(a) Hillslopes</b>				
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>(b) Small and medium catchments</b>				
Intercept	-12.6655	4.2481	8.8889	0.0029
Rainfall	0.4014	0.1315	9.3164	0.0023





Table 7. Data on damage costs induced by muddy floods collected in the visited municipalities. Data available from the ‘public work’ services of the municipalities, except for Herzele and Riemst (data available from the municipal erosion mitigation schemes).

<u>Municipality</u>	<u>Date of event</u>	<u>Type of intervention</u>	<u>Cost (€)</u>
Beauvechain	August 2002	Cleaning of roads	10,125
	September 2005	Cleaning of roads	16,350
Chaumont-Gistoux	May 5, 2006-07-28	Cleaning of roads and cellars	80,000
Ellezelles	2-3 times/year	Cleaning of roads	500 – 1,000
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	4,720
Frasnes-lez-Anvaing	September 8-10, 2005	Cleaning of roads	1,512
		Repair to roads	14,000
Herzele	1999	Cleaning and repairs	327,640
		Fire brigade interventions	9,000
	2001	Cleaning and repairs	83,475
		Fire brigade interventions	2,250
	2002	Cleaning and repairs	83,275
		Fire brigade interventions	2,250
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



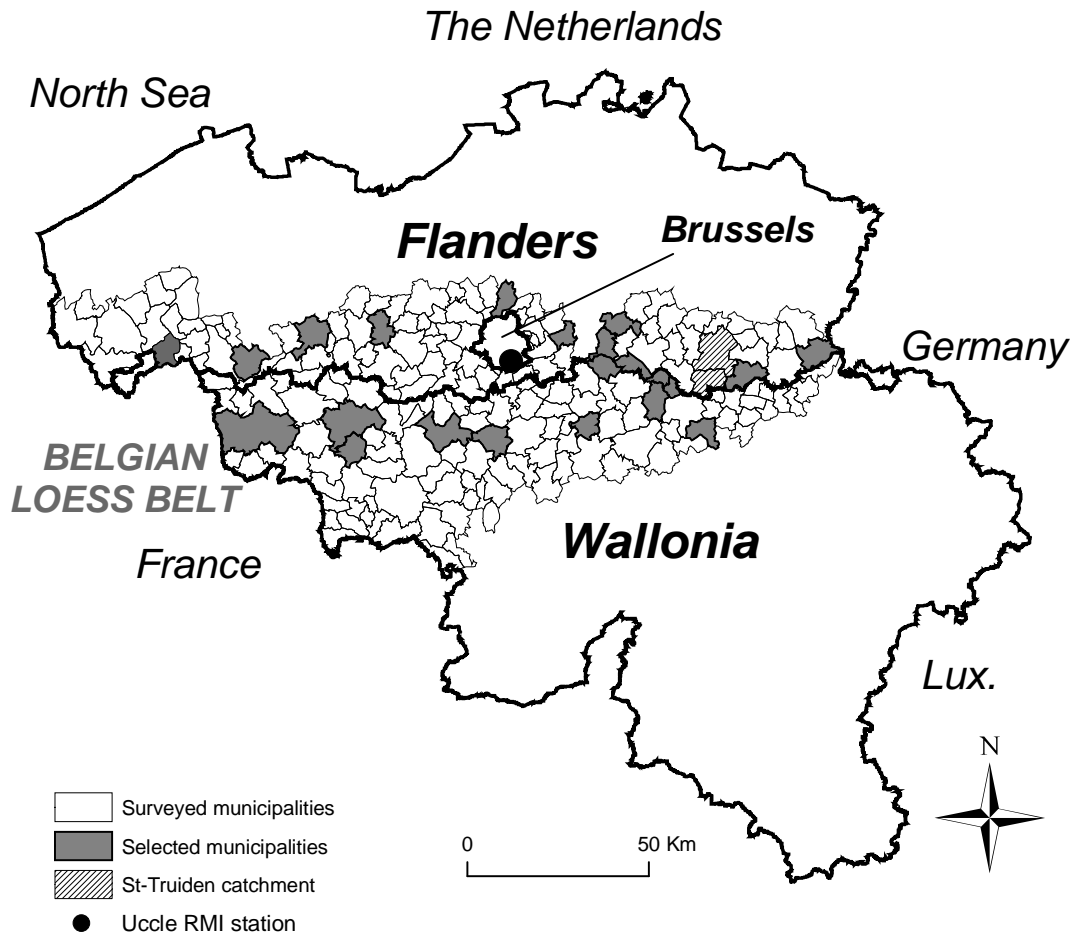


Figure 1

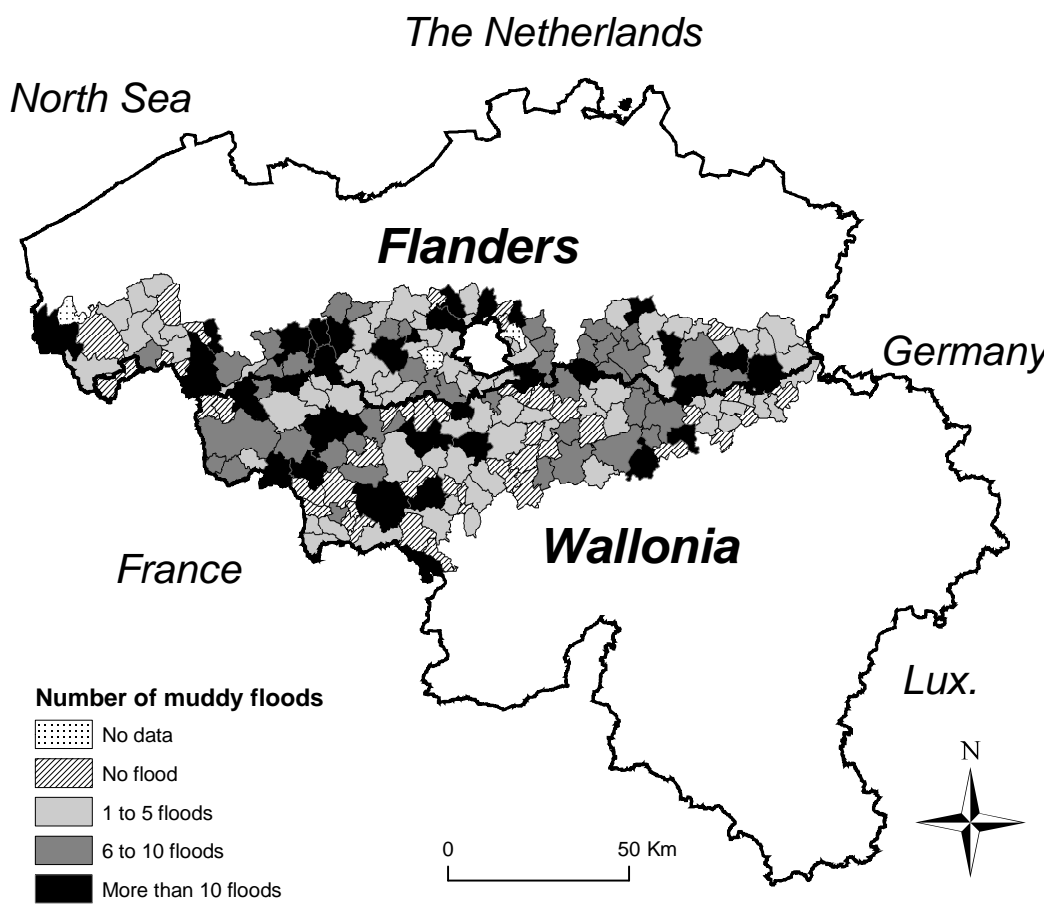


Figure 2

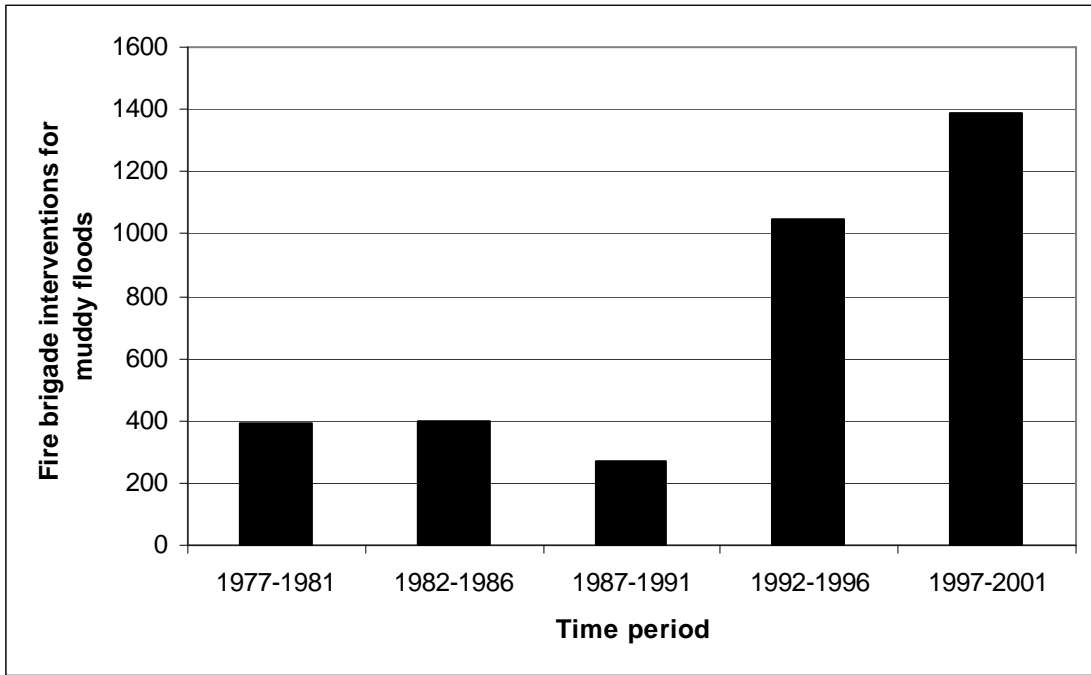


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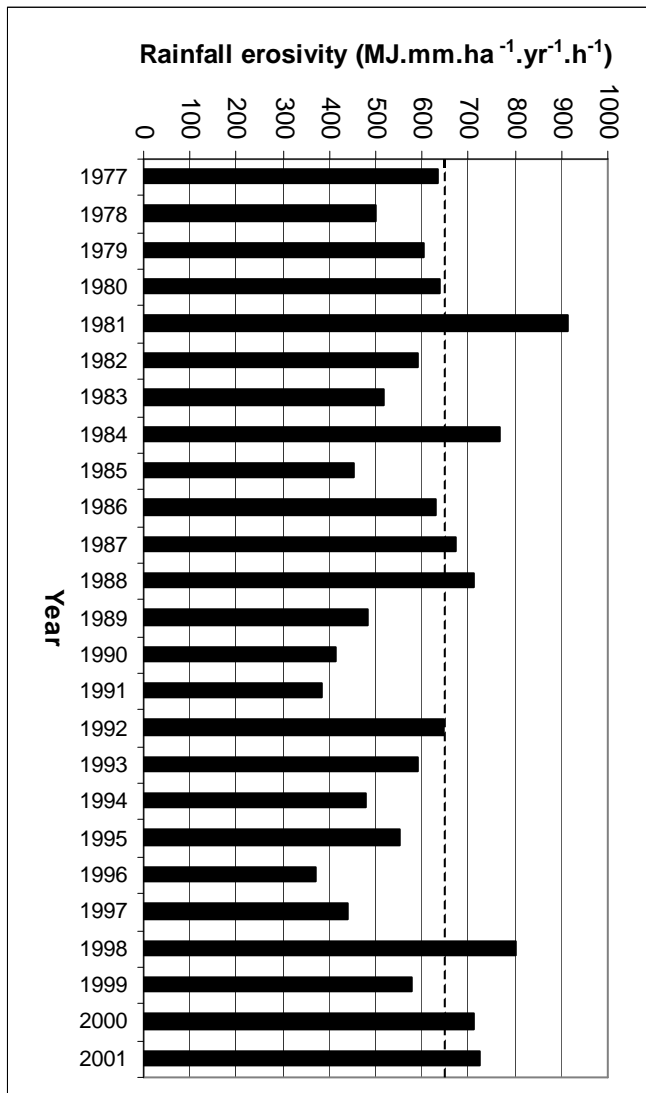


Figure 4

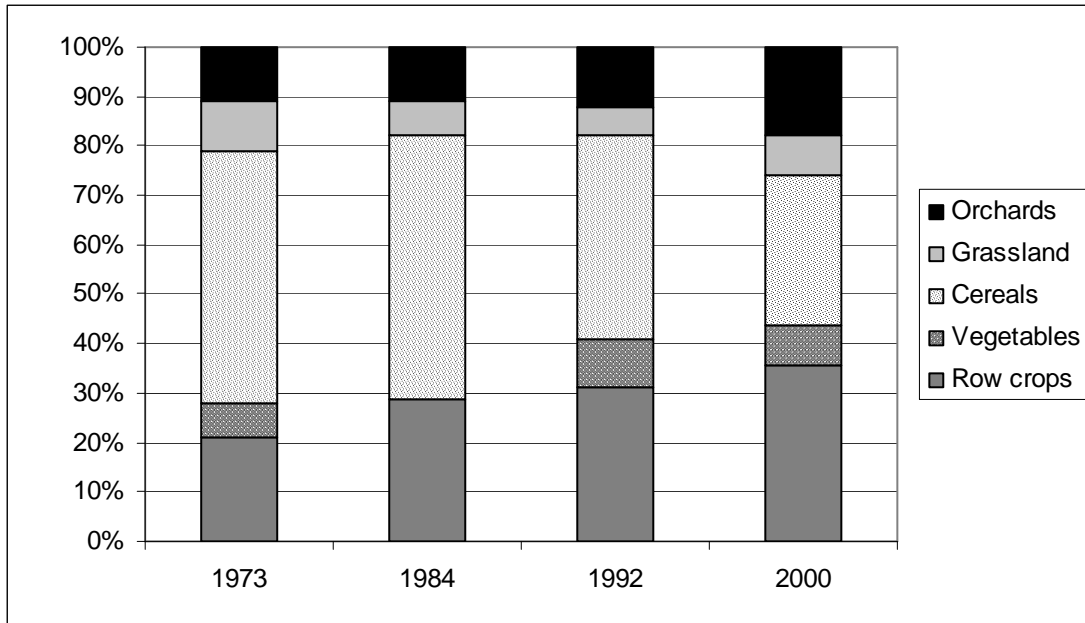
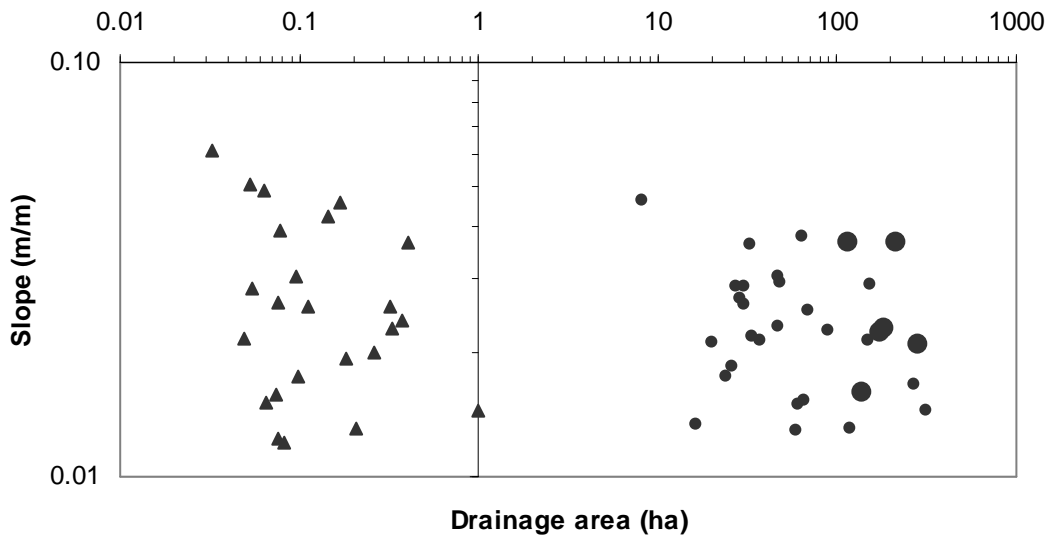
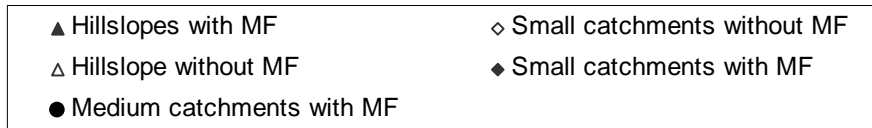
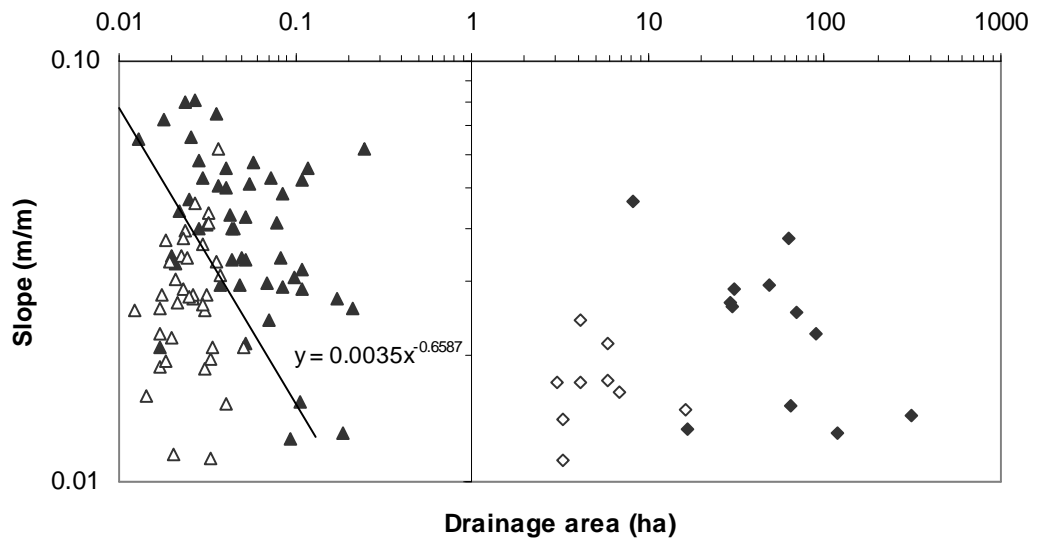


Figure 5



(a)



(b)

Figure 6



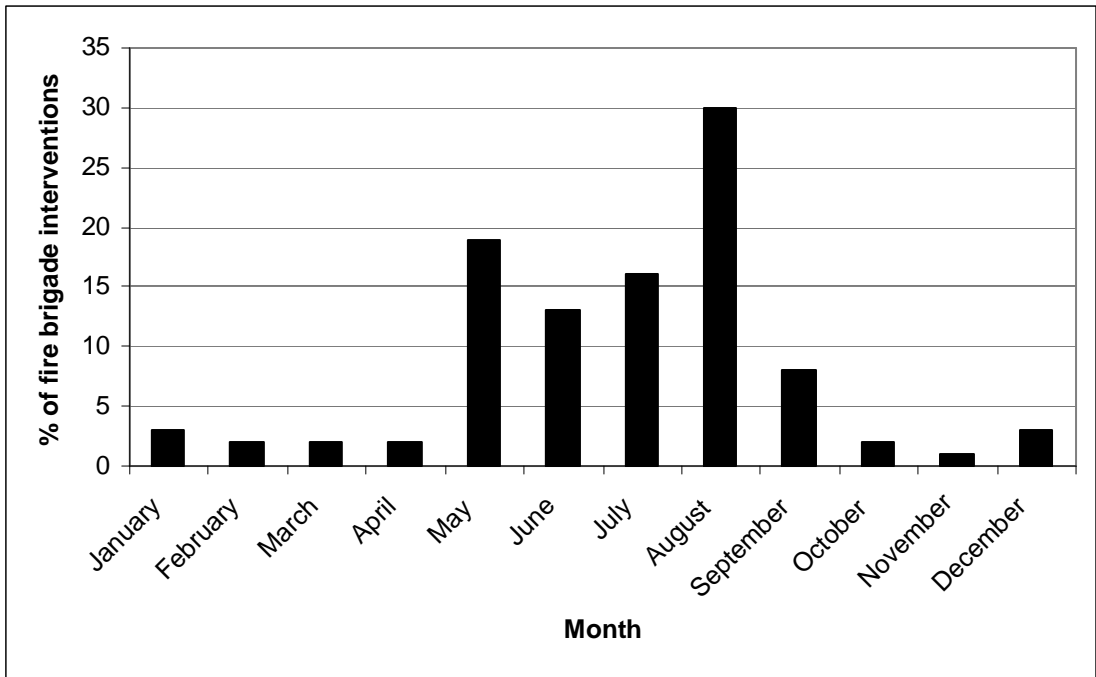


Figure 7

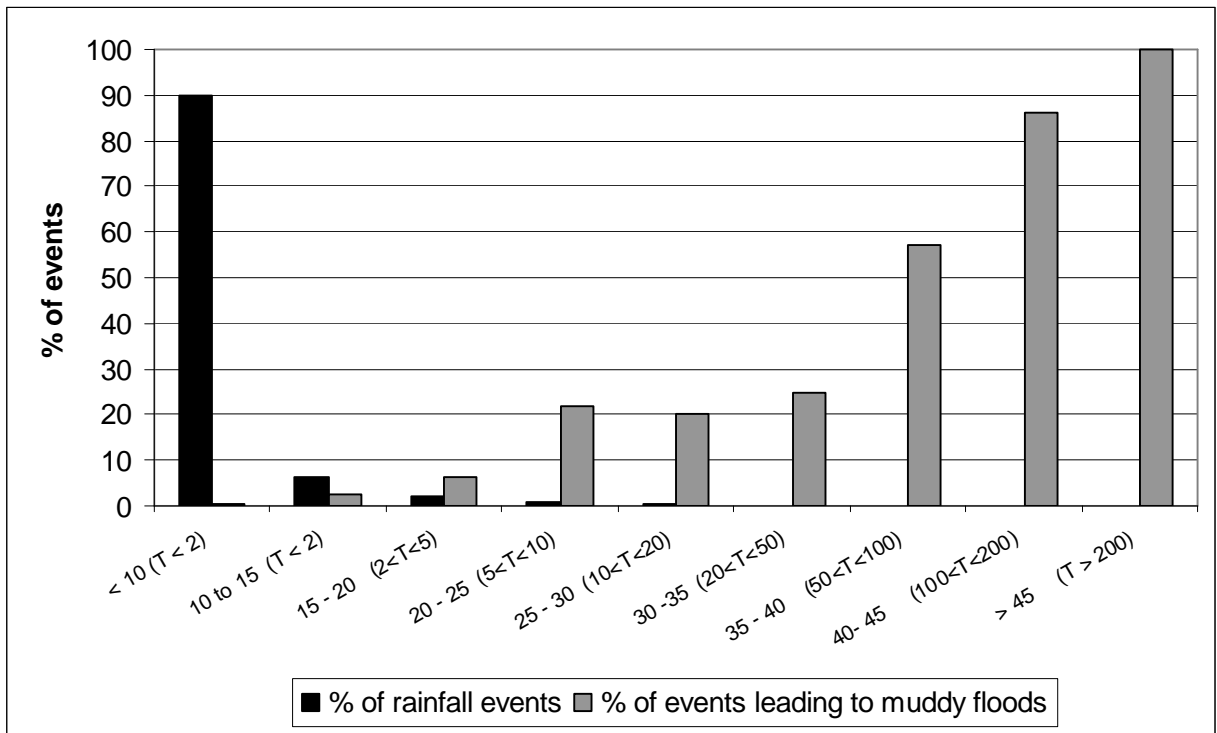


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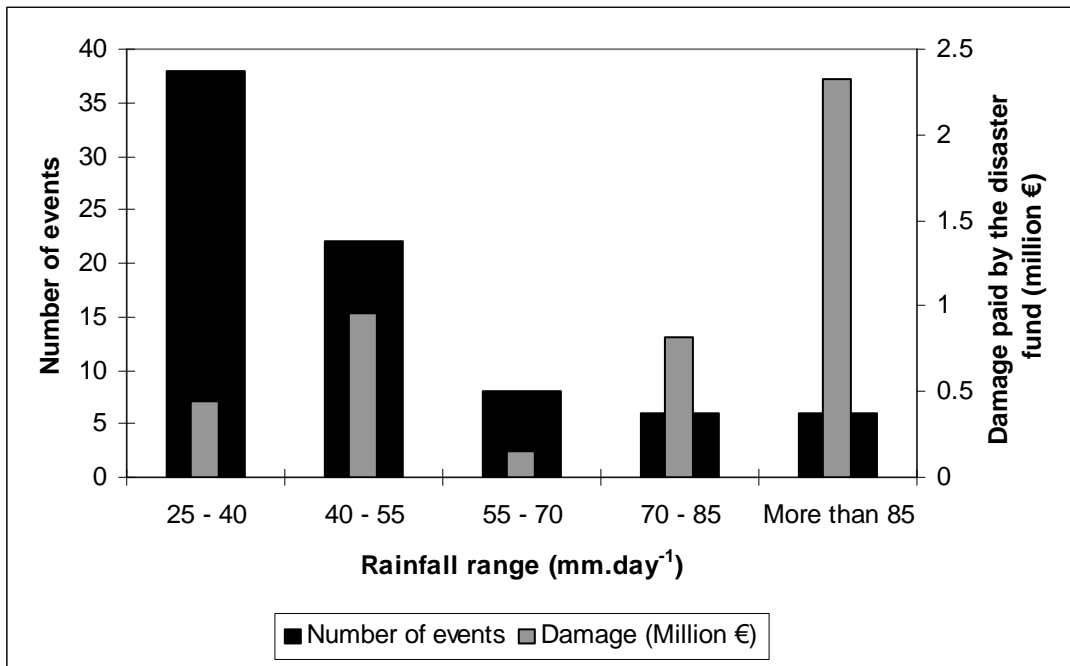


Figure 9

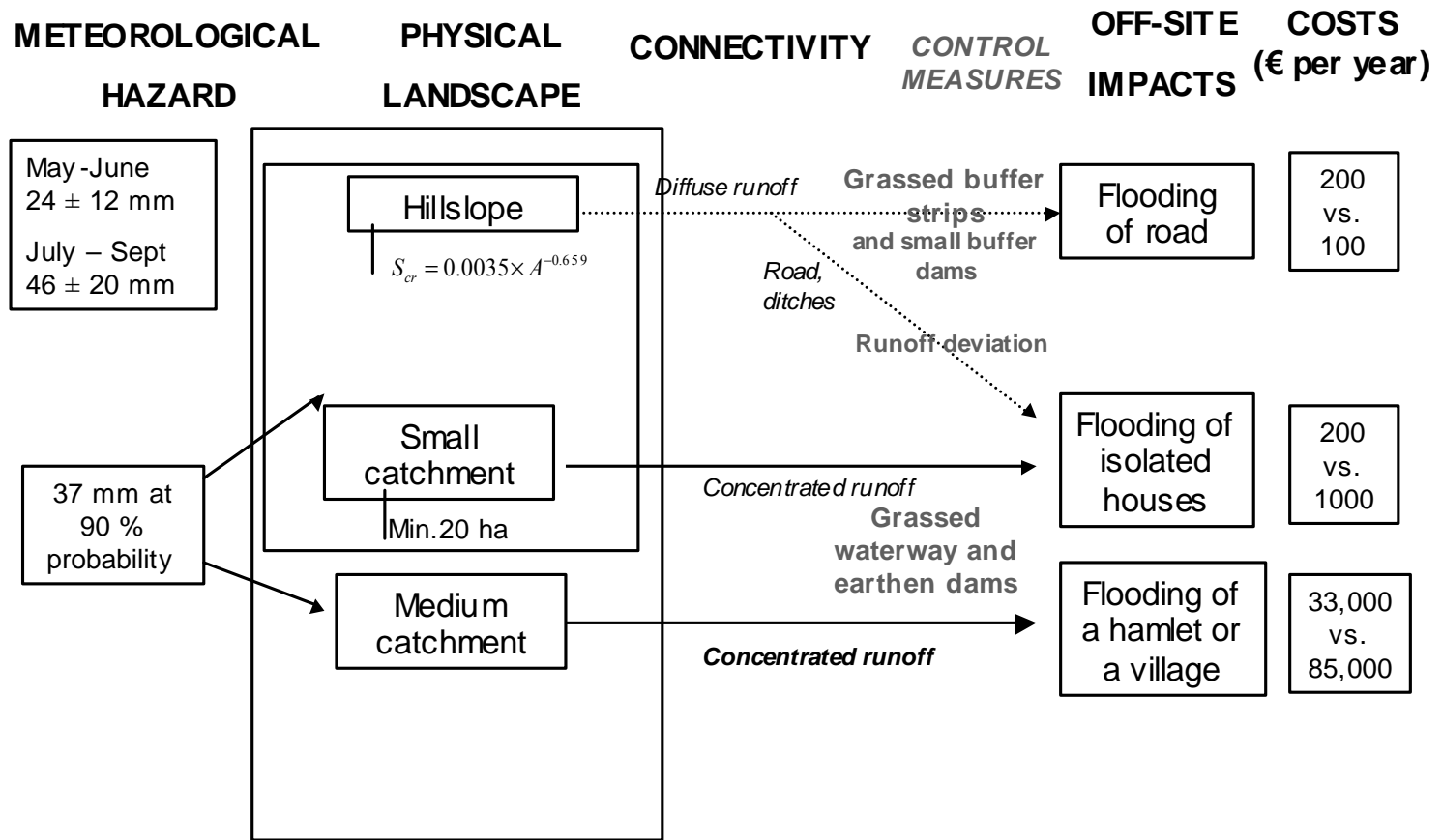


Figure 10