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"Muddy floods in the Belgian loess belt : problems and solutions"

Evrard, Olivier

ABSTRACT

The first part of this thesis aims at defining the conditions triggering muddy floods in the Belgian loess belt. On average, each municipality is confronted with 3.6 muddy floods each year. Annual costs associated with their off-site impacts are estimated at € 16-172 millions for the entire Belgian loess belt. A topographic threshold is derived to predict the source areas of muddy floods. Furthermore, the storms required to produce a flood are, on average, smaller in May and June (25 mm) than between July and September (46 mm). This difference is explained by the variability of soil surface characteristics that determine the runoff potential of cultivated soils (soil cover by crops and residues, soil surface crusting and roughness). Steady state infiltration rates of cropland and grassed areas were characterised in the field using a 0.5 m²-portable rainfall simulator. Overall, grassed areas have a lower infiltration rate (16-23 mm h⁻¹) than croplands (25-52 mm h⁻¹). Muddy floods ar...

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**Muddy floods in the Belgian loess belt :
Problems and solutions**

Olivier Evrard

*Thèse présentée en vue de l'obtention
du grade de Docteur en Sciences*

Université catholique de Louvain

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Composition du jury

Bas van Wesemael *Promoteur*

Professeur, Unité de géographie, Faculté des sciences, Université catholique de Louvain, Louvain-la-Neuve, Belgique

Charles Bielders *Co-promoteur*

Professeur, Unité de Génie Rural, Faculté d'ingénierie biologique, agronomique et environnementale, Université catholique de Louvain, Louvain-la-Neuve, Belgique

Eric Lambin *Président*

Professeur, Unité de géographie, Faculté des sciences, Université catholique de Louvain, Louvain-la-Neuve, Belgique

Veerle Vanacker

Professeur, Unité de géographie, Faculté des sciences, Université catholique de Louvain, Louvain-la-Neuve, Belgique

Karel Vandaele

Docteur, Watering van Sint-Truiden, Sint-Truiden, Belgique

Olivier Cerdan

Docteur, Bureau de Recherches Géologiques et Minières - Aménagement et Risques Naturels, Orléans, France

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List of abbreviations and symbols

List of abbreviations

<i>AEM</i>	Agri-Environmental Measure
<i>ANOVA</i>	Analysis Of Variance
<i>CN</i>	Curve Number
<i>CT</i>	Conservation Tillage
<i>DEM</i>	Digital Elevation Model
<i>GBS</i>	Grass Buffer Strip
<i>GIS</i>	Geographical Information System
<i>GPS</i>	Global Positioning System
<i>GWW</i>	Grassed Waterway
<i>HSD</i>	Tukey-Kramer's Honestly Significant Difference
<i>IPCC</i>	Intergovernmental Panel on Climate Change
<i>MHM</i>	Meshed Hydrological Model
<i>n/a</i>	Not available
<i>NS</i>	Not significant
<i>RMI</i>	Royal Meteorological Institute of Belgium
<i>RUSLE</i>	Revised Universal Soil Loss Equation
<i>SCS</i>	Soil Conservation Service
<i>STREAM</i>	Sealing and Transfer by Runoff and Erosion related to Agricultural Management
<i>USLE</i>	Universal Soil Loss Equation

List of symbols

<i>A</i>	(1) Drainage area	(ha)
	(2) Drainage area (Eq. 8.3)	(km ²)
<i>AUE</i>	Average Unsigned Error	(%)
<i>C</i>	Cross-section of the flow	(m ²)

c	Cross-section of the drain through the dam	(m ²)
D	Rainfall duration	(h)
d	Channel depth	(m)
h	Hydraulic head	(m)
I	Topographic index (also called wetness index)	
I_{α}	Infiltration capacity of a pixel α	(mm h ⁻¹)
I_{max}	Maximum rainfall intensity in 5 minutes	(mm h ⁻¹)
IR	Initial soil moisture content	(mm)
ME	Mean error	
n	(1) Manning's roughness coefficient	(s m ^{-1/3})
	(2) Number of observations	
P	(1) Rainfall depth	(mm)
	(2) Mean annual rainfall depth (Eq. 2.1, 8.7)	(mm)
p	Probability	
Q	Runoff discharge	(m ³ s ⁻¹)
Q_{ip}	Peak discharge of inflow	(m ³ s ⁻¹)
Q_{op}	Peak discharge of outflow	(m ³ s ⁻¹)
R	(1) Rainfall erosivity factor	(MJ mm ha ⁻¹ yr ⁻¹ h ⁻¹)
	(2) Hydraulic radius (Eq. 8.7)	(m)
r	Pearson's correlation coefficient	
RC	Runoff Coefficient	(%)
$RMSE$	Root Mean Square Error	
SC_{α}	Potential sediment concentration of a pixel α	(g l ⁻¹)
S_{cr}	Critical slope gradient	(m m ⁻¹)
SD	Standard Deviation	
S_p	Detention storage volume	(m ³)
S^*_p	Relative storage volume	
SSY	Specific Sediment Yield	(t ha ⁻¹ yr ⁻¹)
T	Rainfall return period	(yr)
T_c	Time of concentration of the catchment	(h)
T_r	Total runoff duration	(h)
v	Runoff velocity	(m s ⁻¹)
V_{in}	Runoff volume to be controlled	(m ³)
w	Channel width	(m)
α	(1) Level of statistical significance	
	(2) Local catchment area per unit contour length	(m ² m ⁻¹)
β	Slope gradient	(m m ⁻¹)

ρ^2 Rho-square (Goodness-of-fit measure)
 χ^2 Chi-square (Statistical test)

Introduction

Background

Runoff and soil erosion represent one of the major environmental threats related to the agricultural land use in Europe (European Environment Agency, 2000). These phenomena lead to several on-site impacts such as yield losses, variable plant growth, nutrient and pesticide loss and the progressive loss of the arable layer which will lead to a productivity decrease over the long term (Boardman et al., 2003). Runoff and erosion also cause numerous off-site impacts, among which muddy floods. These consist of water flowing from agricultural fields and carrying large quantities of soil as suspended sediment or bedload (Boardman et al., 2006). These floods are often associated with the formation of ephemeral or thalweg gullies developed in dry valley bottoms (Boardman et al., 1994). They cause among other consequences damages to human infrastructures and water contamination by sediments and pesticides (Dosskey, 2001).

Despite gentle slopes and temperate climatic conditions, numerous villages of the loess belt of northwestern Europe are affected by muddy floods which have been reported since the 19th century (see e.g. Cochet, 1842; Banse, 1935; Henin and Gobillot, 1950; Lefèvre, 1958; Auzet, 1987). Boardman et al. (1994) reported for the first time the widespread occurrence of muddy flooding in the loess belt of northwestern Europe and identified areas of high risk: the South Downs in England, northern France, the Limburg province in the Netherlands as well as central Belgium. However, this list is not exhaustive and the phenomenon also affects others regions in France (e.g. Alsace, Rhône Valley; Auzet et al., 2006), Germany (Auerswald, 1991) and Slovakia (Boardman et al., 2006), for instance. The affected areas pointed out by Boardman et al. (1994) are all characterised by the presence of cultivated dry valley systems in which soils are highly erodible. Moreover, these regions experienced a recent intensification of agriculture and expansion of urban areas in valley bottom locations, which could have led to an increase in flooding events causing damage to infrastructure (Boardman et al., 1994).

Vandaele (1997) studied the temporal and spatial dynamics of soil erosion processes in cultivated catchments of central Belgium. He found that erosion and runoff are mainly produced (1) in spring and early summer on fields with summer crops at an early development stage and (2) in autumn and winter on fields left bare after harvesting or freshly sown with winter cereals. Nevertheless, Vandaele and Poesen (1995) outlined that 60 to 70 % of the total soil loss due to rill and ephemeral gully erosion occurred in late spring and in summer after intense storms. A few years later, Verstraeten (2000) investigated the sediment export of cultivated catchments to watercourses in central Belgium and outlined the important contribution of muddy floods.

In 1992, the Maastricht Treaty imposed the obligation of integrating the protection of environment into all the policies of the European Union. This obligation led for instance to the introduction of agri-environment schemes in the framework of the Common Agricultural Policy reform in 1992 (Ritson and Harvey, 1997; Souchère et al., 2003). Simultaneously, an increasing interest in soil erosion and its related problems has been observed in Europe, and particularly in Belgium. For instance, the Flemish region recognised erosion as an environmental problem, mainly as a source of sediment in rivers and a cause of muddy floods, for the first time in 1997 (Verstraeten et al., 2003). A survey carried out among 1,500 farmers of central Belgium has shown that 74 % of them take measures to control erosion, e.g. by sowing cover crops during the intercropping period or installing grass buffer strips along field edges (Biielders et al., 2003). In a worldwide context of increasing interest in environmental issues, the Belgian policymakers took legislative initiatives to control soil erosion and its associated problems. The Flemish government adopted a 'Soil Erosion Decree' in December 2001, allowing municipalities to receive subsidies to draw up an erosion mitigation scheme and to install the proposed measures in the field (Verstraeten et al., 2003). More recently, a scheme aimed at controlling floods ('*Plan Pluies*') was adopted by the Walloon government. This scheme proposes an integrated management of flooding, including measures to control runoff and erosion in agricultural areas. The proposed directive related to the '*European Thematic Strategy for Soil Protection*' (2006/0086/EC) also requires that the member states define a strategy to use soils in a sustainable way. This strategy will very likely include measures to control soil erosion and muddy floods.

Local authorities and consulting firms need decision support tools to implement such control measures and evaluate their effectiveness. These tools must be scientifically reliable and easy to use. In this context, the STREAM runoff/erosion expert-based model designed in Normandy (France) offers a potential solution

(Cerdan et al., 2002a). It focuses on the dominant processes controlling runoff and erosion at the catchment scale and was successfully applied to simulate agri-environmental scenarios in Normandy (Souchère et al., 2005).

Problem statement

The general context in which muddy floods are triggered is known. They are generated by intense storms on susceptible cultivated areas (e.g. Verstraeten and Poesen, 1999). However, the morphology of the sites draining to the flooded locations as well as the rainfall threshold leading to muddy floods are not yet well known. Such information is crucial to identify potentially vulnerable sites and implement control strategies. Information regarding costs induced by the floods is also needed to assess the financial feasibility of the potential control measures. The cost of damages associated with muddy floods is related to the peak flow and the volume of runoff and sediment produced. For a given site, these will depend on the soil surface characteristics at the time of the storm.

Even though we know that muddy floods occur when large amounts of runoff are generated on crusted cultivated soils, the effectiveness of flood control measures is best estimated for the period of the year when the runoff risk is the highest. There is hence a need for a consistent methodology to evaluate the hydrological impact of the soil surface properties that are known to vary throughout the year in order to define the periods with a high runoff risk.

Runoff/erosion models generally need numerous input parameters. STREAM, which is an expert-based model, only needs steady state infiltration rates and sediment concentration data. However, this model was designed on data from Normandy and its decision rules are only valid for the local conditions for which they have been derived. STREAM need hence to be calibrated and validated in the context of the Belgian loess belt. Once validated, the model can be used to estimate runoff volumes to control and to guide the implementation of mitigation measures to protect flood prone areas.

Currently, small-scale measures such as dams and grassed waterways are being installed in the field but their design and location are mostly based on expert judgement, without any *a priori* knowledge of their potential effectiveness. There is thus a need to evaluate their effectiveness before generalising their installation in problem areas. The monitoring of these control measures is best carried out at the scale of catchments on which large quantities of runoff

leading to muddy floods can potentially be generated. Once the effectiveness of individual flood control measures is known, simple methods are needed to implement control schemes to protect flood prone areas in the Belgian loess belt and similar environments.

Objectives

The overall objective of this thesis is to define the conditions triggering muddy floods in the Belgian loess belt and to evaluate the effectiveness of measures to control them. Emphasis is laid on measures implemented at the catchment scale. The research is carried out in the Belgian loess belt, where pilot mitigation measures have been implemented after the adoption of a decree allowing the local authorities to implement erosion and flood control measures in problem areas.

To this end, several specific objectives are pursued:

- define the conditions for muddy flood triggering based on a detailed study carried out in municipalities that were severely affected by muddy floods;
- quantify the spatial and temporal variability of soil surface properties in cropland of the Belgian loess belt and the hydrological impact of these properties;
- validate a hydrological runoff/erosion model that integrates the variability of the soil surface properties in the context of the silt-loam soils of central Belgium;
- evaluate the effectiveness of measures to control muddy floods, based on (i) the simulation of a worst-case scenario using a hydrological model and (ii) the intensive monitoring of pilot control measures installed in an experimental catchment;
- propose simple methods to guide implementation and evaluate control measures to protect other flood prone areas.

The thesis will combine multiscale data (plot, field, small catchment, medium catchment) and several methodologies (field observations, rainfall simulations in the field, field and catchment quantitative monitoring, socio-economic questionnaire, hydrologic modelling).

Outline of the thesis

This thesis (except for chapters 1 and 7) is based on articles published in or submitted to international peer-reviewed journals.

To avoid any redundancy in the subsequent chapters, the Belgian loess belt as well as the main study sites are described in detail in chapter 1. After a brief literature review, chapter 2 presents the spatial and temporal variation of muddy floods in central Belgium, their main off-site impacts as well as the potential control measures that can be implemented. Since muddy floods are produced when large quantities of runoff are generated on cultivated soils, chapter 3 addresses the seasonal evolution of runoff generation on agricultural land and its implications for muddy flood triggering. A runoff risk classification is developed at both field and catchment scales and stress is laid on runoff differences arising when taking account of the upscaling from the plot to the field scale. Steady-state infiltration rates obtained in chapter 3 for soil surface conditions representative of the cultivated soils of central Belgium are used to calibrate the STREAM model (Cerdan et al., 2002a). Chapter 4 focuses on the reliability of this expert-based model to simulate runoff and erosion in different environments (central Belgium and southern France) to the one it was designed for (Normandy, northern France).

Numerous pilot measures have been installed in Flanders (Belgium) after the adoption of the 'Soil Erosion Decree' in December 2001. A hydrological model is used to simulate a worst-case scenario and test the impact of the seasonal evolution of crop cover, land consolidation and the installation of a grassed waterway on runoff generated in a 300 ha-cultivated catchment. Modelling results are described in chapter 5. Given the high values of peak discharge obtained in this case-study, two additional earthen dams were installed by the local water board to control runoff generated in the catchment. This 300 ha-catchment was equipped (raingauges, flume, water level recorders) to evaluate the effectiveness of the grassed waterway and the three earthen dams to control muddy floods. The results of this detailed monitoring are presented in chapter 6. Several other measures to control muddy floods were installed in the 200 km²-Melsterbeek catchment. Chapter 7 proposes simple methods to evaluate and implement control measures at the medium catchment scale.

Finally, the last chapter gives a synthetic view of the most important findings and contributions of this thesis. It also provides some recommendations for policy and opens up new perspectives for future research.

Chapter 1

Description of study area

1.1 Study area: Belgian loess belt

Belgium (32,545 km²) 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 km²) regroups both the 'silt-loam' and 'sandy-loam' agro-pedological regions and consists of a plateau in central Belgium (Fig. 1.1). 'Belgian loess belt' and 'central Belgium' are therefore used as synonyms throughout this thesis.

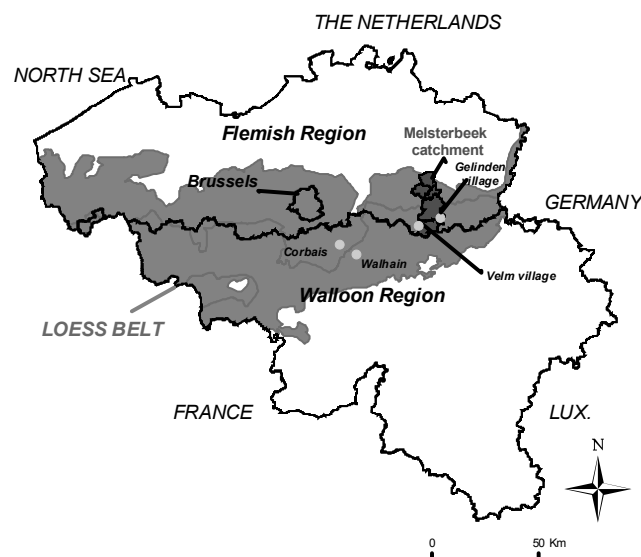


Figure 1.1: Location of the loess belt and the experimental sites in Belgium.

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). Most soils are loess-derived haplic luvisols and haplic regosols (World Reference Base, 1998). A topsoil sample of haplic luvisols contains on average 18% sand (SD=14%), 60% silt (SD= 31%) and 22% clay (SD=18%), as documented in the Aardewerk database restricted to the Belgian loess belt (Van Orshoven et al., 1988). Surface layers of haplic regosols contain on average 20% sand (SD=16%), 56% silt (SD=32%) and 24% clay (SD=18%). Mean soil organic matter content reaches c. 2% (Goidts and van Wesemael, 2007).

Arable land is by far the most important land use in the loess belt, covering c. 65% of the total surface (Statistics Belgium, 2006). The acreage of row (maize *Zea Mays L.*, potatoes *Solanum tuberosum L.*, sugarbeets *Beta vulgaris L.*) and industrial (oilseed rape *Brassica napus L.*, flax *Linum usitatissimum L.*) crops increased at the expense of winter cereals over the last decades. Orchards are mostly found in the region of Sint-Truiden, where they cover up to 65% of the total area vs. less than 5% elsewhere in the loess belt.

The Belgian loess belt includes 204 municipalities (104 in Wallonia and 100 in Flanders). The administrative entities of Flanders and Wallonia are responsible for issues related to 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.

1.2 Main experimental sites

The soils within the experimental sites are loess-derived haplic luvisols and haplic regosols.

1.2.1 Corbais-field and Walhain-catchment

The monitoring of runoff and soil surface characteristics was carried out in an experimental field (Corbais, 6 ha) and a micro-catchment (Walhain, 16 ha, 5

fields) of the Belgian loess belt (Fig. 1.1). These sites consist entirely of cropland and are characterised by common crop rotations alternating winter cereals and summer crops.

1.2.2 Melsterbeek catchment

The region of Sint-Truiden has been repeatedly affected by muddy floods, and the local water agency (Melsterbeek water board) decided to tackle the problem (Fig. 1.1). In the framework of the 'Soil Erosion Decree' adopted by the Flemish government in 2001, the water board drew up an erosion mitigation scheme at the catchment scale (200 km²). Between 2002 and 2005, 120 grass strips and grassed waterways¹ were installed, covering a surface of c. 25 ha (0.13% of total area). Grass species consist of a mix of *Lolium multiflorum* Lam., *Lolium perenne* L., *Festuca rubra* L. subsp. *rubra* and *Dactylis glomerata* L. Furthermore, 35 earthen dams were built.

1.2.2.1 Heulen Gracht catchment

Velm has the local reputation of a 'devastated village', given that it was flooded numerous times during the last decades. Runoff loaded with sediments is generated in cultivated, dry zero-order valleys covering a total area of 930 ha that drain into the Molenbeek river directly upstream of its entry into Velm village (Fig. 1.2). In the 1980s, a culvert with a capacity of 4 m³ s⁻¹ was built to channel the river across the village. This culvert was designed on the basis of bankfull discharge of the Molenbeek draining the large catchment upstream of Gingelom. However, the additional runoff from the seven dry valleys was not taken into account, and consequently the village is flooded whenever an additional large amount of muddy water from these dry valleys drains into the river.

This thesis focuses on one of these dry valleys (locally known as 'Heulen Gracht') with an altitude between 67 and 106 meters and an area of 300 ha (Fig. 1.2, 1.3). Cropland covers 79% of the catchment surface. Orchards (17%) and roads (3%) are the main other types of land use. After repeated floods, it was decided

¹Grass buffer strips are typically installed along field borders or within fields to infiltrate runoff, trap sediments and pesticides. They have generally a width between 3-30 meters in central Belgium, with a mean of 12 m. In contrast, grassed waterways are specifically located in runoff concentration pathways (i.e. in the thalweg of dry valleys).

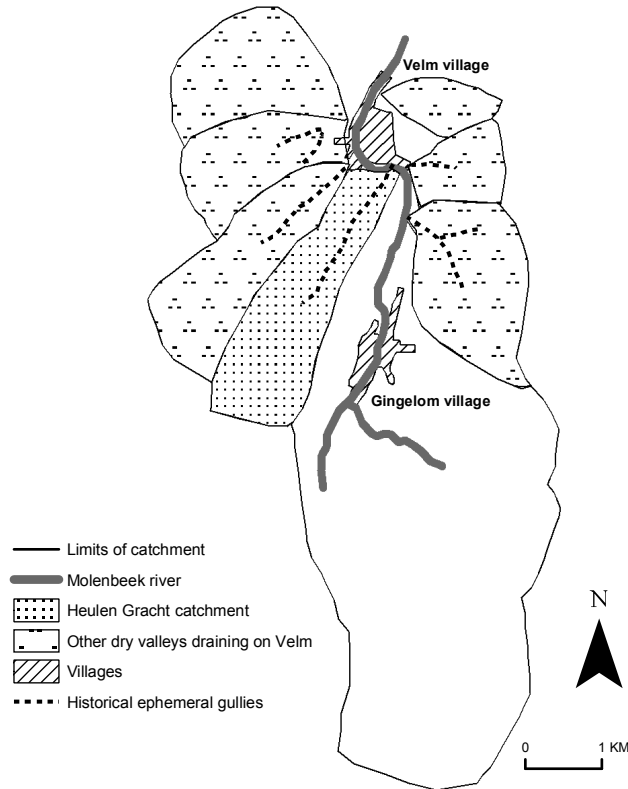


Figure 1.2: Location map of Velm village and the upstream cultivated dry valleys. Dotted lines represent historical gullies observed in the area.

in 2002 to construct an earthen detention² dam with a capacity of 2000 m³ at the catchment outlet and a grassed waterway of 12 ha in the lower part of the thalweg. Two additional dams (having each a capacity of 3500 m³) were built in 2004.

1.2.2.2 Gelinden catchment

Three dry zero-order valleys covering altogether an area of 200 ha are regrouped as 'Gelinden catchment' (Fig. 1.4). The two southern valleys (105 and 50 ha) drain to the Steernboornbeek river, whereas the third northern valley (44 ha)

²'Detention' and 'retention' are usually confused. 'Detention ponds' are designed to retain a certain amount of water while slowly draining to another location. They are specifically used to control floods. In contrast, 'retention ponds' are designed to retain a specific amount of water indefinitely.

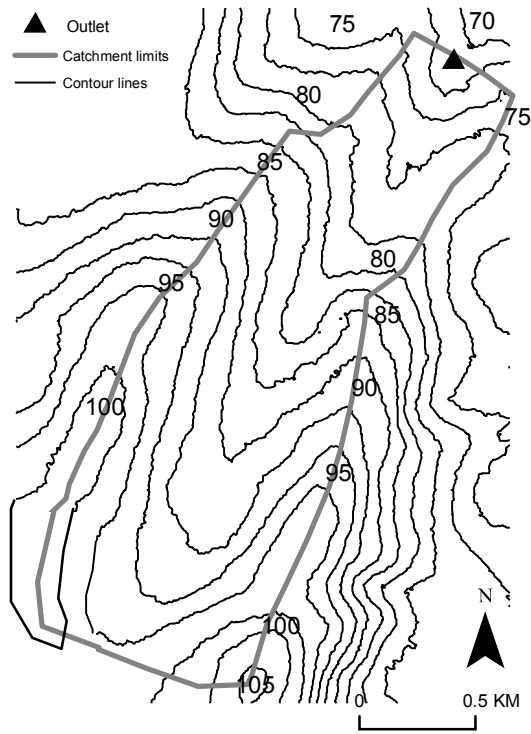
drains to the 'Ovelingen street' hamlet.

Altitude in the catchment ranges between 80 and 102 m and mean slope reaches 2.5%. Cropland and orchards are the most important types of land use. Following repeated floods, three earthen dams were installed at the outlet of the valleys in 2001. Nine to 30 m-wide grass buffer strips were also installed within the catchment, covering altogether an area of 15.9 ha (8% of total catchment surface).

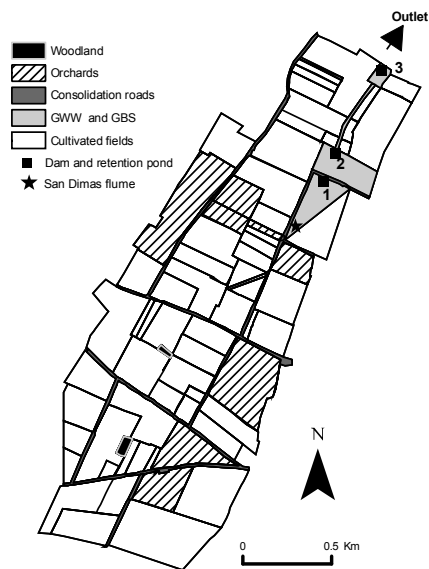
The characteristics of the main experimental sites are summarised in Table 1.1. The use of the corresponding databases throughout the thesis is also indicated.

Table 1.1: Characteristics of the main experimental sites and their use throughout the thesis.

Area (ha)	Name	Number of fields	Main types of land use	Altitude range (m) (Mean slope %)	Use in the thesis
6	Corpals	1	Cropland (100%)	139-148 (3.4)	Rainfall simulations (Chapter 3) Field monitoring (Chapter 3)
16	Walhain	5	Cropland (100%)	157-166 (1.5)	Rainfall simulations (Chapter 3) Catchment monitoring (Chapter 3)
200	Gelinden	45	Cropland (56%) Orchards (38%)	80-102 (2.5)	Catchment modelling (Chapter 7)
300	Heulen Gracht	60	Cropland (79%) Orchards (17%)	67-106 (1.3)	Rainfall simulations (Chapter 3) Catchment monitoring (Chapters 3 & 6)) Catchment modelling (Chapter 4, 5 & 7)

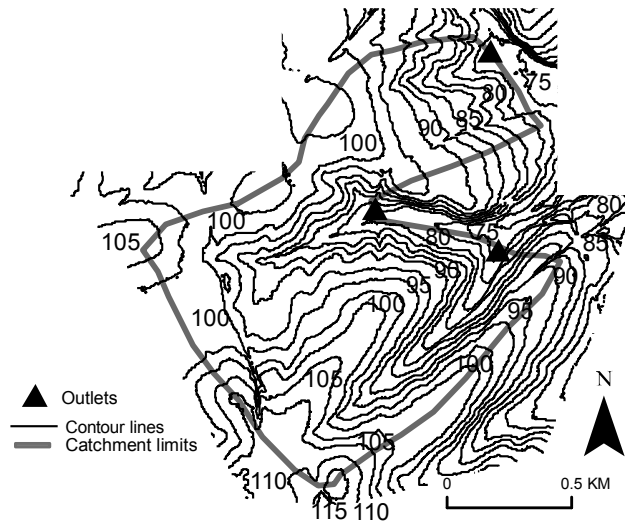


(a) Topography

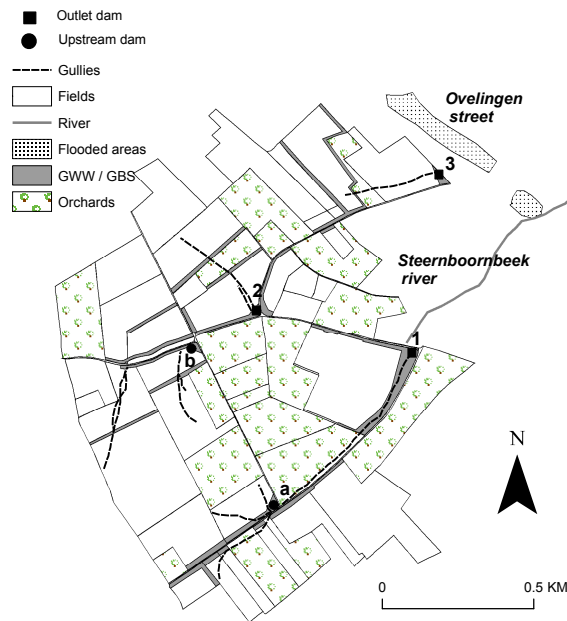


(b) Land use and flood control measures

Figure 1.3: Description of the Heulen Gracht catchment.



(a) Topography



(b) Land use and flood control measures

Figure 1.4: Description of the Gelinden catchment. Dotted lines in (b) represent gullies observed before the construction of the dams in 2001.

Chapter 2

Spatial and temporal variation of muddy floods ¹

This chapter specifically aims at characterising the spatial and temporal variation of muddy floods in the Belgian loess belt, at precisising topographic and rainfall thresholds of muddy flood triggering and at providing an estimation of the costs induced by the off-site impacts of these floods.

Outline

Seventy nine percent of the municipalities in central Belgium experienced at least one muddy flood during a 10 year-period (1991-2000 in Wallonia, 1995-2004 in Flanders). Of these flooded municipalities, 22% were affected more than 10 times. Twenty municipalities were selected for a detailed analysis. A database of 367 locations affected by muddy floods was 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 were identified: hillslopes (1 - 30 ha) without thalweg where runoff is generally dominated by sheet flow; small catchments (20 - 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

¹This chapter is based on an article by Evrard, O., Biielders, C.L., Vandaele, K., van Wesemael, B. (2007); published in *Catena* 70, 443-454.

hillslopes and in small catchments. A critical area - slope threshold for triggering muddy floods was computed, providing a physical basis for the initiation of muddy floods. 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 affect 738 sites in central Belgium leading to a total societal cost of €16-172 millions, depending on the extent and intensity of thunderstorms and monetary values damaged. Recent datasets suggest that the phenomenon has become more frequent in central Belgium since the early 1990s, 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 in the thalweg.

2.1 Introduction

Numerous villages in central Belgium are confronted with floods caused directly by runoff from agricultural land (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 hillslope 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 Belgian loess belt, the South Downs in the UK, from South Limburg in the Netherlands, from France and Slovakia (Boardman et al., 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. Varnes (1984) defines a hazard as the probability of occurrence within a specific period of time and within a given area of a potentially damaging phenomenon. On the other hand, vulnerability is a polysemous term and can basically be defined in two ways: (i) the biophysical vulnerability which expresses the level of damage incurred by a target for a given hazard, and (ii) the social vulnerability which represents the weakness of the element at stake² and its resilience capacity (Veyret, 2007). The muddy flood hazard itself depends on the occurrence of a meteorological hazard on a susceptible landscape. Major factors influencing landscape susceptibility (geomorphology, land use, cropping practices,...) as well as climatic thresholds 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 2.1) and a new overview of muddy floods throughout Europe has been provided (Boardman et al., 2006).

In the continental, western-European loess belt, landscape susceptibility is strongly related to the areal extent of cropland and cropping practices, and in particular to the presence of summer crops which make up up to 50% of the cropland area in some regions (e.g. the loess belt of central Belgium). These summer crops provide a low soil cover during the intense storms of May and June (see references in Table 2.1). Furthermore, they require a fine seedbed that hastens surface seal development and reduces surface roughness, thereby increasing runoff volume and velocity and enhancing peak discharge (Schröder and Auerswald, 2000;

²In French, this 'element at stake' is referred to using the specific term '*enjeu*'. These '*enjeux*' are the entities susceptible to be affected by a given phenomenon (Liégeois, 2005).

Table 2.1: 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)
	Farmers' leeway to reduce runoff	Joannon et al. (2005)
	Design of runoff models	Cerdan et al. (2002a); 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)
Central Belgium	Types of responses to the phenomenon	Boardman et al. (2003)
	General causes: detention ponds as a symptom	Verstraeten and Poesen (1999)
	Farmer perception of erosion: flood extent	Bielders et al. (2003)
	Ephemeral gully development	Poesen et al. (2003); Vanvalleghem et al. (2005)
Limburg, the Netherlands	Effect of farming practices on runoff	Takken et al. (2001); Gyssels et al. (2002)
	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	Auerwald (1991)
	Efficiency of grassed waterways to reduce runoff	Fieer and Auerwald (2003a)

Le Bissonnais et al., 2005). These sources of susceptibility 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 (landscape susceptibility) as well as 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) proposed 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 2.2).

Table 2.2: Rainfall conditions leading to muddy floods in the literature.

Specific information	Study area	Reference
<i>General conditions</i>		
Rainfall intensity $> 10 \text{ mm h}^{-1}$	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)
<i>Extreme events</i>		
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)
70-75 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)

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

2.2 Materials and methods

2.2.1 Study area

This study is carried out in selected municipalities and the Melsterbeek catchment, all located in the Belgian loess belt (section 1.1; Fig. 1.1).

2.2.2 Muddy flooding and flood frequency

A survey on muddy floods was previously carried out for the municipalities of Wallonia (Biielders et al., 2003) and Flanders (Verstraeten and Poesen, 1999). However, these studies can hardly be compared, due to 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 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 change was not expected to significantly affect the occurrence of floods over such a short period. Rainfall erosivity is considered to be homogeneous in the Belgian loess belt and Uccle is generally taken as the reference station (Fig. 2.1; see e.g. Laurant and Bollinne, 1976; Bollinne et al., 1979; Verstraeten et al., 2006). The annual rainfall erosivity (R-factor in the RUSLE model of Renard et al., 1997, $\text{MJ mm ha}^{-1} \text{ yr}^{-1} \text{ h}^{-1}$) can be expressed as a function of the mean annual rainfall depth (P in mm; Bollinne et al., 1979, Eq. 2.1).

$$R = 115.4 \times e^{0.00215 \times P} \quad (2.1)$$

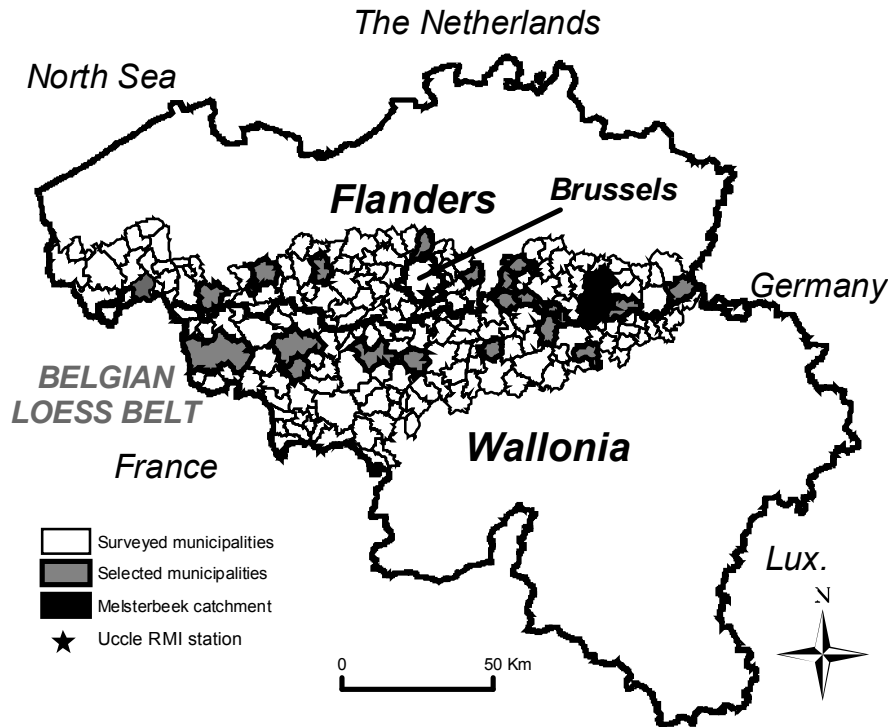


Figure 2.1: Location of the loess belt, the 20 selected municipalities (regional database), the Melsterbeek pilot catchment (Sint-Truiden database) and the Uccle RMI station (rainfall reference station) in Belgium.

Mean rainfall erosivity in Uccle, calculated according to Eq. 2.1, differed by less than 10% for both survey periods compared to the 1995-2004 period ($725 \text{ MJ mm ha}^{-1} \text{ yr}^{-1} \text{ h}^{-1}$ for 1991-2000 vs. $791 \text{ MJ mm ha}^{-1} \text{ yr}^{-1} \text{ h}^{-1}$ 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 (Statistics Belgium, 2006).

The records of the Disaster Fund (Belgian Ministry of Home Affairs) for the 1993 - 2002 period provided a second source of data on muddy floods. 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 €5,000 damage; (3) the rainfall 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 Melsterbeek catchment (Sint-Truiden database) for the 1977-2001 period (Fig. 2.1). The 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'.

2.2.3 Analysis of physical landscape susceptibility

Based on the Walloon survey (Biielders et al., 2003) and the updated Flemish survey, 20 municipalities (10 in each administrative entity, covering a total area of 870 km²) 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 ³. Note that the Sint-Truiden area has not been selected as one of the 20 municipalities comprising the regional database, because the installation of mitigation measures could introduce a bias in the location of the problem areas and the assessment of flood frequency.

The selected municipalities are fairly evenly distributed over the entire study area (Fig. 2.1). In the Walloon municipalities, locations affected by muddy floods were visited 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 locations, which will be subsequently referred to as 'regional database', was 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

³The 20 selected municipalities are in alphabetical order: Ath, Bierbeek, Boutersem, Braine-le-Comte, Braives, Chièvres, Eghezée, Grimbergen, Heers, Hélécinne, Herzele, Hoegaarden, Lincent, Nivelles, Orp-Jauche, Oudenaarde, Riemst, Tournai, Wervik, Zwevegem.

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. 2.2).

$$S_{cr} = a \times A^{-b} \quad (2.2)$$

where S_{cr} is the critical slope gradient (m m^{-1}); 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 (1) 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 (2) 50 comparable locations where no muddy flood has been reported. Critical slope gradient was then plotted versus drainage area for flooded and non flooded sites to derive the a and b parameters of Eq. 2.2.

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 2002) 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 Gorseme (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 hour. 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.

2.2.5 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 areas 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 of Eq. 2.3:

$$\text{logit}(p) = \log\left(\frac{p}{1-p}\right) = \alpha + \beta_n X_n \quad (2.3)$$

where a is the intercept; β_n are slope parameters and X_n are the three topographic variables and the daily precipitation ($n=4$).

The probability values can thus be expressed as Eq. 2.4:

$$p = \frac{\exp(\alpha + \beta_n X_n)}{1 + \exp(\alpha + \beta_n X_n)} \quad (2.4)$$

2.2.6 Cost of muddy floods

Floods lead to various types of damage ⁴ (economic, political, social, psychological, ecological, environmental; Jonkman et al., in press). In this thesis, we will restrict our cost estimation to the economic costs associated with damage to private properties and public infrastructure. Indeed, valuing the cost of the other damage types (e.g. political, psychological, environmental) requires that we place a value on public goods. This requires the use of specific economic

⁴Damage represents the physical harm caused to something which makes it less attractive, useful or valuable (Oxford English dictionary).

techniques⁵ which are beyond the scope of this thesis. Data on costs associated with damage to private property and public infrastructure were available from the Disaster Fund (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 (1) associate a rough damage cost to rainfall events of different intensities as well as to (2) 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 control measures.

2.3 Results and discussion

2.3.1 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. 2.2; Table 2.3). 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 had 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 2.3). 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 un-

⁵Typically, these techniques are based on the hypothesis that changes in the quantity or the quality of environmental resources have an economic value if they have an impact on utility, i.e. when people are willing to acquire some desirable change concerning these resources. Specific techniques (e.g. contingent valuation method, stated and revealed preference approach) are used to estimate the people's willingness to pay (Hanley et al., 2001; Schuler et al., 2006).

noticed 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 2.2.2). 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).

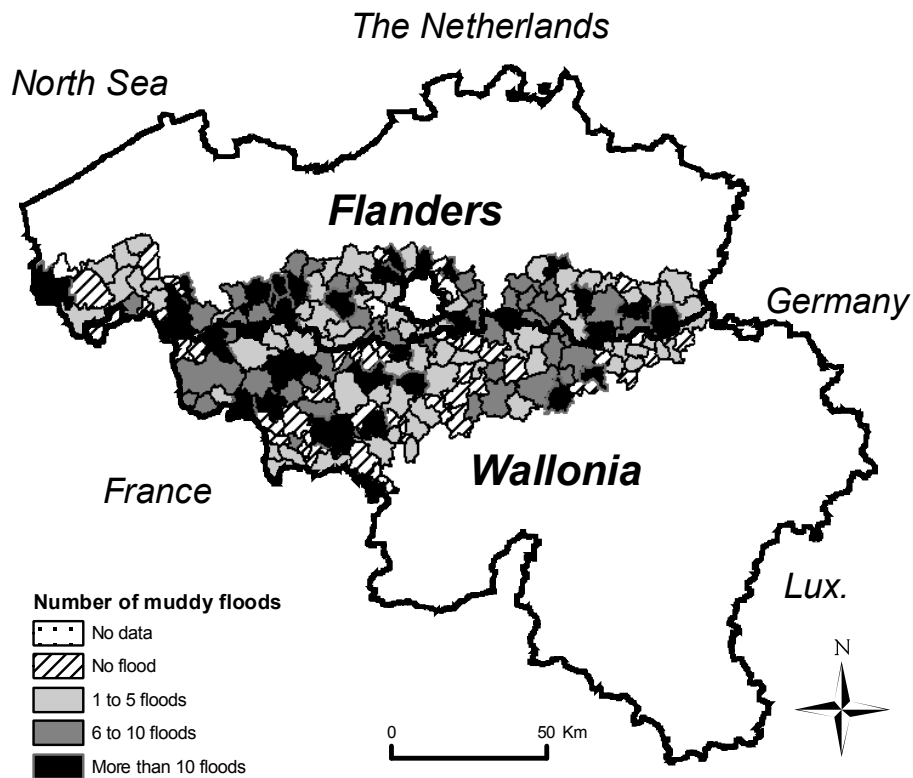


Figure 2.2: Frequency of muddy floods over a 10 year-period in all municipalities of the study area; data for Wallonia (1991-2000) taken from Bielders et al. (2003), data for Flanders (1995-2004) derived from a questionnaire sent to all municipalities in 2005.

The analysis of the Disaster Fund database indicates that muddy floods affect more municipalities than reported by the respondents of the municipality survey (Table 2.3). 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 km² 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 km², mud deposits on roads are quite widespread (42 flooded sites/100 km²). Muddy floods lead to problems to houses in 50% of the cases, representing 21 flooded sites/100 km². The sites indicated by local authorities were flooded at least once between 2000 and 2005. The annual figure would then be 8.4 floods per 100 km² 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 km²) 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 km² yr⁻¹ for the loess belt of Flanders).

The increase in muddy flood frequency is confirmed by the Sint-Truiden database (Fig. 2.3). This increase is neither due to a significant increase in rainfall erosivity (Fig. 2.4), nor to the occurrence of land consolidation in the catchment, which had already been consolidated before 1977. The most important factor

Table 2.3: 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

explaining this increase of muddy floods is the expansion of row crops, vegetables and orchards at the expense of cereals in the area (Fig. 2.5). At the

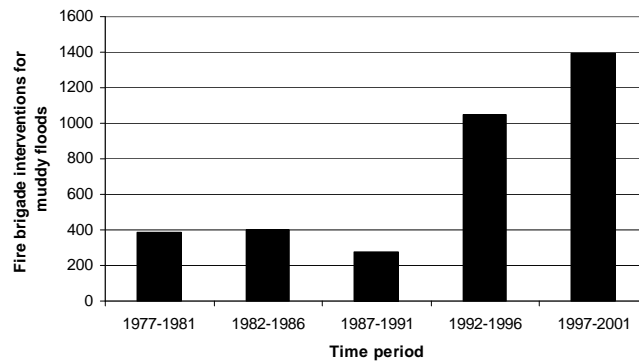


Figure 2.3: Evolution of fire brigade interventions in relation to muddy floods in Sint-Truiden district, central Belgium; period 1977-2001.

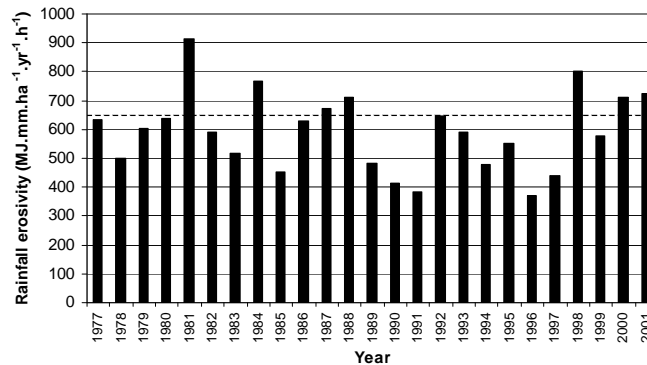


Figure 2.4: Annual rainfall erosivity in Gorseme (Sint-Truiden) for the period 1977-2001 (RMI, 2006). Dotted line represents mean annual rainfall erosivity for the period 1977-2001 ($667 \text{ MJ mm ha}^{-1} \text{ yr}^{-1} \text{ h}^{-1}$).

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 (Fig. 2.5), 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, endanger-

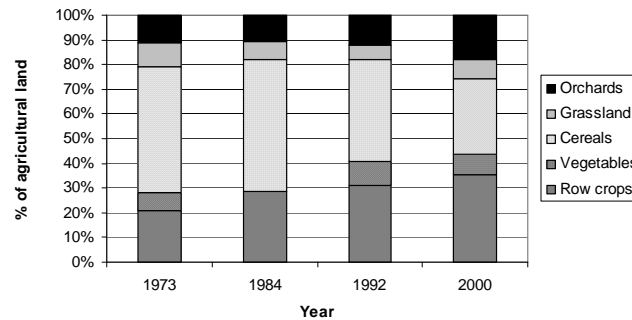


Figure 2.5: Evolution of the relative agricultural land cover in the Sint-Truiden catchment between 1973 and 2000 (Data for Gingelom; Statistics Belgium, 2006).

ing the downstream villages (Chapter 6). 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). 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.

2.3.2 Analysis of physical landscape susceptibility

We were able to assess the connectivity between cultivated land and the affected human infrastructures for the sites in the regional database (Table 2.4). In 36% of the cases, erosion features (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 the cultivated areas connected to inhabited zones (Fig. 2.6). In the cases where this connection is achieved by roads and ditches, muddy floods are always reported, stressing the important role played by roads and ditches in muddy flood triggering. Three types of drainage areas were identified in the field. 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'. About 15% of the

hillslopes where no muddy flood has been reported have similar characteristics to those where floods have been observed (Fig. 2.6). However, on average, the latter are steeper (5.7% vs. 2.5%) and larger (13 ha vs. 11 ha; Table 2.5).

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 (20 - 300 ha) than the hillslopes and are characterised by concentrated runoff in the valley bottom.

The third type of drainage area consists of medium catchments with multiple

Table 2.4: Runoff connectivity between cultivated areas and inhabited areas in central Belgium.

Connector	Number of observations
Erosion features	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

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

Table 2.5: 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 (ha)	Slope (%)	Contour length (m)
Connection achieved by erosion features				
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 between brackets for each characteristic.

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. 2.6). Muddy floods from hillslopes and small catchments (92%) are the most frequent (Table 2.5). 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 2.5). Small and medium catchments have a gentler slope (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 2.5).

A critical slope - area threshold for muddy flood triggering could be plotted (Eq. 2.5).

$$S_{cr} = 0.26 \times A^{-1.04} \quad (2.5)$$

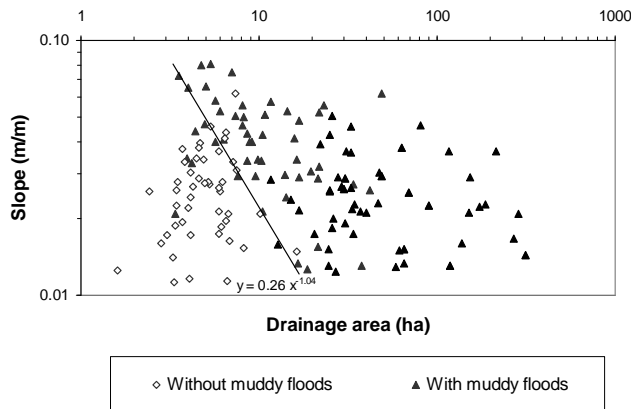


Figure 2.6: Slope gradient versus drainage area for 100 areas draining to flooded locations in central Belgium and 50 non-flooded sites. Solid line represents critical threshold conditions for muddy flood triggering (Eq. 2.5).

This threshold allows to predict the concentration of runoff leading to muddy floods. For a given slope, there is a critical drainage area necessary to produce sufficient runoff which will cause muddy floods. As slope steepens, the critical

drainage area decreases and vice-versa. The calculated threshold could for instance be used in the future to draw up a map pointing out the muddy flood hotspots in the Belgian loess belt.

2.3.3 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. 2.7). 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. 2.8). 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, infiltration capacity decreases dramatically (see e.g. Chapter 3, section 3.3.2). 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.

2.3.4 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 2.6). 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 amount. This finding means that the catch-

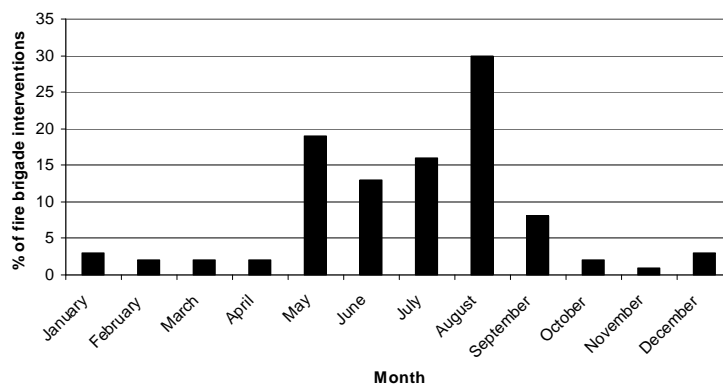


Figure 2.7: Monthly distribution of fire brigade interventions in relation to muddy flood events from the Sint-Truiden database between 1977 and 2001.

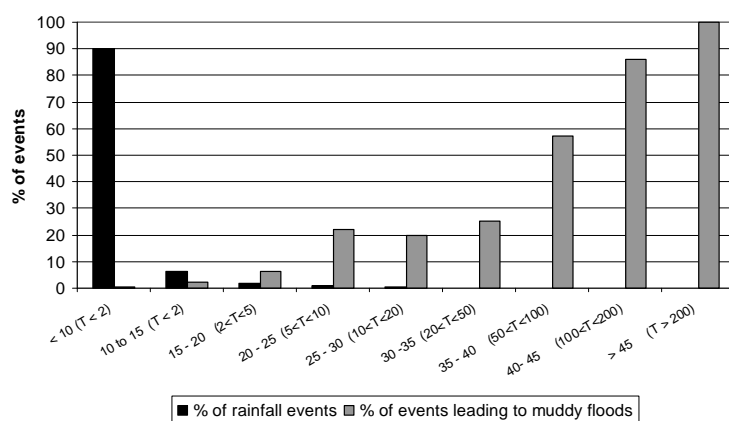


Figure 2.8: Frequency distribution of daily rainfall and percentage of rainfall events leading to muddy floods for different classes of daily rainfall from the Sint-Truiden database. Rainfall data from the Gorseme station of the RMI; muddy flood data according to fire brigade interventions. Rainfall return periods (T) in years for 24 hours-rain (after Delbeke, 2001).

ments intrinsically have the topographic characteristics allowing the triggering of a muddy flood. 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 2.6: Linear logistic regressions relating rainfall and topographic factors to the probability of occurrence of muddy floods ($n=150$): (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	$p > \chi^2$
<i>(a) Hillslopes</i>				
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
<i>(b) Small and medium catchments</i>				
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; $p=0.0011$).

2.3.5 Cost of muddy floods

After a flood, the fire brigade and municipal workers clean up public infrastructure and private property (Table 2.7). Fire brigade interventions cost between €2,250 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 millions 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 hours in some areas).

Table 2.7: 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 - 1,000
Fernelmont	August 27, 2002	Damage to bridges and roads	143,000
Flobecq	1999	Cleaning of streets	11,000
Frasnes-lez-Anvaing	June 4-5, 2002	Cleaning of streets	4,720
	September 8-10, 2005	Cleaning of roads	1,512
Herzele	1999	Repair to roads	14,000
		Cleaning and repairs	327,640
	2001	Fire brigade interventions	9,000
		Cleaning and repairs	83,475
		Fire brigade interventions	2,250
2002	Cleaning and repairs	83,475	
Riemst	July 1999	Fire brigade interventions	2,250
		Repairs to infrastructure	150,000
		Repairs to public buildings	70,000
		Mud storage	32,000
		Staff and material costs	48,000
Walhain	August 2002	Repair to infrastructure	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.)

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 $\text{€}4,436 \pm 3,406$ per house. The number of flooded sites with affected houses obtained from the analysis of the regional database (4.2 floods per $100 \text{ km}^2 \text{ yr}^{-1}$) 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 $\text{€}1.6$ and 16.5 millions yr^{-1} , respectively.

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. $\text{€}18,000$ to dredge one kilometre 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 subject 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 with muddy floods generated by rainfall events of different magnitude was assessed using the Disaster Fund database (Fig. 2.9). 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).

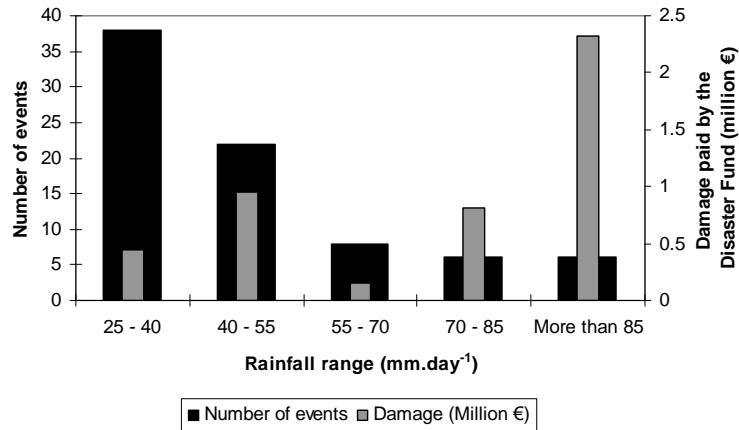


Figure 2.9: Frequency of daily rainfall and total damage paid by the Disaster Fund for muddy floods in 20 municipalities of central Belgium between 1993 and 2002; rainfall data from the RMI; damage data from the Belgian Ministry of Home Affairs, Disaster Fund.

2.3.6 Control strategies to curtail muddy floods

A potential 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). Leys et al. (2007) have shown that conservation farming practices significantly reduce soil erosion and runoff in the Belgian loess belt. Although such practices have been encouraged among farmers for several years in Flanders, very few have adopted them. 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 be installed along field borders or in small and medium catchments (Fig. 2.10).

Grass buffer strips reduce diffuse 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 down runoff and hence allow re-infiltration of diffuse runoff and sediment deposition. In Belgium,

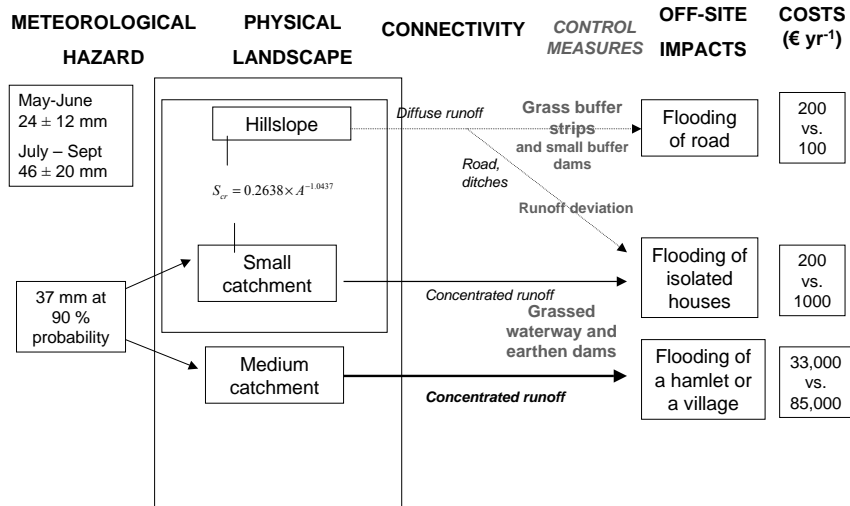


Figure 2.10: Conceptual model of muddy flood triggering mechanisms and possible control measures in central Belgium. Two situations are compared regarding costs: cleaning and damage costs induced by a muddy flood (after data collected in the visited municipalities of the Belgian loess belt) vs. cost to install control measures (after data obtained for the catchment of Sint-Truiden). We assume that a muddy floods occurs on a given site every 5 years.

grass buffer strips along field borders are subsidised. Hillslopes with topographic conditions exceeding threshold conditions mentioned in section 2.3.2 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 m²), the cost will be relatively low (€180 yr⁻¹ in Wallonia or €156-192 yr⁻¹ in Flanders) in comparison with the damage due to the flooding of a house (mean of €4,436) or the cleaning of a road (at least €500⁶). Since consolidation roads collect runoff and facilitate its transfer to villages located downstream (see section 2.3.2), ditches can help draining water from the road and redirect runoff to nearby grassed waterways or grass buffer strips. Runoff from roads should be redirected to a grass buffer strip by grids across the roads or by lowering its shoulders (Fig. 2.10).

⁶Note that in this specific case and assuming that a muddy flood occurs every 5 years, installing a GBS is more expensive than cleaning the road (Fig. 2.10)

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 gullyng, as shown by previous studies (e.g. Fiener and Auerswald, 2003a). To further buffer runoff, small-scale earthen dams can be installed across the waterway (Fiener et al., 2005). 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 Melsterbeek catchment (Fig. 1.3), a 12 ha grassed waterway as well as three earthen detention dams have been installed in 2002-2003 for a 20-year period. Total cost of the works amounts 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. €1.7 million 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.

2.4 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 (20 - 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 km² catchment suggests that the phenomenon has become more frequent in central Belgium since the beginning of the 1990s, 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 millions 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, grass 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 km²-catchment of Sint-Truiden. Their effectiveness is being monitored in order to optimise their design for future application (Chapters 6 and 7).

Chapter 3

Seasonal evolution of runoff generation on agricultural land and implications for muddy flood triggering ¹

In chapter 2, different rainfall thresholds triggering muddy floods are identified according to the season. This is mainly due to the evolution of soil surface characteristics controlling runoff generation in cropland. Chapter 3 aims then at documenting the variability of runoff potential in cropland throughout the year. The attribution of steady-state infiltration rates to orchards, grass buffer strips and grassed waterways is also investigated.

Outline

Muddy floods are triggered when high quantities of runoff are generated on cropland and cause severe erosion. Three soil surface characteristics are relevant to determine the runoff potential of cultivated soils: soil cover by crops and residues, soil surface crusting and roughness. These characteristics have been observed on 65 cultivated fields throughout 2005. A heavy rainfall event representative for events triggering muddy floods in the Belgian loess belt (60 mm h^{-1} during 30 minutes) was simulated using a 0.5 m^2 -simulator on fields with the 17 most observed combinations of soil surface characteristics in central Belgium. In the case of (ploughed) bare uncrusted soils, runoff is not observed, nor in the case of soils covered by crops, showing a transitional crust and a

¹This chapter is based on an article by Evrard, O., Vandaele, K., Bielders, C.L. and van Wesemael, B.; accepted for publication in *Earth Surface Processes & Landforms*.

moderate roughness (1-2 cm). In the cases where runoff was observed, mean runoff coefficients ranged from 13% (wheat in July) to 58% (sugar beet or maize in May and June). Grass buffer strips (GBS) and grassed waterways (GWW) show a higher runoff coefficient (62% for GBS and 73% for GWW) than most cultivated soils (13-58%). Furthermore, it is demonstrated that small plot measurements can be used to estimate runoff generation at the field scale. A classification of runoff generation risk based on the surveys of soil surface characteristics was applied to common crops of central Belgium. February as well as the period between May and September are the most critical for runoff at the field scale. However, it appears from monitoring of a 16 ha-catchment that the highest runoff volumes and peak discharges are recorded between May and August during heavy storms, explaining why 85% of muddy floods are recorded during this period in central Belgium.

3.1 Introduction

In central Belgium, numerous villages are frequently affected by muddy floods (Vandaele and Poesen, 1995; Verstraeten and Poesen, 1999; Bielders et al., 2003, Chapter 2). This situation is also reported from other countries in the European loess belt (Boardman et al., 1994), especially in northern France (Souchère et al., 2003) and in the UK (Boardman et al., 2003). In central Belgium, about 90% of muddy floods are generated on hillslopes (10-30 ha) and in small catchments (30 - 300 ha; Chapter 2). Rommens et al. (2006) calculated the Holocene alluvial sediment storage in a small river catchment (52 km²) of the Belgian loess belt. They found that sediment supply towards the flood plain has occurred at rates of 1.3 t ha⁻¹ yr⁻¹ since the Medieval period, resulting in a gradual filling up of the Pleistocene river valleys. Since 50% of the sediment that was eroded from the hillslopes during the Holocene was stored in colluvial deposits mainly located in dry zero-order valley bottoms, muddy floods represent one of the likely processes transporting sediments from the dry valleys to the flood plains. Other potential explaining processes are deforestation and intensification of agriculture, cultivation of less favourable soils on steeper slopes and Holocene climate variability (see e.g. Bork et al., 1998; Rommens et al., 2006; de Moor and Verstraeten, 2008).

Nowadays, these floods occur when large amounts of runoff are generated on crusted cultivated soils. Mean rainfall depths required to trigger muddy floods are lower in May and June (25±12 mm) than between July and September (46 ±20 mm; Chapter 2). Runoff and erosion are mainly produced in spring and early summer on fields with summer crops at an early development stage (Vandaele and Poesen, 1995). Processes such as slaking of aggregates, raindrop impact, microcracking and physico-chemical dispersion lead to the formation of a soil crust (Bresson and Boiffin, 1990). Several stages of crust development have been characterised. First, a structural crust is formed by local rearrangement of particles. Then, when particles are transported and deposited further away, a depositional crust can be observed (Valentin and Bresson, 1992). Crust development reduces the infiltration capacity as well as surface roughness. Oriented roughness describes the systematic variations in topography due to farm operations. Random roughness is related to soil clodiness and determines depressional storage (Onstad, 1984). Such soil surface features are important controlling factors for runoff. A typology of soil surface conditions of cultivated soils has been proposed in the context of the French silt loam soils (e.g. Bresson and Boiffin, 1990; Le Bissonnais et al., 2005). According to this method, surface

crust development, roughness and vegetation cover are considered the most relevant dynamic characteristics for describing and classifying cultivated soils with respect to their potential for generating runoff and erosion (Le Bissonnais et al., 2005). This typology has been developed in the framework of a runoff/erosion expert-based model (STREAM, Cerdan et al., 2002a). This model focuses on the dominant runoff/erosion processes to avoid over-parameterisation and the associated uncertainties. It is used as a decision support tool for the design of control measures against runoff and muddy floods. The main advantage of expert-based models is that they do not need as many input parameters and variables as physically-based models (e.g. LISEM, De Roo et al., 1996) which require for instance parameters for crust hydraulic properties. STREAM only needs steady infiltration rate and sediment concentration data. However, the main drawback of expert-based models is that the decision rules are only valid for the local conditions for which they have been derived. Although input parameters such as runoff coefficients fitted by trial and error yield reasonable results in hydrological models (e.g. Chapter 5), this approach can lead to an equifinality problem (i.e. obtaining the right results for the wrong reasons), and should be avoided where possible (Beven, 2001b). The measurement of the model input parameters in the field using a consistent methodology should decrease the risk of equifinality.

Several techniques exist to determine the field-saturated infiltration rate. Constant head infiltrometers have extensively been used, but the estimates are unreliable for stratified soils or when the crust is disturbed to install the infiltrometer (Léonard et al., 2006). In other studies, rainfall simulations have been carried out in the laboratory (Pan and Shangguan, 2006), or experimental plots exposed to natural rainfall have been monitored for runoff during several years (Léonard et al., 2006). However, to cover the whole range of soil surface conditions related to different types of land cover, numerous plots are needed. Furthermore, the occurrence of runoff remains highly uncertain over a period of a few years only. Consequently, rainfall simulations performed on selected surfaces representing the range of surface conditions observed throughout the year are more effective. The problem is that rainfall simulations are carried out on small plots (generally up to 1 m²) while required input (e.g. for STREAM) must characterise an entire field (typically 1 to 6 ha). Since a scale effect is likely to occur, the reliability of using micro-plot measurements to characterise a field must be investigated. For instance, Cerdan et al. (2004) calculated a significant decrease in runoff coefficient when the study area increased from 500 m²-plots to catchments (90-1100 ha).

The objective of this chapter is to characterise runoff generation on agricultural land in the Belgian loess belt, based on surveys of soil surface characteristics, rainfall simulations on microplots and field monitoring. More precisely, this chapter aims: (i) to document the temporal variation of soil surface properties of agricultural fields in the Belgian loess belt by identifying the dominant combinations of characteristics observed throughout the year, (ii) to relate these combinations of soil surface characteristics to a final runoff coefficient and (iii) to develop a simple index to assess runoff generation risk at field and catchment scales. The implications of these findings for muddy flood triggering at the catchment scale are finally discussed.

3.2 Materials and methods

3.2.1 Study area

The monitoring of soil surface characteristics and the rainfall simulations were carried out in the Corbais experimental field (6 ha), the Walhain micro-catchment (16 ha) and the Heulen Gracht catchment (300 ha) located in the Belgian loess belt (section 1.2.2.1, Fig. 1.1). These sites consist entirely of cropland, except for the largest one, which is also covered by c. 10% of orchards (Fig. 1.3). They are characterised by common crop rotations alternating winter cereals and summer crops. In addition, several grass buffer strips (GBS) and a grassed waterway (GWW) were installed in the Heulen Gracht catchment. All study sites are equipped with tipping-bucket raingauges. Calibrated sharp-crested weirs and automatic water level gauges (Easylog 3000, Microware Software, Villanova d’Asti, Italy) are installed downstream of the 6-ha experimental field and the 16-ha micro-catchment. A crest stage recorder was installed at the outlet of the Heulen Gracht catchment to measure water level when runoff occurred. Such a recorder consists of a plastic tube with a length of water-sensitive tape which changes colour on contact with water (Table 3.1).

Table 3.1: Characteristics of the rainfall-runoff events recorded in the three monitored sites.

Characteristics	Corbais (6 ha)	Walhain (16 ha)	Heulen Gracht (300 ha)
Number of events	71	83	46
Rainfall range (mm)	1 - 41	10 - 55	6 - 45
Runoff volume range (m ³)	1 - 450	1 - 970	n/a
Monitoring periods	01/2001 - 12/2002 01/2005 - 12/2006	01/2001 - 08/2002 01/2005 - 12/2006	05/2002 - 12/2006

Table 3.2: Classification of soil surface characteristics according to Le Bissonnais et al. (2005).

(a) Classes of soil surface roughness. Roughness is defined as the difference in the heights of the deepest part of microdepressions and the lowest point of their divide.

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

(b) Classes of soil surface crusting.

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

(c) Classes of crop cover.

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

3.2.2 Soil surface characterisation

According to Le Bissonnais et al. (2005), the most relevant dynamic characteristics for characterising runoff and erosion potential of cultivated fields at a given time are : (i) surface roughness (Table 3.2a); (ii) the development of soil surface crusts (Table 3.2b); (iii) the vegetation and plant residue cover (Table 3.2c) and (iv) the presence of wheel tracks. These characteristics were determined by visual observation each month throughout 2005 in all 65 fields of the three study sites. Each field was characterised by one combination of surface features. Field observations were then summarised to select the most frequent combinations on which rainfall simulations should be performed. Selected plots for rainfall simulation tests always had a slope gradient between 3 and 5%, which is common in the Belgian loess belt. Before the experiment, soil moisture varied between 15 and 20%.

3.2.3 Rainfall simulations

For each selected combination of soil surface characteristics, the rainfall simulations have been performed on three replicates using an Amsterdam-type simulator. A detailed description of this type of simulator is given by Bowyer-Bower

and Burt (1989). The dripping plate is 105×55 cm in size and the runoff area covers 0.5 m². Below the dripping plate, a randomiser is attached. It scatters, breaks up and coalesces water drops into a wider distribution of drop sizes than a spray-type simulator. A gutter is installed downstream of the simulator to collect runoff. Water-based sealants (e.g. acrylate kit, silicone) are used to obtain a good seal and prevent leakage into the soil. Before the simulation, a soil sample is taken to determine its moisture content. Simulated rainfall reaches 60 mm h⁻¹ during 30 minutes. Such a rainfall event has a 100-year return period after Delbeke (2001). According to a long-term (1977-2001) database on muddy flood occurrence in a 200 km² river basin of central Belgium (Chapter 2), 85% of muddy floods occur between May and September. They are triggered by heavy thunderstorms (e.g. 60 mm in one hour, Chapter 2). At an intensity of 60 mm h⁻¹, medium drop size equalled 5 mm and, after a fall height of 1.70 m, kinetic energy reached 13 J m⁻² mm⁻¹. Intensity is controlled using a graduated scale on the water reservoir and a chronometer. A wind shield can also be installed if necessary.

Soil infiltration capacity decreases during rainfall, due to the reduction of pressure gradients within the soil and to the degradation of the soil surface structure (Selby, 1993). The steady infiltration rate is one of the parameters required by the STREAM model. It is determined by subtracting measured runoff from the applied rainfall after runoff has reached a steady state. In the results section, mean values are given ± one standard deviation.

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

3.2.4 Comparison of measured runoff coefficients with other methods

The aim of this section is to confront the results of the rainfall simulations with the ones obtained by other studies carried out in similar loess areas of northwestern Europe (Cerdan et al., 2002a; Van Oost, 2003). For two different crops (winter wheat and sugar beet), runoff coefficients have been calculated for a 30 minutes rainfall event with an intensity of 60 mm h⁻¹. The evolution of soil surface characteristics throughout the year has been taken into account

to evaluate runoff coefficients for the two crops. Runoff coefficients at constant infiltration rates derived from the results of the rainfall simulations are compared with (i) the ones obtained using infiltration values proposed by Cerdan et al. (2002a) for the context of Normandy and with (ii) the ones calculated according to the SCS Curve Number (CN) technique (USDA-SCS, 1973) modified by Van Oost (2003). The CN technique is used to estimate runoff depth from rainfall depth (Eq. 3.1 and 3.2).

$$R_{CN} = (P - I_a)^2 / [(P - I_a) + S] \quad \text{for} \quad P > I_a \quad (3.1)$$

$$R_{CN} = 0 \quad \text{for} \quad P < I_a \quad (3.2)$$

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

The CN is related to the retention parameter S for which the empirical equation $I_a = 0.2S$ was adopted (Eq. 3.3).

$$CN = 25400 / (S + 254) \quad (3.3)$$

The modification developed by Van Oost (2003) aims to take the evolution of crop cover and crusting stage of arable land into account to compute the Curve Number (Eq. 3.4).

$$CN = CN_{SCS} - (C_c / 100 \cdot c_1) + (C_r / 4 \cdot c_2) \quad (3.4)$$

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

3.2.5 Estimation of runoff risk at field and catchment scales and implication for muddy flood triggering

Monthly evolution of mean infiltration rates measured on the 6 ha-field was calculated for winter crops (winter cereals) and summer crops (sugar beets, maize). These rates are compared to the ones based on the results of the rainfall simulations performed on 0.5 m²-plots. A classification of runoff risk at the field

scale is then applied to the common crops of central Belgium. A simple index is also developed to evaluate runoff risk at the catchment scale. Relevance of the runoff risk classification is checked, based on the monitoring of runoff in the 16- and the 300-ha catchments. The implications for muddy flood triggering at the catchment scale are finally discussed.

3.3 Results and discussion

3.3.1 Identification of dominant soil surface combinations throughout the year

Among the 60 possible combinations of crust, roughness and soil cover by crop and residues (Table 3.2), only 38 have been observed in the field and 15 represented more than 2% of the fields throughout the year (accounting for 85% of fields in total; Fig. 3.1). Technical problems have prevented to carry out rainfall simulations during winter. The lack of simulations in winter is acceptable since according to an exhaustive database of muddy floods for the 1977-2002 period in a 200 km² area of central Belgium, 90 % of floods occur between April and October (Chapter 2) and c. 70% of rainfall erosivity is concentrated between May and September (Verstraeten et al., 2006). The simulated rainfall event is highly unlikely in winter. Consequently, rainfall simulations have been performed between April and October on the fields having one of the 15 most common combinations of soil surface characteristics (Fig. 3.1).

Only bare soils (C1) and soils with a dense cover (C3) are represented among these 15 selected combinations (Fig. 3.2). This is due to the the rapid crop growth between monthly surveys. However, to take the crop cover effect fully into account, simulations have also been carried out on two soil surface state combinations with an intermediate soil cover by vegetation (C2). They correspond to growing maize and sugarbeet or cover crops in spring and autumn (C2-F11-R2 and C2-F12-R2; Table 3.3). Moreover, rainfall has also been simulated on maize lines as well as on wheel tracks. In total, simulations have hence been carried out on 19 different soil surface states.

Ploughed and bare fields are common in winter and spring (e.g. C1-F0-R4, C1-F0-R3 right after tillage; Fig. 3.2). Between April and June, soils are prepared for the sowing of maize or row and industrial crops. Ploughing and preparation of a seedbed destroy the crust and increase roughness. This leads to an evolution of the soil surface conditions from C1-F11-R3, C1-F11-R2 and C1-F12-R2 before

Table 3.3: Soil surface combinations selected for rainfall simulation, typical agricultural situations and observation of runoff during the simulations.

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

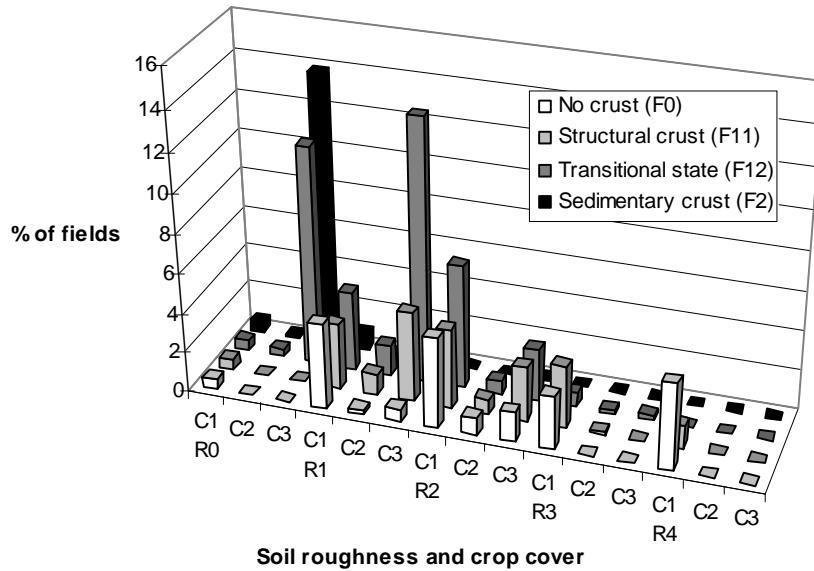


Figure 3.1: Combination of soil surface characteristics for all observed fields ($n=65$) in 2005. The classification of soil surface characteristics is given in Table 3.2.

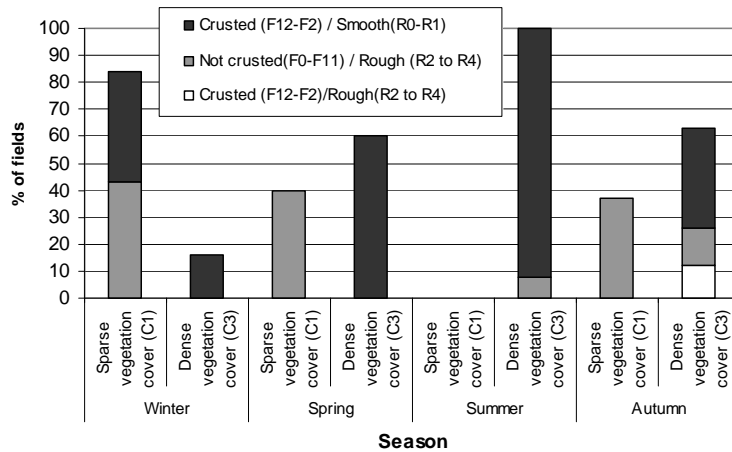


Figure 3.2: Combination of soil surface characteristics for the observed fields ($n=65$) and for each season in 2005.

sowing to C1-F0-R1 and C1-F0-R2 right after sowing. At the end of spring, two main types of fields can be observed : (i) soils with a dense crop cover in the case of winter cereals, flax or oilseed rape (C3-F12-R1, C3-F12-R0, C3-F2-R0); and (ii) soils poorly covered by growing crops, mainly sugar beets, maize, potatoes and carrots (C1-F11-R1; C1-F12-R1). In summer, most soils are densely covered

Table 3.4: Mean steady state runoff coefficient and steady infiltration rate for the cultivated soils and grassed areas. Standard deviation (SD) is indicated for each characteristic. Means within a column followed by the same letter are not significantly different at $\alpha=0.05$ level using the Tukey-Kramer's Honestly Significant Difference (HSD) test.

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

by the crops but the crust is disturbed by earthworm activity and desiccation (e.g. C3-F12-R1 for winter wheat and sugar beet). Finally, in autumn, soils are generally covered by crop residues (C3-F11-R1) or cover crops (C2-F11-R2, C2-F12-R2, C3-F12-R1, C3-F2-R2). A few bare soils have also been observed during this season (C1-F0-R1, C1-F11-R1).

3.3.2 Runoff generation on cultivated soils

Overall, the steady state infiltration rates measured for cultivated soils in this study (mean of 25-52 mm h⁻¹) are rather high compared to the ones measured in other regions (e.g. 2-50 mm h⁻¹ in Normandy; Cerdan et al., 2002a). Among the 17 selected combinations of soil surface characteristics, only 8 have produced runoff during the rainfall simulations (Table 3.3). Runoff has been observed on maize lines as well as on wheel tracks, for which steady state infiltration rates are very low (mean of 3-6 mm h⁻¹; Table 3.4). In winter and early spring, bare and rough surfaces with a fragmentary state have not produced runoff (C1-F0-R4, C1-F0-R3, C1-F0-R2, C1-F11-R3). Such ploughed fields are not crusted and infiltration rates are very high. Moreover, no runoff has been observed for surfaces with a dense crop cover that are not completely crusted (C3-F11-R1). On rough and imperfectly crusted fields with growing crops (C2-F11-R2) or fully developed crops (C3-F11-R2, C3-F12-R2), no runoff has been observed either.

A high runoff coefficient (58±8%) has been observed for sugar beets and maize (C1-F12-R1) in May and June (Table 3.4). Strongly crusted surfaces with a

dense crop cover (C3-F12-R0, C3-F2-R0) are also characterised by runoff coefficients of c. 50%. The runoff coefficient strongly decreases when the soil is less crusted or rougher ($13\pm 5\%$ for C3-F12-R1). This is typically the case of winter wheat before the harvest in July and early August. This increase of infiltration is explained by the seasonal activity of burrowing animals as well as the appearance of desiccation cracks due to shrinkage in the soil surface (Schröder and Auerwald, 2000; Lamandé et al., 2003). This crust cannot be regenerated by splash erosion during subsequent rainfall because of the dense crop cover intercepting rainfall.

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

The runoff coefficients of the cultivated surfaces have been plotted for the different classes of crop cover, surface crusting and roughness (Fig. 3.3). Runoff

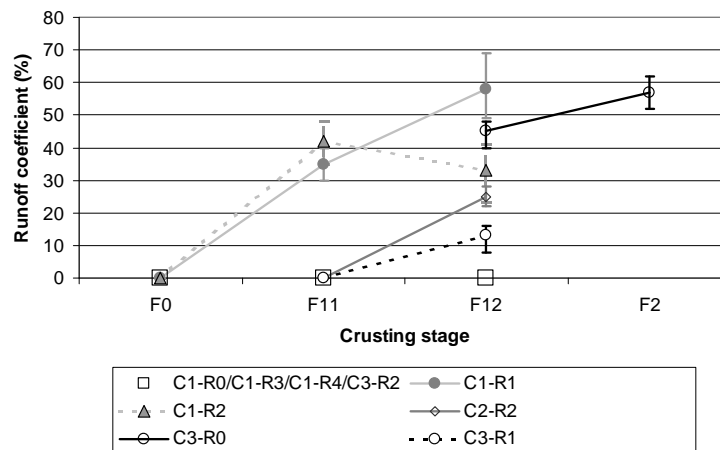


Figure 3.3: Relative importance of soil surface characteristics for runoff generation. Bars represent one standard deviation.

increases with crust development. The only exception to this rule is observed in the case of densely covered (C3) and smooth (R0) soils when the crust evolves from the transitional (F12) to the sedimentary state (F2; Fig. 3.3). This exception can be explained by the development of desiccation cracks at the soil surface and the activity of burrowing animals, which is not taken into account

by the crusting classification that we used ². No runoff has been observed for the fragmentary (F0) rough and bare soils. In contrast, the highest runoff coefficients are observed for the strongly crusted soils (F12, F2). Roughness increases the apparent infiltrability by decreasing the runoff contributive area (Léonard et al., 2006). Rougher soils produce less runoff and runoff has never been observed on very rough soils (R3-R4; Fig. 3.3). A dense vegetation cover leads to a high interception of raindrops, reducing the kinetic energy of the raindrops and hence preventing soil crusting (Morgan, 1995). In addition, the runoff coefficient of soils with scattered depositional crust and a low roughness (C1-F12-R1) is reduced by c. 60% when the crop cover increases (C3-F12-R1), mainly because of desiccation cracks and the activity of soil fauna creating pores at the soil surface.

3.3.3 Runoff generation on grassed areas

Overall, grassed areas have a higher runoff coefficient ($62\pm 5\%$ for GBS and $73\pm 3\%$ for GWW) than cultivated soils (between 13 ± 5 and $58\pm 8\%$), except for maize lines ($90\pm 3\%$) and wheel tracks ($95\pm 3\%$; Table 3.4). A possible explanation is that soils where grass has been sown are not ploughed anymore. The soil surface is hence progressively compacted. This is particularly true for GWWs with agricultural traffic. These are used by farmers as access to their fields. Bulk density was measured on the GBS and GWW where rainfall simulations had been carried out. They reach 1.50 ± 0.05 g cm⁻³ in GBS and 1.59 ± 0.06 g cm⁻³ in GWW. These values are very high in comparison with mean bulk densities measured for cropland (1.43 ± 0.1 g cm⁻³) and grassland (1.29 ± 0.05 g cm⁻³) in the Belgian loess belt (Goidts and van Wesemael, 2007). Another possible explanation for the rather low steady state infiltration value in the GWW is the deposition of the finest soil particles which fill in the pores of the soil.

GBSs and GWWs are generally known to reduce runoff, sediments and pollutants from cultivated areas (Fiener and Auerwald, 2003a; Le Bissonnais et al., 2004). Previous studies concluded that the infiltration capacity of grassed buffer strips is higher than that of arable land. Runoff reinfiltration in GBSs and GWWs is however very variable (10-91%) depending on the experimental conditions and the rainfall characteristics (Mersie et al., 2003; Le Bissonnais et al.,

²This situation corresponds to an additional crusting stage (F3) which had not been retained in the final classification proposed by Le Bissonnais et al. (2005) in order to keep it simple and widely applicable.

2004; Vianello et al., 2005). GWWs are generally wider than GBSs and are installed in thalwegs. According to research conducted between 1994 and 2001 on a 290 m-long and 37 m-wide GWW in Germany, runoff was reduced by 87% and sediment delivery by 93% (Fiener and Auerswald, 2005b). Our rainfall simulations show that the runoff coefficient of grassed areas with heavy agricultural traffic is higher than that of cultivated fields (Table 3.4). Grassed areas have hence a more important role in reducing sediment concentration than in enhancing infiltration. Furthermore, they lead to a decrease in runoff velocity because of their high hydraulic roughness (Fiener and Auerswald, 2003a; Prosser et al., 1995; Fiener and Auerswald, 2003b, 2005a). Sedimentation is thus likely to occur. The subsequent decrease of peak discharge also reduces the flood risk in the downstream villages (Chapter 5).

Runoff generation is very heterogeneous in orchards. Three soil surface states having a different behaviour can be distinguished (Fig. 3.4). Runoff is first of all generated on grassed wheel tracks (runoff coefficient of $78\pm 5\%$), given the high soil compaction. Infiltrability is higher on the grassed rows between trees (runoff coefficient of $33\pm 9\%$). In contrast, runoff has not been observed on the tilled soil under the trees and is unlikely to occur, given the high roughness and the absence of a crust.



Figure 3.4: Different soil surface conditions in orchards (A=tilled soil under the trees; B=grassed wheel tracks; C=grassed rows between trees).

3.3.4 Comparison of measured runoff coefficients with other methods

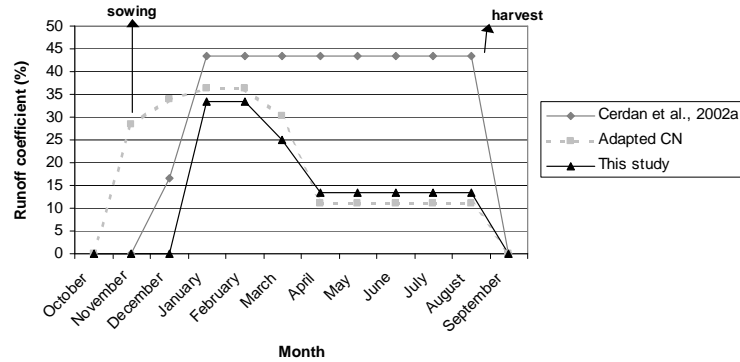
Evolution of the runoff coefficient for a 30 mm-rainfall event throughout the year has been calculated for winter wheat and sugar beet (Fig. 3.5). The runoff coefficient on a winter wheat field is at its maximum in winter (Fig. 3.5a). Runoff coefficients calculated based on the tables of Cerdan et al. (2002a) and the CN method adapted by Van Oost (2003) follow the same evolution as the ones obtained during our rainfall simulations. However, runoff coefficients obtained based on Cerdan et al. (2002a) are overestimated by 60% on average in spring and summer. This difference can be attributed to the presence of cracks at the soil surface during this period, which is not taken into account in the version of crust classification that we used (see remark in section 3.3.2). For instance, for wheat in July (C3-F12-R1), Cerdan et al. (2002a) estimated a runoff coefficient of 45%, while we obtained a value of c. 15%. This justifies the local parameterisation for central Belgium. Runoff coefficients calculated with the CN method adapted by Van Oost (2003) are very close to the ones measured during the rainfall simulations, except in autumn. This can be explained by the fact that the roughness parameter is not taken into account in Eq. 3.4. Runoff coefficient is hence incorrectly high in November and December, although the soils are quite rough (R2) and enable thereby much infiltration.

In the case of sugar beet (Fig. 3.5b), runoff coefficients obtained with the three methods are in the same order of magnitude and follow a similar evolution throughout the year. Again, the coefficients calculated from the infiltration values proposed by Cerdan et al. (2002a) overestimate runoff in summer.

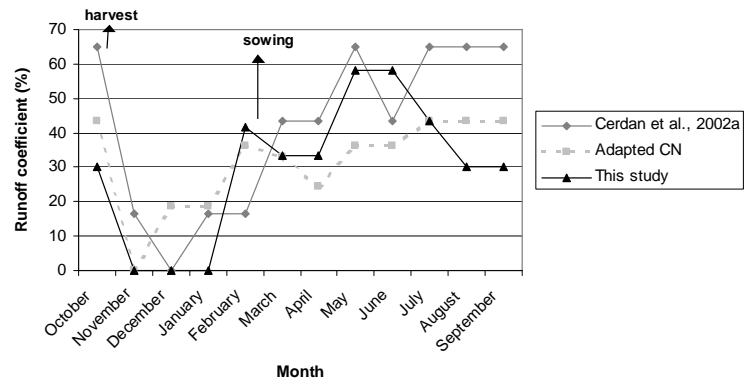
Overall, runoff coefficients measured during the rainfall simulations are consistent with the ones obtained with the two other methods. However, our results show the necessity to derive data valid for the local conditions even if similar studies are available for other regions located within the European loess belt (e.g. Le Bissonnais et al., 2005, see also section 4.4.1). The importance of soil surface roughness and cracks at the soil surface to explain runoff triggering is also demonstrated.

3.3.5 Estimation of runoff risk at the field and catchment scales and implications for muddy flood triggering

Monthly evolution of mean infiltration rates has been calculated for winter crops and summer crops, based on the 4-years monitoring of the 6 ha-field. The



(a) Winter wheat field



(b) Sugarbeet field

Figure 3.5: Evolution of runoff coefficient calculated after three methods for a 30 mm-rainfall event on fields planted with two different crops.

measurements obtained on 0.5 m² plots and the 6-ha field remain in the same order of magnitude and are very well correlated (Pearson's correlation coefficient of 0.94, Fig. 3.6). This homogeneity is explained by homogeneous soil surface characteristics and farming practices at the field scale, confirming the results obtained in a former study carried out in the European loess belt (Cerdan et al., 2004). However, on average, infiltration rates derived from the results of the rainfall simulations are 25% higher than field measurements (Fig. 3.6). This effect is explained by runoff transmission losses. With increasing plot length, runoff flow depth increases due to upslope runoff accumulation, submerging a larger area downslope (Dunne et al., 1991; Joel et al., 2002). Furthermore, there is an increasing probability of observing preferential infiltration pathways (cracks, macropores) with increasing plot size (Le Bissonnais et al., 1998).

Runoff generation risk has been evaluated for common crops in central Belgium based on the monthly surveys of soil surface characteristics (Table 3.5a). Risk

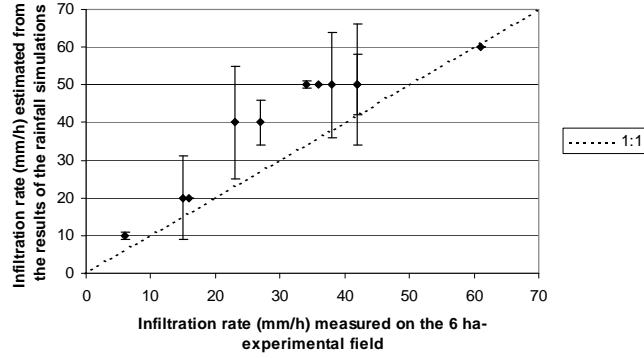


Figure 3.6: Comparison of infiltration rates obtained for monthly soil surface characteristics of fields planted with summer and winter crops based on (i) rainfall simulations and (ii) long-term monitoring of the 6 ha-field. Error bars represent one standard deviation.

classes have been defined based on infiltration rates measured at the field scale (Table 3.5b). For the combinations of soil surface characteristics containing at least one of the three parameters whereby runoff was never observed during the rainfall simulations (F0, R3, R4), an infiltration rate higher than 60 mm h^{-1} has been attributed. Crops with a high risk are mainly observed between May and September (sugarbeet, maize, potatoes). It coincides with the period when rainfall intensity is at its highest in central Belgium (Verstraeten et al., 2006). Large quantities of runoff can then be generated when a heavy rainfall event occurs. High risk is also observed on bare and crusted soils in February, but it is unlikely to observe large quantities of runoff because of low intensity rainfall.

An index of runoff risk can be calculated at the catchment scale, taking the relative surface covered by the different crops into account (Eq. 3.5).

$$I_{CATCHMENT} = 1/A \sum_i I_{RUNOFF_i} \cdot A_i \quad (3.5)$$

Where $I_{CATCHMENT}$ is the runoff risk at the catchment scale, A is the catchment area (ha), I_{RUNOFF_i} is the runoff risk of the crop i given in Table 3.5b, A_i is the area of catchment cropland surface (ha) covered by the crop i . Runoff risk classification at the catchment scale is given in Table 3.5b.

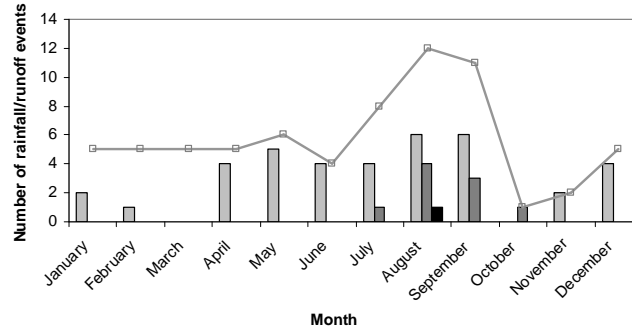
Runoff risk has been mapped for the fields of the Heulen Gracht catchment (Fig. 3.7). Mean runoff risk index for the entire catchment reached 2.7 (high risk) in May 2002, while it equalled 1.9 (medium risk) in May 2006. Furthermore, high risk fields were concentrated in the lower part of the catchment in May 2002

(Fig. 3.7a). A muddy flood affected the village after a thunderstorm on May 9. The situation observed in May 2006 is very different (Fig. 3.7b). Fields with a high risk are less numerous and evenly distributed within the catchment, and a grassed waterway has been installed in the catchment thalweg. Although the infiltration rates are low in the GWW, it has been classified as low risk zone. The GWW slows down runoff and protects the soil from erosion (Fiener and Auerswald, 2005a, Chapter 5). Even though several thunderstorms occurred with a rainfall intensity and duration similar to 2002, no muddy flood affected the village downstream.

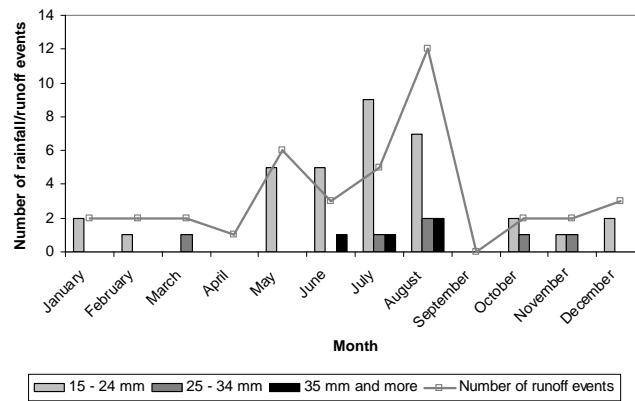


Figure 3.7: Spatial distribution of runoff generation risk in the Heulen Gracht catchment. Risk estimated according to the distribution of crops observed in the field.

Monthly distribution of heavy rainfall and runoff events has been plotted for the catchment databases (Fig. 3.8). Given these datasets cover 4 and 5 years respectively (Table 3.1), we assume that the effect of crop rotation is taken into account. It appears from Fig. 3.8 that most runoff events have been recorded between May and September (60% in Walhain and 68% in Heulen Gracht). This confirms the runoff risk classification at the field scale (Table 3.5c). The rather high number of runoff events recorded during winter in Walhain is explained by



(a) Walhain catchment

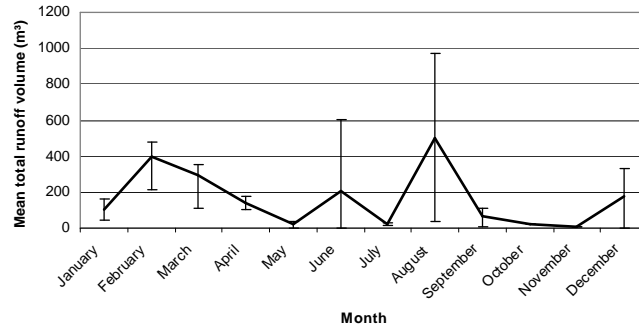


(b) Heulen Gracht catchment

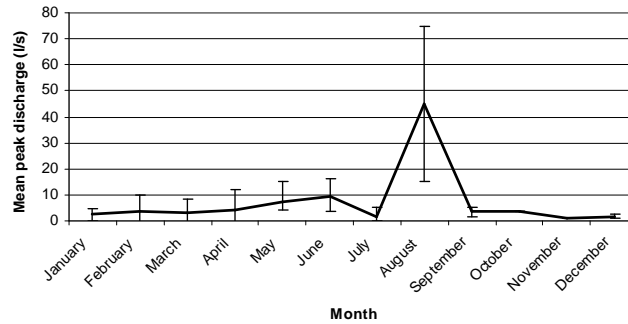
Figure 3.8: Monthly distribution of the observed rainfall events with > 15 mm of cumulative precipitation, and number of recorded runoff events in the Walhain and Heulen Gracht catchments.

very wet winter months in 2001 and 2002. This situation caused the generation of saturation overland flow. This finding is in agreement with former studies carried out in the Netherlands (Kwaad, 1991; Van Dijk and Kwaad, 1996). However, the saturation flow produced by long-duration rainfall of low intensity was distributed over entire days. Large quantities of runoff must be generated over a much shorter period to generate a muddy flood (Boardman et al., 2006). This situation occurs after local convective thunderstorms in spring and summer (Fig. 3.8). This is illustrated by the monthly distribution of mean runoff volumes and peak discharges recorded at the outlet of the 16-ha catchment (Fig. 3.9). The largest quantities of runoff and the highest peak discharges are recorded between May and August. This is consistent with the muddy flood data available for central Belgium, showing that 90% of floods are recorded between May and September (Vandaele and Poesen, 1995; Verstraeten and Poesen, 1999, Chapter

2).



(a)



(b)

Figure 3.9: Monthly distribution of (a) mean runoff volumes (m^3) and (b) mean peak discharges (l s^{-1}) measured at the outlet of the 16 ha-catchment. Error bars represent the maximal range of measurements over the 4 year period.

3.4 Conclusions

The simulation of a heavy rainfall event (60 mm h^{-1} during 30 minutes) has been carried out on 17 representative combinations of soil surface characteristics (crop cover, surface crusting and roughness) throughout the year, as well as on maize lines and on wheel tracks. Runoff has been observed in 10 cases only, rainfall infiltrating completely in the case of (ploughed) bare soils that are not yet crusted and soils with a dense crop cover, a moderate roughness and an incomplete crust. The highest runoff coefficients have been observed for wheel tracks ($95 \pm 3\%$) and fields with maize lines in May and June ($90 \pm 3\%$). In May and June, sugar beet as well as crusted soils with a dense crop cover also generate runoff (mean runoff coefficients of 57 and 58%, respectively). Overall, grassed

areas have a higher runoff coefficient (63% for GWWs and 72% for GBSs, on average) than cultivated fields (13-58% on average).

The obtained database allows parameterising erosion and runoff models (e.g. STREAM). Such an expert-based model requires a local calibration and validation. The different values obtained in this study in comparison with the ones observed in Normandy justify the local parameterisation and the use of a portable rainfall simulator in the field. Measurements obtained thanks to rainfall simulations on 0.5 m²-plots can be used to estimate runoff generation at the field scale. A runoff risk classification has been applied to common crops in central Belgium. It is shown that February as well as the period between May and September are the most critical months for runoff generation at the field scale. However, runoff monitoring at the catchment scale shows that muddy floods are most likely to occur between May and September. During this period, local convective thunderstorms producing large quantities of hortonian runoff over a short period on fields with a high runoff risk (e.g. maize, sugarbeet, potatoes) occur.

Chapter 4

Reliability of expert-based runoff and erosion models: application of STREAM to different environments

1

In this chapter, the STREAM runoff/erosion expert-based model is parameterised for the soils of the Belgian loess belt, based on the monitoring of the surface conditions and related infiltration characteristics determined by rainfall simulations (Chapter 3). The ability of this model to provide reliable runoff/erosion predictions in environments different from the one for which it was developed is then investigated.

Outline

During the last decades, the European loess belt has been confronted with a significant increase in environmental problems due to erosion on agricultural land. Spatially distributed runoff and erosion models operating at the catchment scale are therefore needed to evaluate the impact of potential mitigation measures. Expert-based models offer an alternative solution to process-based and empirical models, but their decision rules are only valid for the local conditions for which they have been derived. The STREAM model, which was developed in Normandy (France), has been applied in two Belgian catchments having similar soil texture, as well as in

¹This chapter is based on an article by Evrard, O., Cerdan, O., Chauvet, M., Le Bissonnais, Y., van Wesemael, B., Raclot, D., Vandaele, K., Andrieux, P. and Bielders, C.L.; submitted to *European Journal of Soil Science*.

a catchment of southern France differing by soil, land use and climatic characteristics. The performance of hydrological models can be assessed for instance by calculating the Nash-Sutcliffe efficiency criterion (E_{NS}). When applied to Belgium, the model results are very poor to poor without adaptation of the decision rules ($-0.55 < E_{NS} < -0.09$ for runoff; $-54 < E_{NS} < -39$ for erosion). After such adaptation, runoff ($0.90 < E_{NS} < 0.93$) and erosion ($0.85 < E_{NS} < 0.89$) predictions are much improved. Given the important environmental differences between Normandy and southern France, the model rules were adapted for application in the latter environment. However, model results were very poor ($E_{NS} = -7.89$ for runoff), because of the importance of saturation processes that STREAM does not take into account. In conclusion, STREAM is a reliable model providing satisfactory runoff and erosion predictions in the regions where hortonian overland flow dominates. Nevertheless, an adaptation of decision rules based on local multi-scale (plot, field, catchment) data is needed, before running the model.

4.1 Introduction

During the last decades, a significant increase in environmental problems such as eutrophication, pollution of water bodies and reservoir sedimentation has been observed in Europe, as a result of soil erosion on agricultural land (Boardman and Poesen, 2006). Among these off-site impacts, muddy floods affect numerous villages of the European loess belt (Boardman et al., 2006) and induce high costs (e.g. between €16 and 172 millions each year in central Belgium; Chapter 2).

Mitigation measures are being implemented in some of the most affected areas, e.g. in Normandy, France (Souchère et al., 2003), on the South Downs, UK (Boardman et al., 2003) and in central Belgium (Gyssels et al., 2006, Chapter 2). Unfortunately, monitoring of runoff and erosion is rare and is often implemented after mitigation measures have been taken. Since a long enough record of the initial situation is lacking, it is difficult to obtain quantitative data on the impact of these measures on runoff and erosion. In such a context, there is a need for reliable distributed models operating at the catchment scale and able to assess the impact of mitigation measures on runoff, erosion and sedimentation. It is especially important to obtain good runoff/erosion predictions for heavy storms, given that these storms generate the bulk sediment export from cultivated catchments (Steegen et al., 2000; Verstraeten et al., 2006). They also cause large-scale muddy floods (Chapter 3).

Different types of erosion models have been developed in the past (see e.g. Jetten and Favis-Mortlock, 2006, for a review of models). The ability of empirical models (e.g. USLE) to integrate the dominant processes at the catchment scale is uncertain (Imeson and Kirkby, 1996), whereas process-based models require numerous input data that are generally not available and difficult to measure (Takken et al., 1999). In such a context, expert-based models (e.g. STREAM, Cerdan et al., 2002a) can offer an alternative solution. They focus on the dominant processes to avoid over-parameterisation and the associated uncertainties. The model simulations rely on decision rules derived by expert judgment from databases of field measurements carried out in a specific region. Even though the framework of these models is theoretically applicable in other similar areas, their main drawback is that these decision rules are only valid for the local conditions for which they have been derived. STREAM was designed on data from Normandy (Cerdan et al., 2002a) and it was successfully used to simulate the impact of different agri-environmental scenarios on runoff in this environment (Souchère et al., 2005). Soils in Normandy contain at least 60% silt in the top-

soil and are very sensitive to soil crusting. Although similar soil characteristics can be observed in other parts of the European loess belt such as in central Belgium, the ability of the model to reliably reproduce runoff and erosion rate in these regions must be tested before it can be used to guide the implementation of flood control measures. Furthermore, this model should be applied to other contrasted environments differing by soil, land use or climate characteristics to evaluate its applicability after an adaptation of its decision rules.

The objective of this chapter is to test an expert-based model relying on decision rules (STREAM) in various environments and to determine the conditions in which it can simulate runoff and erosion intensity with sufficient accuracy to be used as a basis for the design of measures to control muddy floods. The exercise consists in modifying the model decision rules based on local databases. The model is then applied without further calibration. The model will first be applied to two catchments in central Belgium, keeping the decision rules developed for Normandy. STREAM will then be run for these catchments after an adaptation of the rules. Secondly, the model will be run for a Mediterranean catchment after a local revision of the decision rules. As a conclusion, the accuracy of the model predictions will be discussed, in function of the environment. The question of the quality of spatial predictions is also addressed.

4.2 Materials and methods

4.2.1 Description of the model

STREAM (*Sealing and Transfer by Runoff and Erosion related to Agricultural Management*) is an expert-based runoff and erosion model at the catchment scale (10-1000 ha). It is spatially-distributed, and lumped at the event-scale (Cerdan et al., 2002a). The model assumes that the following surface characteristics are the main determinants of runoff and infiltration at the field scale: soil surface crusting, roughness, crop cover and antecedent moisture content (Cerdan et al., 2002a). These characteristics are assumed to be homogeneous at the field scale and are set for each field using classification rules detailed by Le Bissonnais et al. (2005). A table is used to assign a steady-state infiltration rate value to each combination of these characteristics. A runoff/infiltration balance (B_α) is computed for each pixel α (Eq. 4.1).

$$B_\alpha = R - IR - (I_\alpha \times D) \quad (4.1)$$

Where R is the rainfall depth (mm); IR the initial abstraction (mm); I_α is the infiltration capacity (mm h^{-1}) of the pixel α and D is the rainfall duration (h). Note that negative values of B_α indicate that water infiltrates, and positive values indicate runoff.

The runoff flow network is then derived from topography (derived from the DEM), landscape features (e.g. ditches, roads) and tillage direction (Souchère et al., 1998). Flow accumulation is finally calculated for each pixel combining the runoff circulation network and B_α (Eq. 4.1). A *Visual Basic Application* (VBA) programme is run in ArcGIS to determine flow accumulation at the catchment scale (Cerdan et al., 2002a).

Interrill and concentrated erosion modules have also been integrated into STREAM. Within the interrill erosion module, a table is used to assign a potential sediment concentration value (SC) to each combination of surface characteristics (Cerdan et al., 2002c). At the catchment scale, sediment is transported in proportion of the runoff volumes computed with the STREAM runoff module (Eq. 4.2 and 4.3). Sediments are routed with the flow, and each pixel (having an area a) can correspond to an area able to infiltrate a part or the totality of the upslope runoff (Eq. 4.2) or to an area producing runoff (Eq. 4.3).

- if $(R_e - I_\alpha D) < 0$, for a pixel α with i upslope pixels then:

$$md_\alpha = \sum mu_i + \frac{(R_e - I_\alpha D)a \sum mu_i}{\sum Vu_i} \quad (4.2)$$

where R_e is the effective rainfall which equals $R - IR$ (mm); md_α is the mass of sediments leaving the pixel α (g); mu_i is the mass of sediments coming from upslope pixel I (g), Vu_i is the runoff volume from upslope pixels I (l), I_α is the infiltration capacity of the pixel α (mm h^{-1}), D is the rainfall duration (h) and a is the pixel area (m^2).

- if $(R_e - I_\alpha D) \geq 0$, for a pixel α with i upslope pixels:

$$md_\alpha = \sum mu_i + (R_e - I_\alpha D)aSC_\alpha \quad (4.3)$$

where SC_α is the potential sediment concentration (g l^{-1}) of pixel α .

For each pixel α , if:

$$\frac{md_\alpha}{(R_e - I_\alpha D)a + Vu_i} > SC_i \quad (4.4)$$

Then

$$md_{\alpha} = [(R_e - I_{\alpha}D)a + Vu_i] SC_t \quad (4.5)$$

where SC_t is the threshold value (g l^{-1}) of sediment concentration above which deposition starts (see Cerdan et al., 2002d, for details). Sediment deposition occurs when sediment load in the flow exceeds its transport capacity. The flow transport capacity in STREAM is affected by changes in topography (vertical curvature, slope gradient), or a reduction of the flow rate due to an increase in infiltration rate or to an increase in vegetation cover (Eq. 4.4 and 4.5; see Cerdan et al., 2002d, for further details).

The module calculating gully erosion within the catchments is based on slope gradient and parameters influencing runoff velocity or soil resistance (vegetation type, crop cover, soil roughness, soil surface crusting). Its description can be found in Souchère et al. (2003).

4.2.2 Study areas and sites

The region where STREAM was first developed (Upper Normandy) as well as the three study sites in central Belgium and southern France are all located in regions where intensive agriculture dominates (Fig. 4.1). A comparison of the main catchment characteristics is given in Table 4.1.

4.2.2.1 Upper Normandy, northern France

Upper Normandy has a humid temperate climate. Soils are mainly Haplic Luvisols (World Base Reference, 1998). Mean annual rainfall varies between 800 and 900 mm, with a high frequency of low to moderate intensity rainfall in winter. Mean annual temperature reaches 13°C, and annual potential evapotranspiration is 500 mm. Winter wheat (*Triticum aestivum L.*), high-protein and industrial crops have increased over the last 30 years, at the expense of grassland and secondary cereals, leading to increased environmental problems, e.g. erosion and muddy floods (Souchère et al., 2003).

Blosseville catchment

The Blosseville catchment (94.4 ha) is characterised by a smooth topography (mean slope of 4.6%), the slopes with a gradient between 5-10% covering less than 10% of the total surface. Main land uses are cropland (96%) and grassland (4%). The outlet is equipped with a calibrated flume and an automatic water

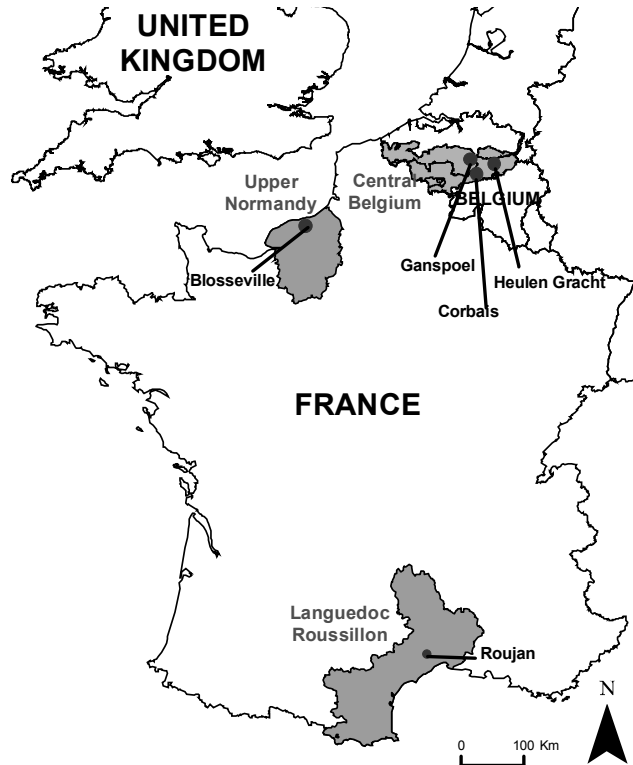


Figure 4.1: Location of the sites (Ganspoel, Heulen Gracht, Roujan) and the experimental field (Corbais) in Belgium and France. The Upper Normandy region and the Blosseville catchment where the STREAM model was initially developed are also located.

level gauge. A detailed catchment description can be found in Cerdan et al. (2002b).

4.2.2.2 Central Belgium

A description of central Belgium is given in section 1.1.

Ganspoel catchment

The Ganspoel catchment (117 ha) is characterised by a dense network of dry valleys, with slopes ranging between 0 and 20% (Van Oost et al., 2005). Crop-land is the main land use with a common rotation of winter cereals followed by sugar beets, potatoes or corn. A grassed ditch is installed in the thalweg. A San Dimas flume equipped with a flowmeter (ISCO-4220, ISCO, Lincoln, NE, USA)

and a sediment sampler (ISCO-6700) are installed at the outlet. A detailed description of the catchment can be found in Van Oost et al. (2005).

Heulen Gracht catchment

The Heulen Gracht catchment (300 ha) is described in detail in section 1.2.2.1. A San Dimas flume equipped with a flowmeter (ISCO-720) and a sediment sampler (ISCO-6700) are installed just upslope of the grassed waterway.

4.2.2.3 Languedoc-Roussillon, southern France

Languedoc-Roussillon has a sub-humid Mediterranean climate with a long dry season in summer. Annual rainfall varies between 500 and 1400 mm, with two major rainy periods, in spring and autumn (Moussa et al., 2002). Rainfall mainly occurs as storm events (Le Bissonnais et al., 2007). Heavy rainfall and soil degradation lead to a decrease of infiltration, which reduces agricultural productivity and can lead to catastrophic floods. Soils are generally classified as Luvisols, Calcisols and Cambisols (World Reference Base, 1998). Most important types of land cover in the region are vineyards, orchards and vegetables (Léonard and Andrieux, 1998).

Roujan catchment

The Roujan catchment (91 ha) is primarily agricultural and man-made, with terraced slopes and a network of ditches (11 km) collecting runoff and conducting it up to the outlet. It is divided into 160 fields and consists of four distinct geomorphologic units (Table 4.1; Léonard and Andrieux, 1998). Geological investigations have highlighted a shallow phreatic aquifer (Moussa et al., 2002). Vineyards are the most important land cover (70% of the catchment surface). The rest is occupied by fallow (16%), shrubland (6%), lucerne (*Medicago sativa* L.; 4%) and vegetables (3%). The catchment outlet is equipped with a Venturi flume (Techniflow, Echirolles, France) where runoff discharge and sediment concentration are continuously measured. More information about the catchment can be found in Léonard and Andrieux (1998).

4.2.3 Quantifying the errors on field measurements

Errors on field measurements can affect the runoff volumes and the sediment exports measured at the catchment outlet.

Table 4.1: Characteristics of the studied catchments.

Characteristic	Ganspoel	Roujan	Heulen Gracht	Blosseville ^a
Location	Central Belgium	Southern France	Central Belgium	Normandy, France
Coordinates (outlet)	50°48'N, 4°35'E	43°30'N, 3°19'E	50°46'N, 5°8'E	49°51'N, 0°46'E
Topography	Plateau and valley	Succession Plateau(1)-Terrace(2)-Glacis(3)-Depression(4)	Dry valley	Dry valley
Area (ha)	111	91	300	94
Average field size (ha)	1	0.4	4.3	5
Geology	Loess	Marl - limestone	Loess	Loess
Soil classification ^b	Haplic Luvisols	(1)Chromic Luvisols (2)Calcic Regosols (3)Calcic Cambisols (4)Gleyic Cambisols	Haplic Luvisols	Orthic Luvisols
Soil surface texture				
% silt	70 - 80	15 - 58	78 - 80	57 - 61
% clay	7 - 15	10 - 38	8 - 12	11 - 13
% sand	5 - 23	4 - 75	10 - 12	25 - 27
% organic carbon	1	1 - 2	1	1
Average precipitation(mm)	750	650	750	850
Main land use	Intensive cropping	Vine growing	Intensive cropping	Intensive cropping

^a The STREAM model was first developed in the Blosseville catchment.

^b Soil classification after World Base Reference (1998).

4.2.3.1 Runoff volume at the outlet

Runoff volumes are measured in flumes installed at the catchment outlet, using pressure sensors connected to data loggers. Runoff discharge (Q ; $\text{m}^3 \text{s}^{-1}$) is calculated at each time step from the water height (H ; m) in the flume using Eq. 4.6.

$$Q = a \times H^b \quad (4.6)$$

where a and b are constants depending on the flume characteristics.

Runoff volume (V ; m^3) can then be calculated at each time step (T ; s) using Eq. 4.7.

$$V = Q \times T = a \times H^b \times T \quad (4.7)$$

The relative error on water height (ϵ_H) is determined by Eq. 4.8.

$$\epsilon_H = \frac{\Delta H}{H} \quad (4.8)$$

The law of error propagation (also called the law of covariances) can be used to estimate the error made on runoff volume due to the imprecision on the water height measurement (Wells and Krakiwsky, 1971, Eq. 4.9).

$$\Sigma_y = J \Sigma_x J^T \quad (4.9)$$

where Σ_y and Σ_x are the variance-covariance matrices of two random vectors of the variable y and x , respectively \underline{y} and \underline{x} , with \underline{y} a non linear function of \underline{x} . J is the Jacobian matrix of $\underline{f}(\underline{x})$ (with J^T the transposed J) and is defined as Eq. 4.10:

$$J = \begin{pmatrix} \frac{\delta f_1}{\delta x_1} & \dots & \frac{\delta f_1}{\delta x_n} \\ \vdots & \dots & \vdots \\ \frac{\delta f_m}{\delta x_1} & \dots & \frac{\delta f_m}{\delta x_n} \end{pmatrix} = \frac{d\underline{y}}{d\underline{x}} \quad (4.10)$$

Applied to the runoff volume equation (Eq.4.7), where $volume$ is the one dimensional vector \underline{y} function of \underline{x} , the Jacobian matrix becomes (Eq. 4.11):

$$J = \begin{pmatrix} \frac{\delta f_1}{\delta x_1} & \dots & \frac{\delta f_1}{\delta x_n} \end{pmatrix} = \begin{pmatrix} \frac{\delta V}{\delta H} & \frac{\delta V}{\delta T} \end{pmatrix} \times (abH^{b-1}T \times aH^b) \quad (4.11)$$

The general error propagation equation (Eq. 4.9) can be re-written and solved (Eq. 4.12):

$$\begin{aligned} \Sigma_V = \sigma_V^2 &= J \Sigma_x J^T \\ &= (V)^2 \times [X] \end{aligned} \quad (4.12)$$

with

$$X = b^2 \frac{\sigma_H^2}{H^2} + \frac{\sigma_T^2}{T^2} + 2b \frac{\sigma_{HT}}{HT} \quad (4.13)$$

4.2.3.2 Sediment export

Steegeen and Govers (2001) investigated the problems related to the estimation of sediment export from cultivated catchments in central Belgium based on flow-proportional samples taken at a fixed height at the outlet. They proposed a correction procedure based on measurements carried out in a 250 ha-catchment presenting similar texture, land use and topographic characteristics as the Blossville, Ganspoel and Heulen Gracht catchments. The measured sediment export ($SE; t$) can be corrected ($SE_{corr}; t$) for each runoff event, depending on the season during which the event occurs (Eq. 4.14 for summer and 4.15 for winter):

$$SE_{corr} = 0.8594 \times SE \quad (4.14)$$

$$SE_{corr} = 0.7054 \times SE \quad (4.15)$$

4.2.4 Adaptation of the model decision rules

Table 4.2 shows the model decision rules derived from a synthesis of several datasets available for both Normandy (Cerdan et al., 2002a,c) and central Belgium (Chapter 3). Only the decision rules for runoff generation (I_α) and potential sediment concentrations (SC_α) have been adapted for central Belgium and southern France. The rules for ephemeral gully prediction described by Souchère et al. (2003) have been applied without any modification.

4.2.4.1 Central Belgium

The decision rules have been adapted for the context of central Belgium, based on two datasets:

- Steady-state infiltration rates determined by rainfall simulations performed on 0.5 m²-surfaces. They were carried out on representative soil surface conditions in order to cover the variation of the soil surface characteristics throughout the year (Chapter 3). The simulations were performed

Table 4.2: STREAM decision rules for the contexts of Normandy and central Belgium.

(a) Final infiltration capacity (mm h^{-1}) according to parameters of soil surface crust, roughness and vegetation cover. Values for the silty soils of Normandy after Cerdan et al. (2002a); the infiltration values for the silty soils of central Belgium are given in brackets (after chapter 3).

Roughness ^a	Crop cover ^b	Crusting stage ^c			
		F0	F11	F12	F2
R4	C3				
	C2				
R3	C1	50 (60)	20 (60)		
	C3				
R2	C2				
	C1	50 (60)	20 (60)	10 (50)	
	C3	50 (60)	50 (60)	20 (60)	
R1	C2	50 (60)	50 (60)	10 (50)	
	C1	50 (60)	20 (40)	10 (40)	
	C3	50 (60)	20 (60)	10 (50)	
R0	C2	50 (60)	20 (50)	10 (40)	
	C1	20 (60)	10 (40)	5 (20)	
	C3			10 (40)	5 (20)
	C2				2 (10)
	C1	10 (60)	10 (50)	5 (20)	2 (10)

^a Soil surface roughness state. See Table 3.2.

^b Crop cover classes. See Table 3.2.

^c Soil surface crusting stage. See Table 3.2.

(b) Potential sediment concentrations (g l^{-1}) in the flow, according to field data from Normandy (Cerdan et al., 2002c). Potential sediment concentrations for the silty soils of central Belgium are given in brackets.

Roughness	Crop cover	Crusting stage			
		F0	F11	F12	F2
R4	C3				
	C2				
R3	C1	12 (12)	30 (30)		
	C3				
R2	C2				
	C1	12 (12)	30 (30)	5 (5)	
	C3	7 (7)	20 (20)	12 (12)	
R1	C2	7 (7)	20 (20)	12 (12)	
	C1	12 (12)	25 (40)	10 (10)	
	C3	2 (2)	12 (12)	5 (5)	
R0	C2	2 (2)	15 (35)	5 (5)	
	C1	7 (7)	15 (35)	10 (10)	
	C3			2 (3)	2 (3)
	C2				2 (3)
	C1	10 (60)	25 (40)	10 (10)	2 (3)

on three replicates. Runoff samples were dried in an air-forced oven at 105°C during 2 days. Sediment concentration (due to interrill erosion) was determined as the ratio of dry sediment mass to runoff volume;

- 5-years observation (2001-2006) of soil surface characteristics, and measurement of rainfall and runoff from a single experimental field (6 ha) in central Belgium (Corbais). This field has similar soil characteristics (Haplic Luvisol with 78% silt, 13% clay, 9% sand and 1% of organic matter; Hang, 2002) as the Belgian study catchments (Table 4.1). In Chapter 3, we have shown that infiltration rates for both datasets remain of the same order of magnitude, given the calculated standard deviation (between 2-8 mm h⁻¹). The mean steady-state infiltration rate obtained during the rainfall simulations performed on three replicates can then be attributed to the corresponding combination of soil surface characteristics, given that only one value can be introduced into the model.

4.2.4.2 Southern France

Steady-state infiltration rates and values of potential sediment concentrations were attributed to the defined classes, based on numerous studies that were previously carried out in the Roujan catchment:

- Single ring infiltration experiments (Chahinian et al., 2006b,a);
- Rainfall simulations on 1 m²-plots (Léonard and Andrieux, 1998; Andrieux, 2006);
- Field and catchment monitoring (Louchart et al., 2001; Moussa et al., 2002).

The STREAM model could have been run for the Roujan catchment using the model decision rules derived for Normandy. However, we knew in advance that the environmental contexts of these two regions are very different and that good predictions cannot be expected in Roujan with the default rules for Normandy.

4.2.5 Evaluation of the model predictions

The model has been run for the rainfall events recorded in the three catchments (Table 4.3).

For each event, the accuracy of the simulated total runoff volume and sediment delivery has been assessed by calculating several goodness-of-fit indices.

The coefficient of simulation efficiency (E_{NS} ; Nash and Sutcliffe, 1970) is given by Eq. 4.16.

$$E_{NS} = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (4.16)$$

where n is the number of observations; y_i is the observed value; \hat{y}_i is the simulated value and \bar{y} is the mean observed value. E_{NS} values vary between minus infinity and 1, with 1 indicating a perfect fit between observed and simulated values. The coefficient of determination (R^2) indicates how well the Least Squares line fits the sample. The mean error (ME) enables to measure the estimation bias (Eq. 4.17).

$$ME = \frac{1}{n} \sum_{i=1}^n [\hat{y}_i - y_i] \quad (4.17)$$

The root mean square error (RMSE) enables to measure the accuracy of the estimation (Eq. 4.18).

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^n [\hat{y}_i - y_i]^2 \right)^{0.5} \quad (4.18)$$

Table 4.3: Characteristics of rainfall events that led to runoff in the studied catchments and used for STREAM evaluation. Data for Ganspoel from Van Oost et al. (2005). Data for Blossesville from Cerdan et al. (2002a,b).

Characteristic	Mean	Median	SD	Min.	Max.
(a) Ganspoel (n=16)					
Rainfall (mm)	14.4	9.7	13.6	2.5	60.5
60 min-intensity (mm h ⁻¹)	23.1	15.5	21.8	7	82
Duration (h)	1.3	0.7	2.2	0.1	9.2
48h-antecedent rainfall (mm)	6.7	6.2	5	0	14
(b) Heulen Gracht (n=23)					
Rainfall (mm)	15.9	12	11.2	5	50
60 min-intensity (mm h ⁻¹)	52.3	45	24.6	15	120
Duration (h)	4.7	3	5.2	3	22
48h-antecedent rainfall (mm)	10.2	7.2	10.2	0	34.2
(c) Roujan (n=20)					
Rainfall (mm)	31.7	30.1	23.6	3.7	96.1
60 min-intensity (mm h ⁻¹)	14.9	11.5	10.5	5	45
Duration (h)	3.5	2.4	4.4	0.3	18.8
48h-antecedent rainfall (mm)	6.8	1.4	10.8	0	34.5
(d) Blossesville (n=18)					
Rainfall (mm)	14.7	10.5	10.9	3.3	40.9
60 min-intensity (mm h ⁻¹)	16.4	19.2	8.6	2.4	27.6
Duration (h)	3.6	3	2.7	0.7	9.6
48h-antecedent rainfall (mm)	29.8	32.8	17.4	2.9	58.1

The average unsigned error (AUE) measures the error proportion in relation with the measured value (Eq. 4.19).

$$AUE = \frac{1}{n} \sum_{i=1}^n 100 \times \frac{\hat{y}_i - y_i}{y_i} \quad (4.19)$$

4.2.6 Evaluation of the quality of spatial predictions

Runoff concentration pathways have been mapped using a GPS in the Heulen Gracht catchment for the event of June 14, 2006 (Table 4.4c). Observed and simulated runoff patterns are compared, taking the distribution of the land cover within the catchment into account.

4.3 Results

4.3.1 Quantifying the errors on field measurements used for validation

4.3.1.1 Runoff volume at the outlet

The absolute error on water height (ΔH) is estimated at 0.01 m for all the catchments at the outlet of which similar pressure sensors connected to data loggers were installed. Constants a and b (in Eq. 4.7) depend on the flume characteristics. However, the flumes installed at the outlet of the studied catchments are very similar. We calculate the error value for the Heulen Gracht catchment ($a=2.475$, $b=1.2456$; from Eq. 4.12) and we hypothesise that this value is also valid for the other catchments (Eq. 4.20).

$$\frac{\sigma_V^2}{V^2} = \frac{0.00015}{H^2} - \frac{0.0009}{HT} \quad (4.20)$$

It appears from Eq. 4.20 that the maximum error reaches 0.8 m³ (per minute) when estimating runoff volume during the most intense event recorded in the flume (peak discharge of 1.47 m³ s⁻¹). This value consists in a volume underestimation of *ca.* 1%, which is negligible.

4.3.1.2 Sediment export

Given sediment export was measured using flow-proportional samples at the catchment outlet, we hypothesise that we overestimated the sediment export

values by *ca.* 15% in summer and *ca.* 30% in winter, using the correction factors proposed by Steegen and Govers (2001).

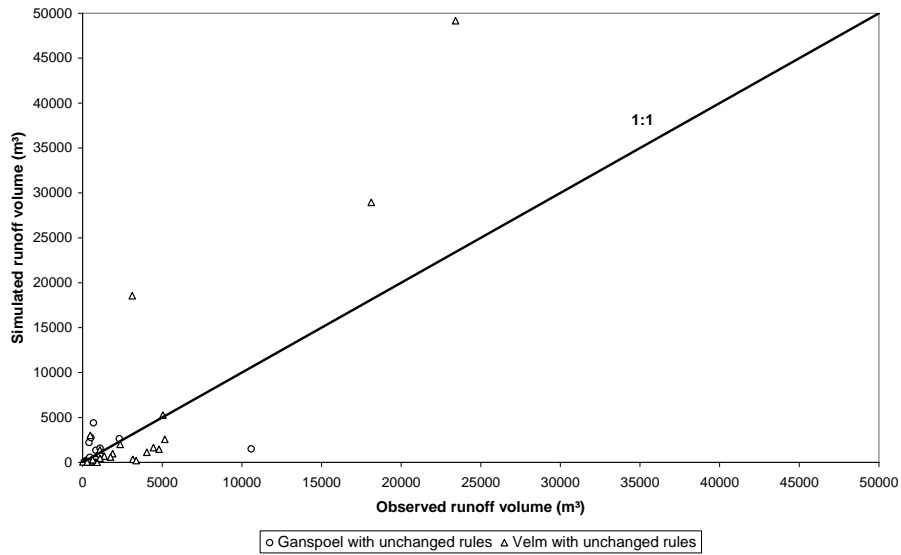
4.3.2 Central Belgium

4.3.2.1 Adaptation of the model decision rules

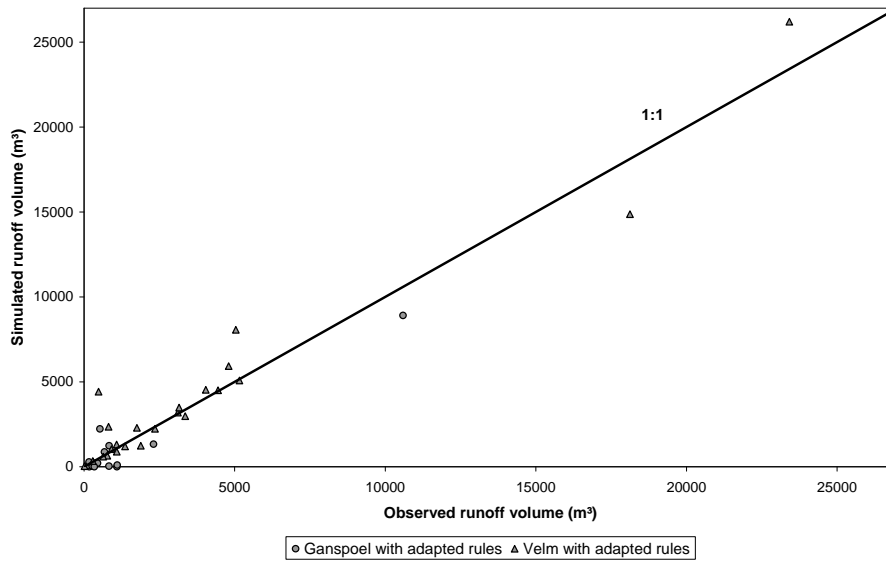
Among the 60 potential combinations of soil surface conditions, only 30 were observed in the field, and infiltration rates were therefore only defined for these 30 observed combinations (Chapter 3). The mean value obtained for the three replicates was attributed for each observed combination (Table 4.2a). Minor modifications were also made to the table of potential sediment concentrations in a similar way, based on the results of the rainfall simulations (Table 4.2b; Chapter 3). Cerdan et al. (2002b) showed that the attribution of the maximum/minimum value of such class ranges did not significantly modify the model results (up to 20% difference; which is for instance close to the uncertainty on sediment export measurements - mean of 18% according to Steegen and Govers, 2001). This potential bias is inherent to the classification approach of the expert-based model.

4.3.2.2 Model simulations

Observed and simulated runoff volumes and sediment exports together with their goodness-of-fit indices and plots of observed vs. predicted runoff volumes/sediment deliveries allow the evaluation of the model in the different catchments (Fig. 4.2, 4.3; Tables 4.4 and 4.5).

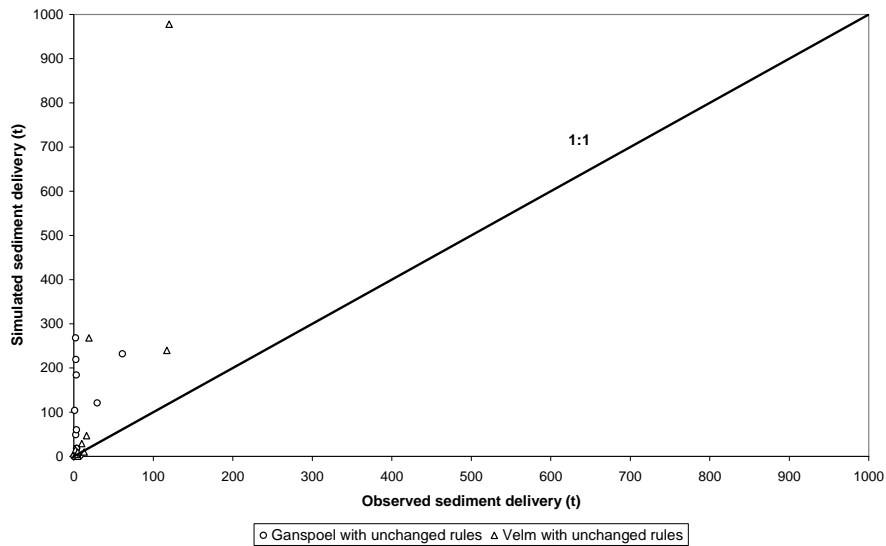


(a) Decision rules for Normandy

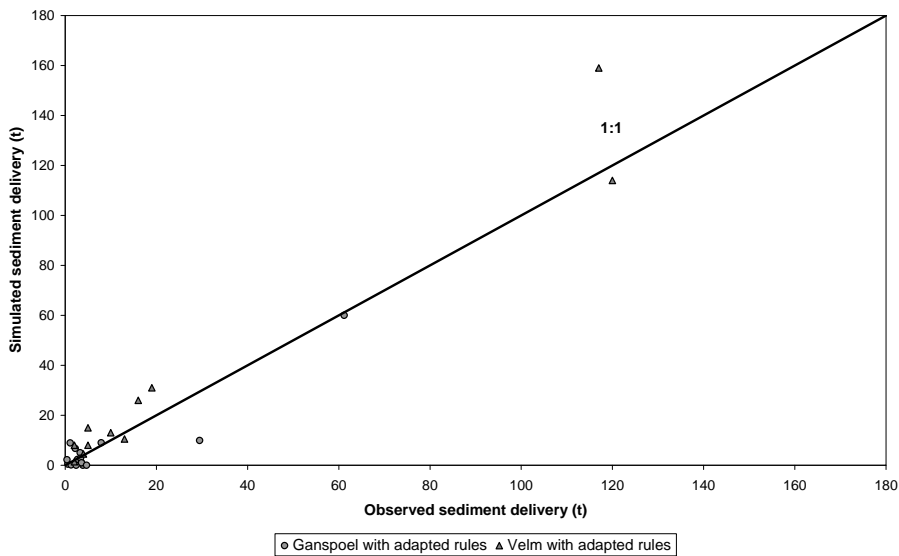


(b) Decision rules for central Belgium

Figure 4.2: Simulated vs. measured runoff volumes at the outlet of the Ganspoel catchment ($n=16$) and at the upstream end of the grassed waterway (GWW) in the Heulen Gracht catchment ($n=23$), (a) applying the decision rules developed for Normandy; (b) applying the adapted rules for central Belgium.



(a) Decision rules for Normandy



(b) Decision rules for central Belgium

Figure 4.3: Simulated vs. measured sediment exports at the outlet of the Ganspoel catchment ($n=16$) and at the upstream end of the GWW in the Velm catchment ($n=11$), (a) applying the decision rules developed for Normandy; (b) applying the adapted rules for central Belgium.

Table 4.4: Runoff coefficients, runoff volumes and sediment exports measured in the catchments (obs.) and modelled (sim.) by STREAM (1) with the default model rules for Normandy; (2) with the locally adapted rules.

Event date	Total Rainfall (mm)	Runoff coefficient (%)		Runoff volume (m ³)		Sediment (t)	
		Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
		(1)	(2)	(1)	(2)	(1)	(2)
(a) Roujain							
13/10/1995	40.3	6.4	18.3	2348	6730		
08/12/1995	21.2	7.4	0	1433	0		
05/05/1997	11.2	1.3	15.1	130	1546		
01/06/1997	37.6	3.5	0	1211	0		
05/06/1997	24.7	5.7	0	1291	0		
11/08/1997	36.9	1	10.2	326	3433		
01/09/1997	36.2	1.7	0.9	563	295		
07/10/1997	8.7	1.4	22.9	110	1546		
03/11/1997	6.7	8.2	2	4989	1247		
20/11/1997	3.7	3.2	0	110	0		
25/11/1997	8.7	12.1	0	951	0		
16/12/1997	49.5	13.2	0	5934	0		
29/04/1998	15.7	1.9	11.6	275	1663		
02/05/1998	9.3	5.5	2	468	170		
07/09/1998	35.6	5.7	2.7	1860	885		
26/04/1999	11.7	0.7	0	75	0		
03/05/1999	96.1	6.3	0	5551	0		
17/05/1999	37.5	9.3	0	3178	0		
02/08/1999	19.1	1	0	182	0		
06/08/1999	62.7	10.3	53.6	5885	30593		
(b) Ganspoel							
20/05/1997	8.5	2.6	2.5	252	233	40	7.9
22/05/1997	6.5	2.4	0	178	0	0	3.9
11/07/1997	13	15.4	18.3	2307	2637	1327	29.5
17/07/1997	21.5	1.6	9.3	404	2210	231	3.3
			1			184	5

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Event date	Total Rainfall (mm)	Runoff coefficient (%)		Runoff volume (m ³)		Sediment (t)				
		Obs.	Sim.	Obs.	Sim.	Obs.	Sim.			
		(1)	(2)	(1)	(2)	(1)	(2)			
25/12/1997	6.5	1.4	1	106	70	42	0	0.4		
05/01/1998	8	2.9	0	270	0	44	1.3	0	0.1	
28/04/1998	11	1.3	0	2.3	164	0	286	0	2.2	
26/08/1998	5.5	7.1	9.1	451	554	209	3.6	18	1	
09/09/1998	22.5	1.9	11	530	2751	2226	2.7	219	2.3	
14/09/1998	60.5	15.2	2.2	7.3	10591	4912	61.2	232	60	
14/11/1998	15.5	4.7	7.8	7.2	834	1346	1.1	104	8.9	
29/11/1998	18.5	3.2	21.4	4.2	679	4398	870	2.2	268	6.7
08/12/1998	7	13.5	11.2	0	1091	867	0	2.4	49	0
16/01/1999	16	6	8.9	0.5	1101	1576	98	3.4	60	2.8
28/01/1999	8	9	3.4	0.4	826	299	35	3.6	18	1
07/02/1999	2.5	4.7	0	0	343	0	0	4.7	0	0
(c) Heulen Gracht										
05/05/2006	10.8	0.05	0.1	0.1	17	43	34			
18/05/2006	6	0.9	0.1	1	290	32	339			
21/05/2006	18	5.8	3	3.8	1884	976	1235			
14/06/2006	24.7	9.6	57.3	9.8	3114	18553	3193	120	978	114
03/08/2006	12.9	9.7	1.1	10.8	3156	346	3486			
04/08/2006	17.6	12.5	3.5	14	4038	1120	4532			
05/08/2006	8.2	5.4	1.8	7.1	1755	600	2297			
14/08/2006	22.5	14.8	4.5	18.3	4800	1456	5925			
15/08/2006	10	10.4	0.6	9.2	3360	210	2981			
16/08/2006	10.3	15.9	7.9	15.7	5160	2559	5081			
19/08/2006	7.9	1.5	9.3	13.7	480	3011	4426			
21/08/2006	23.4	15.5	16.3	24.9	5040	5274	8061	19	268	31
07/12/2006	7	2.4	0.02	2.01	769	6	652			
08/12/2006	12	2.5	0.06	7.3	814	19	2360	5	0.01	15
12/12/2006	6.2	2.8	0.01	3.2	913	3	1041			
26/02/2007	16	4.2	2.2	3.4	1360	691	1099	13	10	10.5
28/02/2007	10	5.4	2.3	4.9	1089	467	980	4	5	7

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Event date	Total Rainfall (mm)	Runoff coefficient (%)		Runoff volume (m ³)		Sediment (t)	
		Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
07/03/2007	11	2.9	1.3	637	285	2	4
25/05/2007	14	3.8	4.6	1080	1387	2	15
11/06/2007	43	27.2	57.2	23414	49176	117	300
18/06/2007	5	23.5	20.1	2355	2006	10	29
02/08/2007	19.4	11.5	4.2	4447	1640	5	10
09/08/2007	50	18.1	28.9	18125	28955	16	47

Table 4.5: Calculation of goodness-of-fit indices for the different evaluation datasets applying (1) the default rules for Normandy; (2) the rules adapted to the local context. Values for Blosseville catchment from Cerdan (2001) for runoff and Cerdan et al. (2002d) for erosion.

(a) Runoff volumes						
Index	Ganspoel n=16		Heulen Gracht n=23		Roujan n=20	Blosseville n=17
	(1)	(2)	(1)	(2)	(1)	(1)
R^2	0.03	0.92	0.86	0.94	0.18	0.94
E_{NS}	- 0.09	0.90	- 0.55	0.93	- 7.89	0.93
ME (m^3)	-106	- 283	1336	407	575	-121
RMSE (m^3)	2573	797	6863	1446	6097	397
AUE (%)	59	- 24	11	54	173	162
(b) Sediment exports						
Index	Ganspoel n=16		Heulen Gracht n=11		Blosseville n=17	
	(1)	(2)	(1)	(2)	(1)	
R^2	0.18	0.86	0.65	0.95	0.92	
E_{NS}	- 54	0.85	- 39	0.89	- 0.31	
ME (t)	68	- 1.4	117	7	- 4.9	
RMSE (t)	110	5.8	272	14	7.9	
AUE (%)	41	144	297	63	215	

Simulated runoff volumes obtained when applying the model with the default rules for Normandy in the two Belgian catchments are rather poor ($E_{NS}=-0.09$ for Ganspoel; $E_{NS}=-0.55$ for Heulen Gracht) with either large overestimations or underestimations of runoff volumes (Fig. 4.2a). RMSE is quite large for both catchments (2573 m^3 in Ganspoel and 6863 m^3 in Heulen Gracht). Prediction of sediment export by the model is also very poor for both catchments ($E_{NS}=-39$ in Heulen Gracht; $E_{NS}=-54$ in Ganspoel). Furthermore, sediment deliveries at the Heulen Gracht catchment outlet are largely overestimated (AUE=297%). In Ganspoel, sediment exports are either largely overestimated or underestimated (AUE=41%; Fig. 4.3a).

When the model is run with the rules adapted for the Belgian context, the results regarding runoff clearly improve, in both Heulen Gracht ($E_{NS}=0.93$) and Ganspoel ($E_{NS}=0.90$; Fig. 4.2b). Overall, the quality of the model predictions regarding runoff obtained after recalibration in central Belgium remains of the same order of magnitude as in Normandy ($E_{NS}=0.94$; Table 4.5). Sediment export is even better predicted in Belgium than in Normandy (Fig. 4.3b; $E_{NS}=0.89$ for Heulen Gracht; $E_{NS}=0.85$ for Ganspoel vs. $E_{NS}=-0.31$ in Normandy).

4.3.3 Southern France

4.3.3.1 Adaptation of the model decision rules

The variation in surface roughness is lower for vineyards and therefore this parameter is not strictly required to explain runoff generation and potential sediment concentration for fields located in Mediterranean areas where vineyards largely dominate the landscape. In Roujan, two types of agricultural practices are carried out in vineyards: (i) no tillage, with chemical weeding of the whole field or (ii) superficial tillage of the interrow and chemical weeding of the row (Léonard and Andrieux, 1998). In the first case, surface roughness remains constant throughout the year. In the second case, surface roughness is low after tillage and decreases afterwards along with the degradation of the soil surface. Steady-state infiltration rates in vineyards were determined by Chahinian et al. (2006a). These rates were used to attribute an infiltration value to vineyards for different crusting stages. Roughness is hence taken into account in an indirect way through the soil crusting parameter. Consequently, only the vegetation cover and the soil surface crusting parameters are taken into account to adapt the model decision rules for southern France (Table 4.6).

Table 4.6: STREAM decision rules adapted to the context of southern France.

(a) Final infiltration values (mm h^{-1}) according to parameters of soil surface crust and vegetation cover for the Roujan catchment.			(b) Potential sediment concentrations (g l^{-1}) in the flow, according to field data from Roujan catchment.				
Crop cover ^a	Crusting stage ^b			Crop cover	Crusting stage		
	F0	F11	F2		F0	F11	F2
C3		25	15	C3		3	5
C2		20	10	C2		5	7
C1	35	18	5	C1	10	5	10

^a Crop cover classes, see Table 3.2.

^b Soil surface crusting stage, see Table 3.2.

4.3.3.2 Model simulations

Runoff volumes are poorly predicted ($E_{NS}=-7.89$) after the local calibration (Table 4.5, Fig. 4.4). Overall, the average accuracy on prediction is rather low (RMSE=6097 m^3) and runoff is overestimated (AUE=173%). Sediment production was not simulated, given the bad quality of runoff predictions.

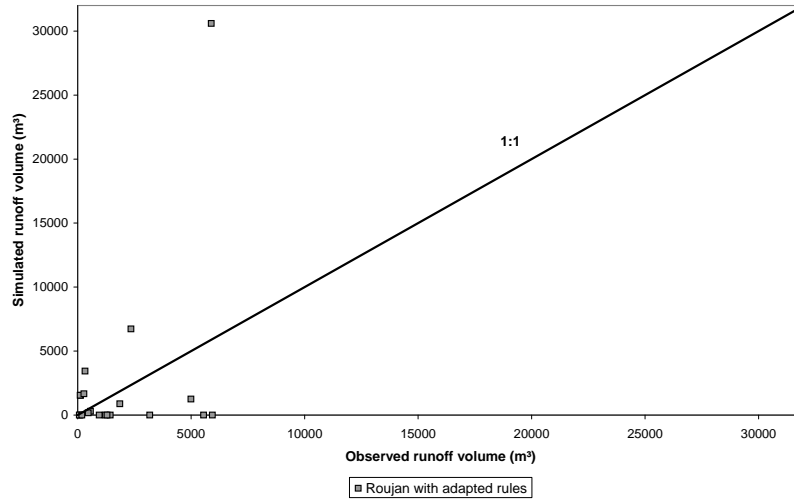


Figure 4.4: Simulated vs. measured runoff volumes at the outlet of the Roujan catchment ($n=20$) applying the decision rules adapted for southern France.

4.3.4 Quality of spatial predictions

During the event of June 14, 2006 in Heulen Gracht catchment, runoff was generated on fields planted with summer crops (sugarbeets, peas *Pisum sativum* L., potatoes and carrots *Daucus carota* L.; Fig. 4.5). The model predicts it very well. In contrast, no runoff was observed on surfaces densely covered by flax and winter cereals, which is also well reproduced by the model (Fig. 4.5). Furthermore, the model simulates a low runoff generation in orchards, which is corroborated by field observations. The final infiltration value attributed to orchards is hence appropriate (20 mm h^{-1}). The selection of a mean infiltration rate for orchards proved to be difficult, since rainfall simulations have shown that runoff generation is very heterogeneous in orchards, being nil on the tilled soil under the trees but very high on wheel tracks (Chapter 3). Once runoff is produced, it concentrates on the consolidation road located in the thalweg, up to the grassed waterway. Concentrated runoff pathways have been mapped in the grass buffer strip after the event and they are correctly predicted by the model (Fig. 4.5). The introduction of the tillage direction and landscape features (e.g. ditches, backfurrows, roads) in the model clearly improves its spatial predictions.

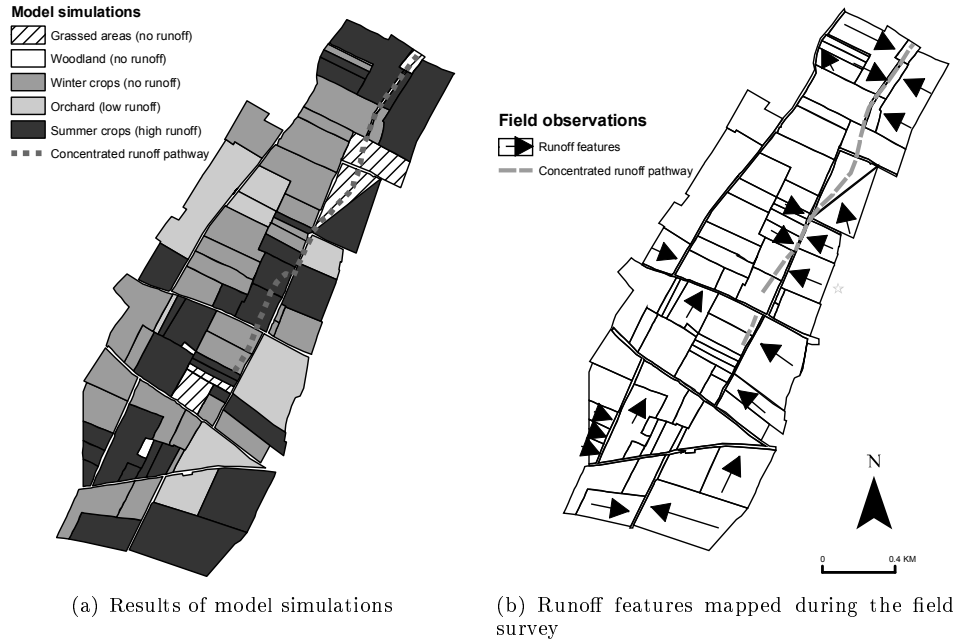


Figure 4.5: Model spatial predictions for the event of June 14, 2006 in Heulen Gracht catchment.

4.4 Discussion

4.4.1 Application of STREAM to other catchments of the loess belt

Even though the processes governing the temporal dynamics of soil hydraulic properties are rather complex as demonstrated by several laboratory experiments (see e.g. Fohrer et al., 1999), the cultivated soils in the European loess belt can be characterised by a decrease in infiltration rate following tillage and sowing, which is mainly driven by surface crusting. However, the range of final infiltration rates is consistently higher in Belgium compared to Normandy (Table 4.2a). For instance, lowest infiltration rates reach 2 mm h^{-1} in Normandy vs. 10 mm h^{-1} in Belgium, although there is no significant difference in soil texture between the two regions (Table 4.1). However, very slight differences in soil texture, such as the slightly coarser sand and loam in Belgium, could partly explain the different infiltration rates (Le Bissonnais, 1996; Legout et al., 2005). Different local climatic conditions and their interaction with the crop types and the farming practices can also explain the observed differences. In Normandy, an important area is planted with cereals, peas and flax in Octo-

ber and November (Joannon et al., 2006). Peas and flax require a very fine loosened seedbed, with highly fragmented clods. Such a surface is prone to crusting due to the degrading action of cumulative rainfall. Since 63% of annual precipitation in Upper Normandy falls between October and March, this leads to the progressive formation of a continuous soil surface crust (Fig. 4.6). Therefore, the lowest infiltration rate (2 mm h^{-1}) is observed in winter on such crusted fields in very humid conditions. In contrast, 64% of the annual precipitation in central Belgium is observed in spring and in summer (Fig. 4.6) and the lowest infiltration rates (10 mm h^{-1}) are observed on fields planted with summer crops in June (Chapter 3). During this period, the soil surface crust can also be locally disturbed by earthworm activity, which increases the soil infiltrability (Schröder and Auerswald, 2000; Lamandé et al., 2003). Moreover, large amounts of rainwater are absorbed by desiccation cracks during the early stages of rainstorms in summer (Schröder and Auerswald, 2000; Römkens and Prasad, 2006). In contrast, only minor differences are observed with respect to values of potential sediment concentration in the flow, except for uncrusted soils with a low roughness and sparsely covered by vegetation (Table 4.2b). These combinations of soil surface characteristics are observed during periods of low intensity rainfall (in winter and early in spring, typically). The differences in potential sediment concentrations can then be explained by the different mode of data acquisition. The French values were derived from field monitoring (Cerdan et al., 2002c) whereas the Belgian values were obtained by the simulation of an intense storm. However, given sediment is transported proportionally to the runoff volume and given low runoff volumes are generated in winter and early spring, these differences are compensated for by the model.

It must be stressed that the calibration for Belgium is based on independent measurements (Chapter 3). The adaptation of the rules was achieved by introducing in the model final infiltration rates and potential sediment concentrations measured in the field. Consequently, the equifinality problem is avoided given we do not adapt the model parameters by trial-and-error until we obtain satisfactory results (Beven, 2001a; Favis-Mortlock et al., 2001). Results obtained with the model are satisfactory to good in central Belgium after a local adaptation of the rules ($0.90 < E_{NS} < 0.93$ for runoff; $0.85 < E_{NS} < 0.89$ for erosion). The model performance in central Belgium and in the area for which it was developed (Cerdan, 2001) are comparable for runoff (Table 4.5). Erosion is globally overestimated by the model in central Belgium ($63\% < \text{AUE} < 142\%$) but these results remain better than those generally obtained with other models (AUE between 600 and 1400%; Favis-Mortlock, 1998).

The model is much more efficient to predict runoff during summer intense rainfall ($E_{NS} = 0.93$ for events between April-September in Velm and Ganspoel) than during low intensity events in winter ($E_{NS} = -2.57$ for events between October-March in Velm and Ganspoel; Fig. 4.7). This finding is in agreement with other studies showing the difficulty to predict runoff during low intensity rainfall because of its higher spatial variability (e.g. Gómez et al., 2001). This difference in model performance due to rainfall intensity can also explain the slightly better quality of runoff predictions in Velm (mean rainfall intensity of 52.3 mm h^{-1} ; $E_{NS}=0.93$) compared to Ganspoel (mean rainfall intensity of 23.1 mm h^{-1} ; $E_{NS}=0.90$). It is also known that saturation overland flow can be generated during winter wet periods in the European loess belt (e.g. Kwaad, 1991; Van Dijk et al., 1996b, Chapter 3). STREAM was not designed to simulate this type of runoff processes. Obtaining good runoff/erosion predictions during low intensity rainfall is beyond the scope of STREAM, since it has been designed to test different scenarios (e.g. crop changes, installation of erosion control measures) for which heavy thunderstorms are generally simulated (e.g. Souchère et al., 2005).

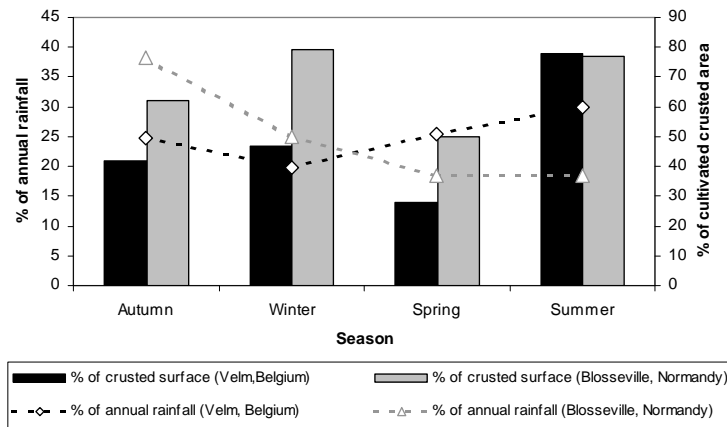
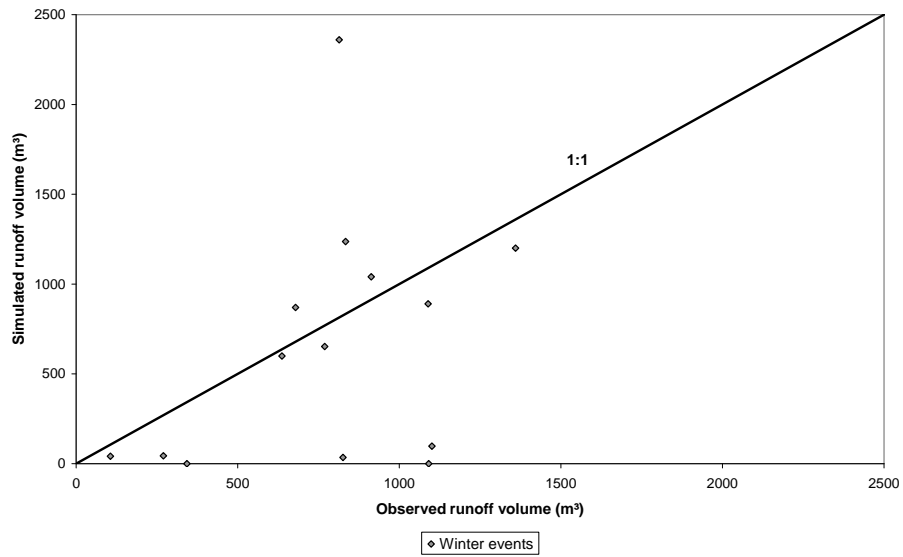
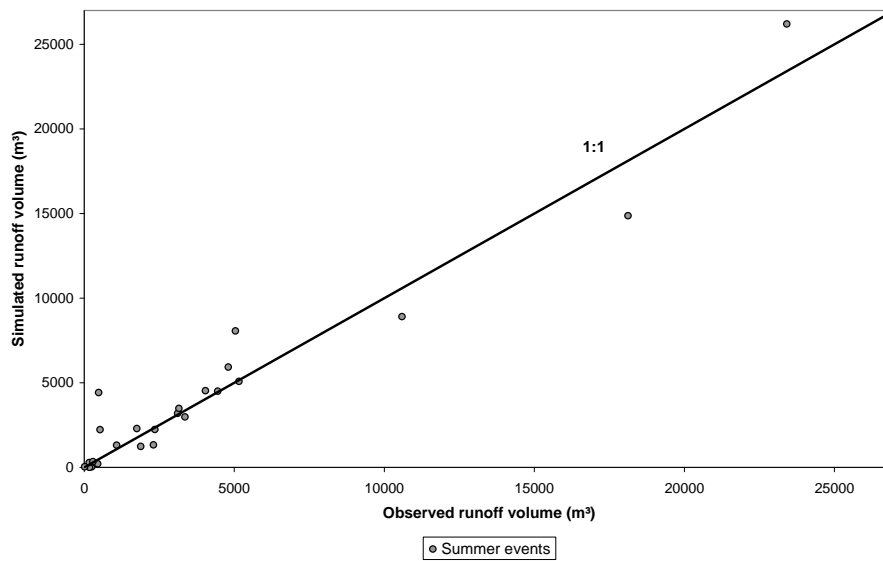


Figure 4.6: Mean seasonal rainfall distribution in central Belgium and Upper Normandy and percentage of crusted cultivated area (F12 and F2 crust stages). Belgian rainfall data from the Gorsem station of the Royal Meteorological Institute, which is the closest (5 km) to the Heulen Gracht (Velm) catchment. French rainfall data from the Saint-Valéry-en-Caux station, located at 5 km from Blosseville catchment. Soil crusting data available from field surveys carried out (i) on the 55 fields of Heulen Gracht catchment during the period 2003-2006 for central Belgium and (ii) on 600 fields of Upper Normandy during the period 1992-1998 (Le Bissonnais et al., 2005).



(a) Winter events



(b) Summer events

Figure 4.7: Simulated vs. measured runoff volumes at the outlet of the Ganspoel catchment ($n=16$) and at the upstream end of the GWW in the Velm catchment ($n=23$), (a) for winter events (between October-March; $n=14$); (b) for summer events (between April-September; $n=25$).

4.4.2 Application of STREAM to a Mediterranean catchment

When applied to Roujan, the model is used in a very different climatic context than the one it was initially designed for. There is a larger variation in soil type within this Mediterranean catchment than in the European loess belt (Table 4.1), and the land use is dominated by vineyards. The hydrological processes involved are different. In the Roujan catchment, the groundwater level fluctuates between 1 and 5 m depth on the plateau, and hence temporary springs occur on the slopes to the valley bottom (Louchart et al., 2001). Model predictions for runoff are very poor in Roujan. STREAM predicts either no runoff when a small runoff volume is observed at the outlet, or overestimates it when heavy rainfall is simulated. Runoff underestimation can be due to the fact that the ground water reaches the surface during some events (Moussa et al., 2002). This process generally occurs in winter, after long rain periods. In such saturated conditions, the water table feeds a base flow in the grassed ditches, which can explain the runoff underestimation by the model. In contrast, the ditches facilitate runoff re-infiltration during drier periods after heavy rainfall. This phenomenon can explain runoff overestimation by STREAM for such events.

4.4.3 Reliability of STREAM predictions and guidelines for further application

STREAM only provides satisfactory to good runoff/erosion predictions for events dominated by processes of hortonian overland flow. In contrast, the model poorly predicts runoff/erosion in areas or during events dominated by saturation flow processes. The quality of the model runoff predictions ($397 \text{ m}^3 < \text{RMSE} < 1446 \text{ m}^3$) is satisfactory to simulate summer events (generating up to c. $25,000 \text{ m}^3$ in a 300 ha-catchment for a 150 yr-event in June; Table 4.4). Errors regarding sediment exports ($5.8 \text{ t} < \text{RMSE} < 14\text{t}$) are also acceptable given they correspond up to ca. 15% of total erosion measured during the most intense events.

There was no previous consultation between the French modellers and the Belgian users to adapt the model to the context of central Belgium. In the modellers' mind, the Belgian catchments were *a priori* located in the area where the decision rules developed for Normandy could be applied without any modification. However, the differences outlined in this chapter show that a direct application of the French rules to other catchments in the European loess belt is

not possible. A survey of soil surface characteristics similar to the one proposed by Le Bissonnais et al. (2005) must first be carried out. The observed combinations of soil surface characteristics must then be associated with steady-state infiltration rates, e.g. by the way of rainfall simulations. A classification of the monthly runoff/erosion risk associated with the common crops planted in the study area can then be carried out (see e.g. Chapter 3 for central Belgium) to avoid further field surveys and allow a widespread use of the model in a given area (e.g. to design flood control measures).

4.5 Conclusions

STREAM provides satisfactory to good runoff/erosion predictions in environments or during events dominated by processes of hortonian overland flow. As shown in this study, expert-based models can perform satisfactorily if (i) a good concept lies behind the model rules (i.e. decrease in infiltration rate of cultivated soils after sowing/tillage, mainly driven by surface crusting processes) and (ii) if the rules are adapted to the local context (e.g. by assigning a measured final infiltration rate to the classes). Indeed, even though Normandy and central Belgium, both located in the European loess belt, are characterised by similar soil textures, differences in the range of final infiltration rates are observed between both regions. These differences mainly arise from a different distribution of rainfall throughout the year and its interaction with the crop type and the farming practices. The model decision rules need to be adapted to the regional context, by combining plot, field and catchment measurements.

Chapter 5

Effectiveness of a grassed waterway to control muddy floods: Case-study ¹

This chapter constitutes a modelling case-study. A worst-case scenario is simulated with a hydrological model to quantify the impact of seasonal land cover, land consolidation and flood control measures on runoff from a cultivated dry valley of the Belgian loess belt. The evaluation of the effectiveness of a grassed waterway in the thalweg and an earthen dam at the outlet to control muddy floods is emphasised.

Outline

During the previous decade, 79 per cent of the municipalities in the Belgian loess belt were confronted with muddy floods from agricultural catchments after intense rainfall. A typical problem area is the village of Velm where a permanent river is constrained by a culvert designed to accommodate its peak discharge. However, the design of the culvert does not take the additional runoff from seven dry valleys just upstream into account. This case-study focuses on runoff from one of these agricultural catchments (c. 300 ha). The *Meshed Hydrological Model* (MHM) is used to evaluate the effectiveness of mitigation measures to reduce flooding. Seasonal variation of soil cover in cropland and difference in land use patterns i.e. before and after land consolidation is explicitly taken into account. The land cover spatial pattern was mapped at regular intervals dur-

¹This chapter is based on an article by Evrard, O., Persoons, E., Vandaele, K., van Wesemael, B. (2007); published in *Agriculture Ecosystems & Environment* 118, 149-158.

ing 2003. One of the largest potentials of runoff generation occurs in winter, and therefore represents a worst-case scenario. Mitigation measures implemented after the extreme event of August 2002 (i.e. a 12 ha grassed waterway and a detention dam in the thalweg) alleviate the flooding risk in Velm. The model simulates a peak discharge reduction of *ca.* 50%. The detention pond would buffer the generated runoff volume entirely for the worst-case scenario. Land consolidation carried out in the 1970s led to an increase in peak discharge by 33 per cent and in runoff volume by 19 per cent. The major role played by a new consolidation road built in the thalweg on runoff concentration is highlighted. Implementation of additional soil conservation measures is therefore needed to limit runoff generation within the catchment.

5.1 Introduction

Numerous villages of the Belgian loess belt are confronted with muddy floods from small and medium agricultural catchments (c. 10-300 ha; Chapter 2). These floods occur after intense rainfall, mainly at the end of spring or early in the summer, and cause important damage to infrastructure and housing property in the villages located downstream (Verstraeten and Poesen, 1999; Verstraeten et al., 2003). Previous studies focused on erosion phenomena at the small catchment scale (Vandaele and Poesen, 1995; Beuselinck et al., 2000; Chaplot and Le Bissonnais, 2000; Steegen et al., 2000; Cerdan et al., 2002b), but very few investigated the flood risk issue and the effectiveness of erosion control measures for villages located downstream of one or several small cultivated catchments (e.g. Souchère et al., 2005). Since discharges are not normally measured in the thalweg of these small catchments, expert-based models can offer a solution (Cerdan et al., 2002a).

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

Several types of measures can be implemented to mitigate muddy floods. A first type of actions aims at preventing runoff generation. Cover crops during the intercropping period and alternative agricultural practices, such as conservation tillage, aim to prevent the generation of runoff. Grass buffer strips or grassed waterways (GWW) slow down runoff and in some cases enhance infiltration. Grass buffer strips, located along field borders, increase infiltration of diffuse runoff and decrease net soil loss (Le Bissonnais et al., 2004). GWW are generally wider (min. 10 m-wide) and installed in the thalweg (Fiener and Auerswald, 2003a). They have a potential to reduce runoff volume and peak discharge rate, especially in micro-catchments, up to 8 ha (Fiener and Auerswald, 2005a). Finally, earthen dams and detention ponds can be built in order to buffer runoff

and reduce peak discharges in the villages downstream.

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

This chapter aims at assessing the effectiveness of erosion control measures to reduce the downstream impacts of muddy floods from a dry zero-order valley. A spatially-distributed hydrological model designed to simulate heavy storms and based on expert-judgement is used to assess flooding under different patterns of seasonal crop cover. Furthermore, the influence of the land consolidation operation carried out in 1977 on runoff is also addressed.

5.2 Materials and methods

5.2.1 Study area

This study is carried out in the Heulen Gracht catchment (see section 1.2.2.1), which is one of the dry valleys draining to Velm village (Fig. 1.2). After repeated floods in the village, it was finally decided in 2002 to construct an earthen detention dam with a capacity of 2000 m³ at the outlet and a 12 ha-grassed waterway in the lower part of the thalweg.

5.2.2 Field surveys

Several land cover classes are permanent throughout the year in the study area (Chapter 1). However, for cropland, four field surveys were carried out in 2003 to document the seasonal variability of the soil cover by vegetation (Fig. 5.1). The April and December surveys followed the spring and fall sowings, respectively. The June survey corresponds to the situation before the harvest of both winter and summer crops, when the crop cover is well developed. Finally, the September survey outlines the intermediary situation occurring just after the harvest of winter wheat (*Triticum aestivum* L.) and flax (*Linum usitatissimum* L.) when fields are not yet ploughed, and before the harvest of potatoes and sugar beets.

5.2.3 The hydrological model

The '*Meshed Hydrological Model*' (MHM) has been selected for this study because of the availability of several calibration datasets and expert knowledge on runoff from previous studies carried out in the Belgian loess belt (e.g. Randriamaherisoa, 1993; El Idrissi and Persoons, 1997; Hang, 2002). This model, coupled with geographical information systems (GIS) functionalities, is able to simulate the discharge at every point in the catchment, from slope, flow direction and land cover. This deterministic spatially-distributed model is based upon several hypotheses that are only valid in the case of heavy rainfall. It subdivides the catchment into regular grid cells whose physical properties are supposed to be uniform. For this study, two-meters-cells were used, in order to account for the road network and to obtain a trade-off between precision of the results and computing time. A hydrological class ij is assigned to each cell, from its land cover i and slope j . A runoff coefficient and a runoff velocity are attributed to each hydrological class. The model relies on two different functions. A runoff production function determines the transformation of total rainfall into net runoff (Eq. 5.1).

$$C_{ij} = \frac{R_{ij}}{P} \quad (5.1)$$

where C_{ij} is the runoff coefficient for hydrological class ij (dimensionless); R_{ij} is the runoff for the class ij (mm); P is the total rainfall (mm). Runoff coefficients evolve asymptotically towards a constant value during rainfall, while soil saturation is progressively reached. The MHM model, however, is based on linearity and permanence of the production function through an event. This is an acceptable hypothesis in the case of intense rainfall, when rainfall intensity rapidly exceeds the infiltration capacity of the soil. The production function determines the proportion of rainfall that runs off from each cell. A transfer function determines the flow of runoff between the cells to the outlet. This function is based on the runoff velocities given for each hydrological class ij . Transfer velocities are considered constant during an event and the transferred volume cannot infiltrate in gridcells downstream. This is acceptable in case of heavy rainfall when infiltration capacity is exceeded all over the catchment. In the absence of a drainage network, the Linsley method is used to represent the rainfall-runoff relationship (Linsley et al., 1992). This method subdivides the catchment in n areas (A_n) of equal transfer time to the outlet. Isochrones represent the contour lines $n\Delta t$ between such areas, where Δt is the time interval between two isochrones. This subdivision is made on the basis of the velocity

matrix, as well as on the flow directions. The hydrograph at the outlet consists of runoff from successive isochrone areas located each a temporal lag Δt further upstream. The transfer function needs to be associated with the production function to determine rainfall that runs off for each isochrone area (Eq. 5.2).

$$Q(t) = \sum_{k=1}^n A_k \times C_k \times I(t - k + 1) \quad \text{for} \quad (t - k + 1) > 0 \quad (5.2)$$

where $Q(t)$ is the discharge at the outlet at time t ($\text{m}^3 \text{s}^{-1}$); A_k is the area of the isochrone k ;

$$C_k = \sum^{ij} C_{ij} \times \frac{A_{ij}}{A_k} \quad (5.3)$$

is the runoff coefficient for each isochrone area k ; $I(t)$ is the rainfall intensity at time t . The final result is a surface runoff hydrograph (Randriamaherisoa, 1993; El Idrissi and Persoons, 1997; Hang, 2002).

5.2.4 The model input dataset

Five data layers are needed to compute runoff at the catchment outlet. First, a land cover dataset is created assigning a cover class at each field of the catchment field pattern dataset. Then, the slope and flow direction spatial datasets are calculated from the digital elevation model (DEM), with 2 m size grid cells. The DEM is obtained by digitising the contour lines (equidistance 2.50 m) of the 1:10,000 topographical map (National Geographical Institute of Belgium). The 'Inverse Distance Weighted' (IDW) method is used for interpolation. An intense storm is then simulated, with a 10 year return period. Finally, a configuration dataset containing runoff coefficients and velocities for each hydrological class is built. For grassed areas, road network and woodland, the coefficients were taken from previous studies carried out in the Belgian loess belt (Ministère de l'Équipement et des Transports - Direction des Routes de Liège, 2002; ADALI Convention, 2002). Unfortunately, croplands were only characterized by a global runoff coefficient and velocity in these studies. In order to study the temporal variability of these parameters for croplands, the field survey method developed by Cerdan et al. (2002a) for the STREAM model was combined with the experimental data for other types of land use from the studies mentioned above. The STREAM model takes surface crusting, soil roughness and vegetation cover into account to determine a relative category of runoff sensitivity (Table 3.2). These categories were determined by field surveys (Table 5.1). Runoff coefficients and velocities were then attributed to these relative categories, in such a way that cropland values fall within the range of values for the other types of land use

from previous experimental studies carried out in the Belgian loess belt (Table 5.2). The following sequence of increasing probability to generate runoff was used (e.g. Musy and Higy, 2004): Woodlands < Grasslands < Dense crops < Sparse crops < Bare soils < Roads

Table 5.1: Runoff sensitivity relative categories for the different crop cover classes and survey periods (after Cerdan et al., 2002a).

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

^a Soil surface roughness state. See classification in Table 3.2.

^b Soil surface crusting stage. See classification in Table 3.2.

^c The runoff sensitivity category ranges from 0 to 2. The greater the value of the category, the greatest potential to generate runoff.

Table 5.2: Runoff coefficients and velocities for different months and different land cover classes in the study area.

Land cover	Study area covered (%)	Runoff coefficient	Runoff velocity (m s ⁻¹)
April			
Woodland	0.28	0.015	0.06
Road network	3.50	0.5	0.4
Orchard	13.33	0.02	0.1
Grassed areas	4.89	0.02	0.1
Dense crops	36.35	0.03	0.1
Sparse crops	21.67	0.1	0.5
Bare soil	21.48	0.15	0.13
June			
Woodland	0.28	0.015	0.06
Road network	3.50	0.5	0.4
Orchard	13.33	0.02	0.1
Grassed areas	4.89	0.02	0.1
Dense crops	74.20	0.03	0.08
Sparse crops	2.45	0.3	0.28
Bare soil	0.89	0.3	0.28
September			
Woodland	0.28	0.015	0.06
Road network	3.50	0.5	0.4
Orchard	13.33	0.02	0.1
Grassed areas	4.89	0.02	0.1
Dense crops	40.89	0.03	0.1
Sparse crops	8.98	0.15	0.13
Bare soil	11.44	0.15	0.13
December			
Woodland	0.28	0.015	0.06
Road network	3.50	0.5	0.4
Orchard	13.33	0.02	0.1
Grassed areas	4.89	0.02	0.1
Dense crops	0	0.03	0.1
Sparse crops	42.97	0.3	0.27
Bare soil	34.90	0.3	0.27

5.2.5 Simulations

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

5.2.6 Strengthening confidence in the model for extreme events

A validation of the MHM model has already been successfully implemented in catchments under temperate and semi-arid climates (El Idrissi, 1996; Ntaguzwa, 1999; Hang, 2002). The model is also used by the hydrological service (SETHY, *Service d'ETudes HYdrologiques*) of the Walloon Region of Belgium. Since the model does not simulate water reinfiltration, the topographic index (Eq. 5.4) has been computed at both extremities of the GWW to check its topographic sensitivity to surface saturation (Beven and Kirkby, 1979; Moore et al., 1988).

$$I = \ln \left(\frac{\alpha}{\tan\beta} \right) \quad (5.4)$$

where I is the topographic index; α is the local catchment area per unit contour length ($\text{m}^2 \text{m}^{-1}$); β is the slope gradient (m m^{-1}).

Typically, a large local catchment area and a small slope result in a high value of the index, meaning that the groundwater table is close to the surface and that soils can be expected to be wet (Rodhe and Seibert, 1999).

Furthermore, to increase the confidence in the model for this specific application, simulated discharges were compared to observed ones during a number of events,

for which the return period was estimated. Water level measurements behind a dam are used. Few runoff events have been recorded since 2003. A crest stage recorder was installed behind the dam to measure water level when runoff to the outlet occurred. Such a recorder consists of a plastic tube with a length of water-sensitive tape which changes colour on contact with water (Hooke and Mant, 2000). Water is temporally stored in a detention pond and drains through two pipes of 0.25 m and 0.2 m diameter in the bottom of the dam. Water levels were then converted to outflow discharge using Eq. 5.5 (Ilaco, 1985).

$$Q = mc\sqrt{2gh} \quad (5.5)$$

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



Figure 5.1: Seasonal evolution of land cover in the study area.

5.3 Results and discussion

5.3.1 Strengthening confidence in the model for extreme events

The values of the topographic index are very high at the GWW upstream extremity ($I = 16.1$) and the catchment outlet ($I = 16.7$) compared to the ones cited in the literature. Beven and Wood (1983) found that the areas likely to quickly become saturated during rainfall had a topographic index value close to 15. Rodhe and Seibert (1999) found maximum I values of *ca.* 17 in Swedish catchments. The high I values indicate that the GWW will become very quickly saturated during a storm. Reinfiltration is hence highly unlikely, and the basic assumption of the model is hence acceptable. The occurrence of runoff (3 events in 2004) is correctly predicted even if the peak discharge is overestimated by *ca.* 50% (Table 5.3). It remains hence in the same order of magnitude. Other recorded rainfall events that did not produce runoff at the outlet were also simulated with the model. The model correctly simulated very low runoff during these events.

Table 5.3: Rainfall and discharge in 2003 and 2004.

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

^a Discharge at the outlet was recorded for the events with (*).

^b Return periods after Delbeke (2001).

^c Q_{op} obs. is the peak discharge of the outflow calculated from observed water heights using Eq. 5.5.

^d Q_{op} sim. is the outflow discharge simulated by the MHM model.

5.3.2 Selection of a worst-case scenario

The simulation of an event with a 10 year return period shows that the highest peak discharges and runoff volumes are reached in December ($1.0 \text{ m}^3 \text{ s}^{-1}$; 4586 m^3), while they are lowest in September ($0.3 \text{ m}^3 \text{ s}^{-1}$; 1715 m^3 ; Fig. 5.2; Table 5.4). These results are explained by the higher proportion of bare soil (35%) and sparsely covered soil (43%) at the beginning of winter (Fig. 5.1d). The December situation is hence chosen as a worst-case scenario. June is the second highest risk period, because crop cover is quite low and crusts develop on these sparsely covered soils (Fig. 5.1b; 5.1).

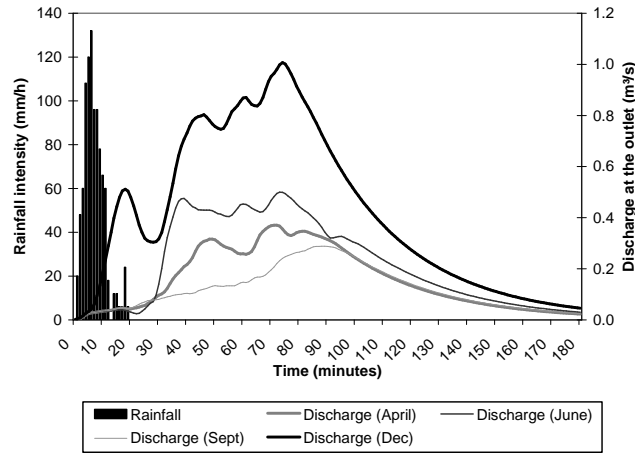


Figure 5.2: Discharge at the catchment outlet in different seasons according to land cover in 2003 (see the corresponding land cover maps in Fig. 5.1).

5.3.3 Potential effect of land consolidation on runoff

After the 1977 consolidation, the mean size of the fields in the study area increased about four-fold from 1.02 ha in 1957 to 4.34 ha in 2003. This is in agreement with the findings of Verstraeten and Poesen (1999) and Beuselinck et al. (2000) who studied land consolidation in an area of central Belgium. The land cover before the consolidation in the 1970s, based on aerial photos of April 1957, (Fig. 5.3a) is compared to that of April 2003 (Fig. 5.3b). For an event with a 10 year return period, runoff volume increases by 19 per cent (from 1443 m³ in 1957 to 1715 m³ in 2003). Peak discharge rises by 33 per cent (from 0.3 m³ s⁻¹ in 1957 to 0.4 m³ s⁻¹ in 2003). The lag time is similar in both situa-

Table 5.4: Peak discharge, total runoff volume and lag time at the catchment outlet for the different situations simulated with the MHM model.

Situation	Peak discharge (m ³ s ⁻¹)	Total runoff volume (m ³)	Lag time (min)
April 2003	0.4	1715	70
June 2003	0.5	2365	73
September 2003	0.3	1326	90
December 2003	1.0	4586	75
Before LC ^a	0.3	1443	73
After LC	0.4	1715	71
Comparison	+ 33%	+ 19%	- 3%
Without GWW ^b	1.0	4586	74
With GWW	0.5	2652	86
Comparison	- 49%	- 42%	+ 16%

^a LC: land consolidation (April situation).

^b GWW: grassed waterway.

tions and is close to 75 minutes (Fig. 5.4). However, the hydrograph shape is different. The rising limb is more gradual before land consolidation. After land consolidation, the first peak in the hydrograph corresponds to the sudden arrival of water that concentrates on the road in the thalweg. Land consolidation

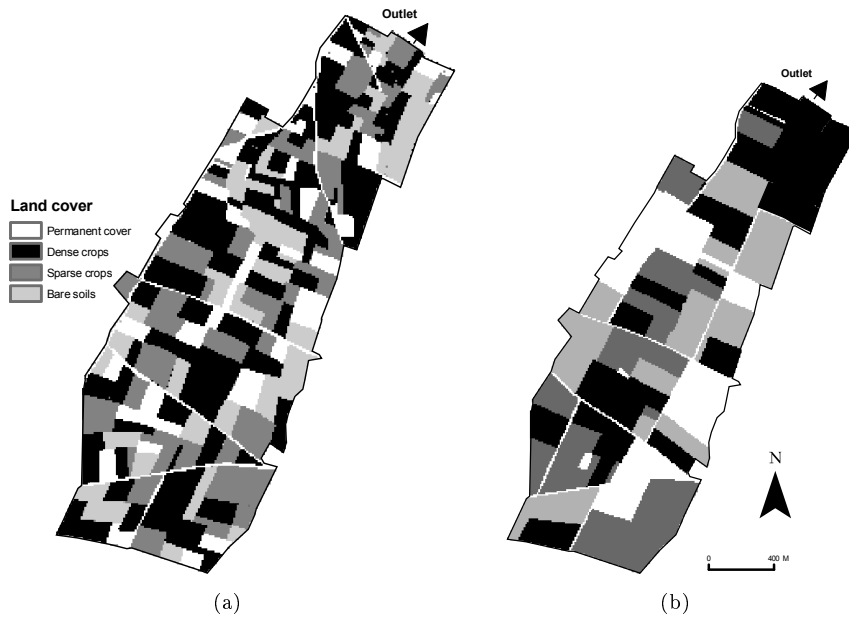


Figure 5.3: Land use and land cover (a) before and (b) after land consolidation.

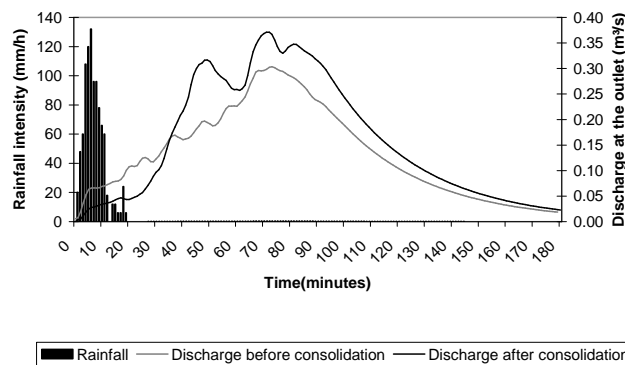


Figure 5.4: Simulated hydrographs at the catchment outlet for the situation before and after land consolidation.

does not lead to the sharp rise of runoff volume reported by other authors (e.g. more than 75% rise according to Souchère et al., 2003). Two reasons can be put

forward. First, the Belgian open field context is different from that of bocage landscapes. In the study area, no grassland or hedgerows were present before 1977. Consequently, there was no ploughing up of grassed areas, which resulted in an important increase of runoff volume in other European regions. Second, the model does not take into account the ditch network of the catchment, where water can be temporally buffered. This impact is hence underestimated in this study, which highlights the major role played by a consolidation road constructed in the thalweg and leading to an increase of the runoff transfer velocity to the outlet (sharp rising limb in 2003 instead of a more gradual rising limb in 1957).

5.3.4 Impact of the mitigation measures

The impact of the GWW (12 ha) installed in 2002 is simulated for the worst-case scenario (Fig. 5.5). Peak discharge decreases by 50% when the GWW

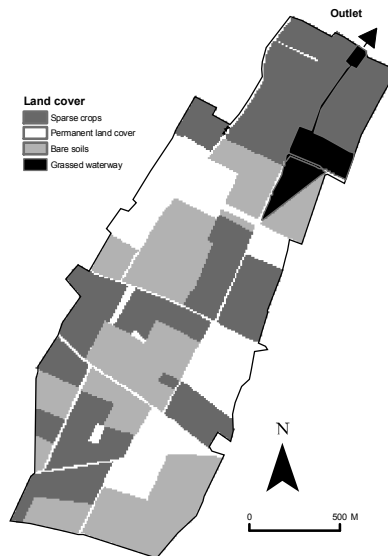


Figure 5.5: Grassed waterway and other land covers in December 2003.

is taken into account ($0.5 \text{ m}^3 \text{ s}^{-1}$ instead of $1.0 \text{ m}^3 \text{ s}^{-1}$; Fig. 5.6; Table 5.4). Runoff volume transferred to the outlet decreases by 40 per cent (2651 m^3 instead of 4586 m^3 ; Table 5.4). Furthermore, the lag time increases with 16%

and the rising limb becomes more gradual. The decrease of peak discharge and reduction of total runoff volume are often reported after the installation of a GWW (Chow et al., 1999; Fiener and Auerswald, 2003b). Still the current catchment is much larger (300 ha) than the ones (*ca.* 8 ha) studied by Fiener and Auerswald (2003b) and slopes are much more gradual than in the terraced catchment of Chow et al. (1999). There are two factors explaining the decrease in total runoff volume (1935 m^3) when the GWW is considered. First of all, less runoff has been produced in the GWW itself due to its lower runoff coefficient. This accounts for a decrease of 680 m^3 . Then the remaining decrease in runoff volume of 1255 m^3 can be explained by the reduction in runoff velocity in the GWW (0.1 m s^{-1} in a GWW instead of 0.3 m s^{-1} on sparsely covered cropland). Such a reduction appears realistic since the mean water depth in the GWW (8 mm) is small compared to the height of the vegetation (*ca.* 5 cm). This leads to a long recession curve in the hydrograph. Since the MHM model is limited to simulations of 180 minutes, this long recession curve is not taken into account. However, the spreading of runoff over more than 180 minutes decreases the flood risk for the village situated 500 m downstream. The maximum observed

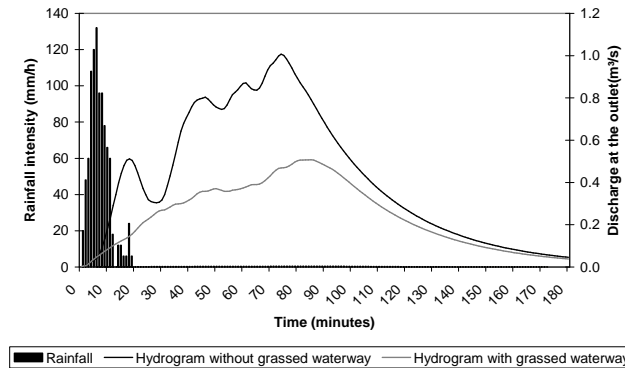


Figure 5.6: Hydrograph at the catchment outlet for the December situation, with and without grassed waterway.

peak discharge at the outflow of the dam reaches $0.5 \text{ m}^3 \text{ s}^{-1}$ for a 10 year return period. This peak discharge of the outflow is similar to the peak discharge of the inflow simulated by the model taking the GWW into account ($0.5 \text{ m}^3 \text{ s}^{-1}$; Table 5.4). Hence, flooding of Velm is unlikely for a 10 year event occurring under the worst-case scenario. Since the inflow and the outflow of such an event are of the same order of magnitude, the detention pond does not serve its purpose. It is suggested to narrow the drain pipes and hence reduce the outflow.

5.4 Conclusions

This case study in a medium agricultural catchment (*ca.* 300 ha) of central Belgium shows that a 12 ha-GWW (4% of total surface) and a detention dam (with a capacity of 2000 m³ i.e. 75% of total runoff during an event with a 10 year return period) alleviate the risk of muddy floods for a village downstream. Peak discharge was reduced by 50%, while the lag time increased by 16%. However, land consolidation carried out in the 1970s led to an increase of peak discharge (33%) and total runoff volume (19%). This can be explained by an increase in field size (from 1.02 ha in 1977 to 4.34 ha in 2003) but also and mainly by the construction of a road in the thalweg of the catchment leading to runoff concentration. Consequently, on-site soil conservation measures are to be installed within the catchment to prevent runoff generation and mitigate its concentration in the catchment thalweg. Since the runoff volume was buffered in the detention pond for the selected worst-case scenario, a reduction of the outflow pipes diameter could be envisaged in order to limit the discharge towards the village.

Chapter 6

Monitoring a grassed waterway and earthen dams to control muddy floods from a cultivated catchment

1

Given the high values of peak discharge obtained in chapter 5 when simulating a storm with a 10 year-return period, the local water board decided to install two additional dams in the thalweg of the Heulen Gracht catchment to prevent muddy floods in Velm village. Chapter 6 focuses on the monitoring of these measures.

Outline

Muddy floods are mainly generated in dry zero-order valleys and are nowadays considered as one of the processes transferring material eroded from cultivated hillslopes during the Holocene to the flood plain. The huge costs of muddy flood damages justify the urgent installation of control measures. In the framework of the 'Soil Erosion Decree' of the Belgian Flemish region, a 12 ha-grassed waterway and three earthen dams have been installed between 2002 and 2004 in the thalweg of a 300-ha cultivated dry valley in the Belgian loess belt. The measures served their purpose by preventing any muddy flood in the downstream village, despite the occurrence of several extreme rainfall events (with a maximum return period of 150 years). The catchment has been intensively monitored between 2005 and 2007 and 39 runoff events were recorded in that

¹This chapter is based on an article by Evrard, O., Vandaele, K., van Wesemael, B. and Bielders, C.L.; accepted for publication in *Geomorphology*.

period. Peak discharge (per ha) was reduced by 69% between the upstream and the downstream extremities of the grassed waterway (GWW). Furthermore, runoff was buffered for 5 to 12 hours behind the dams, and the lag time at the outlet of the catchment was thereby increased by 75%. Reinfiltration was mainly observed within the waterway during low intensity storms (mean reduction of runoff coefficients of 50% during events with a maximum rainfall intensity during 5 minutes $< 35 \text{ mm h}^{-1}$ and total precipitation $< 15 \text{ mm}$). In contrast, the reinfiltration during intense storms was very low (mean reduction of runoff coefficient of 8% during events with a maximum rainfall intensity during 5 minutes $> 35 \text{ mm h}^{-1}$ and total precipitation $> 15 \text{ mm}$). Sediment discharge was reduced by 93% between the GWW's inflow and the outlet. The grassed waterway has prevented the formation of (ephemeral) gullies (which were previously responsible for ca. 80% of sediment production). Before the installation of the control measures, specific sediment yield (SSY) of the catchment reached $3.5 \text{ t ha}^{-1} \text{ yr}^{-1}$ and an ephemeral gully formed nearly each year in the catchment. Since the control measures have been installed, no (ephemeral) gully has developed and the SSY of the catchment dropped to a mean of $0.5 \text{ t ha}^{-1} \text{ yr}^{-1}$ (2006-2007). Hence, sediment transfer from the cultivated dry valley to the alluvial plain should dramatically decrease. Total cost of the control measures that are built for a 20 year-period is very low ($\text{€}126 \text{ ha}^{-1}$) compared to the mean damage cost associated with muddy floods in the study area ($\text{€}54 \text{ ha}^{-1} \text{ yr}^{-1}$). Similar measures should therefore be installed to protect other flooded villages of the Belgian loess belt and comparable environments.

6.1 Introduction

About 90% of muddy floods observed in the Belgian loess belt are generated on cultivated hillslopes (10-30 ha) and in dry zero-order valleys (30-300 ha; Chapter 2). Numerous studies carried out in cultivated catchments of the European loess belt showed that most sediments produced during the Holocene have been stored in the dry valley bottom near the catchment outlet and have not been delivered to downstream rivers (e.g. Bork et al., 1998; Lang et al., 2003; Rommens et al., 2005; de Moor and Verstraeten, 2008). Rommens et al. (2006) also estimated the Holocene alluvial sediment storage in a small river catchment (52 km²) of the Belgian loess belt. They showed that sediment supply towards the alluvial plain has increased dramatically since Medieval times compared to the rest of the Holocene period and occurred at a mean rate of 1.3 t ha⁻¹ yr⁻¹. Since 50% of sediment eroded from hillslopes was stored in colluvial deposits, mainly located in dry zero-order valley bottoms, muddy floods caused by severe erosion on agricultural land are one of the processes transporting sediments from the dry valleys to the alluvial plains. During heavy rainfall in late spring and summer, ephemeral gullies formed in these dry valleys. These shallow (*ca.* 0.1 m) but wide (*ca.* 3 m) gullies act as an important conveyor of sediment and may aggravate the off-site damage produced by muddy floods (Nachtergaele and Poesen, 2002; Verstraeten et al., 2006).

The huge costs associated with this damage, which appears to have occurred more frequently during the last decade, justify the urgent installation of mitigation measures (Chapter 2). Two types of measures can be carried out to control muddy floods. On the one hand, alternative farming practices implemented at the field scale, such as sowing of cover crops during the intercropping period, reduced tillage or double sowing in zones of concentrated flow, limit runoff generation and erosion production (Gyssels et al., 2002; Leys et al., 2007). However, the implementation of these practices directly depends on the farmer's willingness. Except for sowing of cover crops, the adoption of such practices remains rather limited in Belgium (Biielders et al., 2003). It will probably still take several years or even decades before reduced tillage and double sowing become widespread². On the other hand, 'curative' measures aim to reinfiltrate or buffer runoff once it is formed, as well as to trap sediments and pollutants. Typically,

²In France, application of no-tillage is expanding rather quickly, increasing from 21% of cropland in 2001 to 34% in 2006. The larger the farms, the higher proportion of cropland where no-tillage is applied (58% of cropland for farms larger than 400 ha vs. 29% of cropland for farms smaller than 50 ha, Chapelle-Barry, 2008). The difference in farm size (mean of 73 ha in France vs. 30 ha in the Belgian loess belt in 2005) can explain the difference in no-tillage application. No-tillage machinery is rather expensive, and only large farms can afford it.

grass buffer strips, grassed waterways (GWW) and detention ponds (retaining runoff for a certain time behind a small dam) serve this purpose (Fiener et al., 2005). Such curative measures are most effective when they are implemented in the framework of integrated catchment management. Hence, a local water board should be responsible for deciding, in consultation with farmers, where to install these measures within the catchment and for ensuring their maintenance.

From 2001 onwards, municipalities in the Belgian Flemish region are eligible for subsidies to draw up an erosion mitigation scheme (Verstraeten et al., 2003). Several small-scale measures such as dams and GWW are being installed in the field, but there is a need to evaluate their effectiveness before generalising their installation in problem areas. Furthermore, since muddy floods are generated on large surfaces (10 - 300 ha; Chapter 2), the effect of control measures should be investigated at similar scales. However, previous research has focused on the effect of grass buffer strips and has mostly been carried out on experimental plots (typically 500 m², see e.g. Van Dijk et al., 1996a; Patty et al., 1997; Le Bissonnais et al., 2004). With respect to the effect of GWW in the European context, it has only been assessed at the scale of micro-catchments (max. 8 ha; Fiener and Auerwald, 2005a; Fiener et al., 2005). Large quantities of concentrated runoff leading to muddy floods cannot be generated on such small surfaces and a specific study is hence needed at the scale of the larger catchments, which are the source areas of muddy floods.

This chapter evaluates the effectiveness of a GWW and earthen dams installed in a cultivated 300 ha-catchment in the Belgian loess belt in mitigating muddy floods in the downstream village. Cost-efficiency of the control measures is also discussed.

6.2 Materials and methods

6.2.1 Study area

This study is carried out in the Heulen Gracht catchment (see section 1.2.2.1). A first earthen dam had been built close to the catchment outlet in April 2002 to prevent muddy floods (dam # 3 in Fig. 1.3). A 12 ha-GWW had also been sown in the catchment thalweg. Given the high peak discharge values reported in Chapter 5, two additional dams were built across the GWW in August 2004 (dams # 1 and 2 in Fig. 1.3).

6.2.2 Impact of control measures on runoff

Rainfall is measured at 0.1 mm resolution using two tipping bucket rain gauges located at the catchment outlet and just upstream of the GWW (Fig. 1.3). We discretised two rainfall events when they were separated by a continuous period of min. 6 hours without rainfall. The catchment was equipped with a discharge measurement station in April 2006. It consists of a San Dimas flume connected with a flowmeter (Sitrans Probe LU, Peterborough, NO, Canada). Finally, a water level logger (Global Water-WL 15, Gold River, CA, USA) was installed in May 2005 behind each of the three earthen dams built across the GWW. A topographic survey has been carried out in Spring 2005 to determine the volume-depth curves of the detention ponds (Table 6.1). Water temporarily stored in the detention ponds drains through a pipe at the bottom of the dam. Water levels are converted to outflow discharges using Eq. 6.1 (Ilaco, 1985):

$$Q = mc\sqrt{2gh} \quad (6.1)$$

where Q is the discharge ($\text{m}^3 \text{s}^{-1}$); m is the discharge coefficient (0.62); c is the cross-section of the drain (m^2); g is the gravity acceleration (9.81 m s^{-2}) and h is the hydraulic head (m).

Table 6.1: Characteristics of the detention ponds of the Heulen Gracht catchment. Location of the ponds is given in section 1.2.2.1 (Fig. 1.3).

Pond	Max. dam Height (m)	Width of overflow (m)	Max. storage volume (m^3)	Diameter orifice plates (m)	Volume/catchment area (mm)
1	2.1	10.5	3500	0.2/0.25	1.46
2	2.2	12.6	3500	0.2/0.2	2.38
3	0.95	3.0	2000	0.25/0.25	0.67

The error on runoff volume measurements behind the dams is related to the precision of the pressure devices (*ca.* 0.01 m). We estimate that this error ranges between 5% (for high water heights) and 15% (for low water heights) of the total estimated volume.

The impact of the control measures on runoff is estimated by comparing peak discharges per unit area ($\text{l s}^{-1} \text{ ha}^{-1}$), runoff coefficients (%), duration of runoff flow (h) and lag time (h) for each event measured at both the upstream and downstream extremities of the GWW. Since the distribution of these parameters is normal as determined by Kolmogorov-Smirnov tests, paired Student's t -tests have been carried out using the SAS Enterprise Guide statistical package (SAS Institute Inc., Cary, NC, USA) to detect any significant differences between both extremities of the GWW at 95% confidence intervals.

6.2.3 Impact of control measures on erosion

The rills and gullies that were formed during the monitoring period have been mapped and their length, depth and width measured. The cross-sectional area of erosion features has been computed for 67 transects within the catchment. The mass of eroded soil is determined using the mean value of bulk density measured for cropland in loess soils of central Belgium (1.43 g cm^{-3} ; Goidts and van Wesemael, 2007). Sediment thickness in the detention pond located behind dam # 3 (Fig. 1.3) was measured with a meter on a 5 m-grid after each important rainfall event (with $\geq 10 \text{ mm}$ cumulative rainfall). Data are interpolated to estimate sediment volume and mass. The calculated erosion rates are compared to the output of an empirical relationship between catchment area (A , ha) and specific sediment yield (SSY , $\text{t ha}^{-1} \text{ yr}^{-1}$) obtained for 26 cultivated catchments of the Belgian loess belt over a period of 2 to 46 years during the 20th century (Eq. 6.2; Verstraeten and Poesen, 2001).

$$SSY = 26A^{-0.35} \quad (6.2)$$

A suspended sediment sampler (ISCO-6712, Lincoln, NE, USA) has been installed in the San Dimas flume and connected to the water level sensor in order to determine the erosion rate after the installation of the control measures. Since there is no permanent flow, sampling only occurs when the height of water in the flume exceeds 5 cm. A runoff sample is then taken at a 5-minutes time step until the end of the event. Suspended sediment concentration is determined by drying the samples in an oven at 105°C for 24 hours. Runoff samples have also been taken manually at the outlet of the dam pipes during the heaviest storms to compare the sediment concentrations and discharges with the ones measured in the San Dimas flume. A Student t -test has been carried out to detect significant changes in sediment discharge between both extremities of the GWW.

6.2.4 Impact of control measures on muddy floods

The Sint-Truiden fire brigade classifies its interventions according to their nature (road accident, fire, riverine or muddy flood). Such data are available for Velm village since 1977. Corresponding daily rainfall data are available for the Gorseme (Sint-Truiden) station of the Belgian Royal Meteorological Institute, located 5 km from the catchment. These muddy flood reports allow a comparison of flood frequency in Velm village before and after the installation of the control measures, taking account of the rainfall return period.

6.3 Results

Between 2002 and 2007, 77% of events with > 15 mm precipitation occurred between May and September. Similarly, 70% of runoff events occurred during this period (Fig. 6.1).

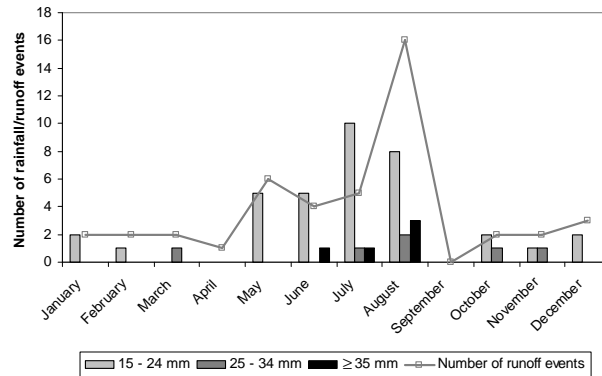


Figure 6.1: Monthly distribution of observed rainfall events during the period 2003-2007 with > 15 mm of cumulative precipitation, and number of recorded runoff events.

6.3.1 Impact of control measures on runoff

The San Dimas flume recorded 39 runoff events in 2006 and 2007 (Table 6.2). Runoff coefficients of the catchment upstream of the GWW calculated based on the San Dimas flume discharge varied between 0.07% and 22.7%, with a mean of 7.4% (Table 6.2). These runoff coefficients which remain relatively low even during extreme events (e.g. 22.7% on June 11, 2007) are in agreement with the high steady state infiltration rates of cropland measured in Chapter 3 (Table 3.4). Usually, runoff coefficients were higher in spring and summer (8.3%) than in autumn and winter (3.8%). The highest coefficients were measured in August 2006, which was a very wet month, as well as during the extreme event of June 11, 2007. The heaviest and most intense storms have led to the highest peak discharges in the flume ($0.44 \text{ m}^3 \text{ s}^{-1}$ on June 14, 2006 and $1.47 \text{ m}^3 \text{ s}^{-1}$ on June 11, 2007; Table 6.2).

Table 6.2: Results of runoff measurements in the San Dimas flume and the detention ponds of the Heulen Gracht catchment.

Date (d/m/y)	Rainfall data			Flume			Pond # 1		Pond # 2		Pond # 3 ^a		
	P (mm)	D (h)	T (yr)	I_{max} (mm h ⁻¹)	Q (m ³ s ⁻¹)	RC (%)	Q (m ³ s ⁻¹)	D (h)	Q (m ³ s ⁻¹)	D (h)	Q (m ³ s ⁻¹)	D (h)	RC (%)
09/05/2002	20	1	15								0.48		
20/06/2002	25	1	10								0.36		
03/08/2002	25	0.5	20								0.11		
20/08/2002	50	3	75								0.22		
28/08/2002	70	1	> 200								> 0.5		
06/02/2003	10	24	< 2								0.05		
24/05/2003	20	5	< 2								0.05		
03/07/2003	18	2	2								0.05		
29/08/2003	40	24	5								0.06		
08/07/2004	14.2	8	< 2								0.05		
17/07/2004	12.2	5.3	< 2								0.05		
21/07/2004	20	0.2	25								0.28		
23/07/2004	23.2	4	2								0.28		
08/08/2004	11	0.8	< 2				0.08	7.25	0.23	16.5	< 0.03		
13/08/2004	11.2	23	< 2				n/a		n/a		0.07		
14/08/2004	20.6	14	< 2				0.04	7.5	0		< 0.03		
01/07/2005	17.4	0.8	2				0.05	6.75	0		< 0.03		
14/08/2005	36.6	20.5	5				0.08	10.7	0.08	12.33	0.09	2	
23/10/2005	25.6	12	< 2				0.06	6.33	0.06	7	< 0.03		
25/10/2005	14.8	10	< 2				0		0		< 0.03		
31/03/2006	26	21	< 2				0		0		< 0.03		
01/04/2006	7	14	< 2	38	0.008	0.07	0		0		< 0.03		
05/05/2006	10.8	3	< 2	34	0.03	2	0		0		< 0.03		1.6
18/05/2006	6	1	< 2	38	0.25	4.4	0.10	9.33	0.10	10.4	0.08	4	5.3
21/05/2006	18	3	< 2	8	0.04	3.4	0.07	11	0.07	11	< 0.03		n/a
26/05/2006	11.1	10	< 2	18	0.14	6.7	0.10	12	0.10	14.4	0.08	7	4.5
29/05/2006	14.6	7	< 2	94	0.44	5.2	0.28	10.4	0.26	11.4	0.24	9.84	5.9
14/06/2006	24.7	1	10	30	0.09	10.2	0		0		< 0.03		8.1
03/08/2006	12.9	4	< 2	36	0.11	9.6	0		0		< 0.03		7.6
04/08/2006	17.6	5	< 2	30	0.29	8.9	0.05	7.25	0.05	6.3	< 0.03		7.1
05/08/2006	8.2	2	< 2	30	0.16	8.9	0.08	11.1	0.08	11.75	0.09	1.66	1.7
14/08/2006	22.5	6	2	29	0.09	14	0.06	10	0.06	12.7	< 0.03		11.2
15/08/2006	10	3	< 2	23	0.33	20.9	0.09	10.4	0.09	12.5	0.07	3.9	4.5
16/08/2006	10.3	1.5	< 2	32	0.12	2.5	0.08	13.25	0.07	14.66	< 0.03		2
19/08/2006	7.9	0.33	< 2	43	0.37	9	0.17	14.33	0.13	15	0.11	8.75	3.9
21/08/2006	23.4	4	2	37	n/a	n/a	0.07	10.5	0.07	8	< 0.03		n/a
17/11/2006	14.8	7	< 2	17	n/a	n/a	0.05	17	0.05	21.9	< 0.03		n/a
19/11/2006	8.4	5.5	< 2	7	0.11	4.6	0.05	14.5	0.05	18.5	< 0.03		3.7
07/12/2006	7	2.5	< 2	6									

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continued

Date (d/m/y)	Rainfall data				Flume Q (m ³ s ⁻¹)	RC (%)	Pond # 1		Pond # 2		Pond # 3 ^a	
	P (mm)	D (h)	T (yr)	I _{max} (mm h ⁻¹)			Q (m ³ s ⁻¹)	D (h)	Q (m ³ s ⁻¹)	Q (m ³ s ⁻¹)	D (h)	Q (m ³ s ⁻¹)
08/12/2006	1.2	3	< 2	10	0.03	2.1	13.5	0.07	16.5	< 0.03	n/a	1.6
12/12/2006	6.2	5	< 2	6	0.03	6.1	n/a	0.06	n/a	0.04	n/a	4.9
18/01/2007	16	17.5	< 2	7	0.03	2.6	21.4	0.07	18.4	< 0.03	4.5	2.1
19/01/2007	13	6	< 2	11	0.12	4.1	17	0.10	18.4	0.08	3.5	3.3
26/02/2007	15.7	14.5	< 2	17	0.14	3.6	15.5	0.09	18.5	0.07	3.5	2.4
28/02/2007	10.2	7	< 2	12	0.09	4.5	9.5	0.06	11	< 0.03	3.5	3.5
07/03/2007	10.6	22	< 2	7	0.06	2.5	8	0.03	8.4	< 0.03	2.0	2.7
25/05/2007	13.5	2	< 2	74	0.19	3.3	4.5	0.04	3.25	< 0.03	2.0	2.0
11/06/2007	4.3	1	150	110	1.47	22.7	14	0.44	15.15	0.37	16.25	16.4
18/06/2007	5	0.33	< 2	19	0.10	19.6	n/a	0.04	19	0.05	3	4.5
25/06/2007	10.8	10	< 2	41	0.05	0.8	n/a	0.03	7.7	< 0.03	0.6	0.6
20/07/2007	14.5	6	< 2	30	0.06	1.2	n/a	0.03	7	< 0.03	0.9	0.9
28/07/2007	15.9	9.5	< 2	16	0.14	4.8	14	0.07	13	0.05	1.5	0.8
02/08/2007	19.4	4	2	20	0.31	9.5	17	0.16	16.5	0.10	8	3.9
09/08/2007	50	14	50	12	0.34	15.1	34	0.28	33	0.26	28.5	9.5
21/08/2007	20.8	17	< 2	34	0.24	6.9	19.5	0.11	20	0.09	8	2.6

^a Data for the period 2002-2004 are available from 'crest stage recorder' measurements.P: Rainfall amount; D: Duration of the event; T: Return period according to Delbeke (2001); I_{max}: Maximum rainfall intensity in 5 minutes;

Q: Peak discharge; RC: Runoff coefficient; n/a: not available.

Some 53 rainfall-runoff events have been measured behind the dams (Table 6.2). Before the installation of dams 2 and 3 in August 2004 (Fig. 1.3), runoff events with a discharge $> 0.03 \text{ m}^3 \text{ s}^{-1}$ have been observed at dam 3 during low-intensity precipitation (e.g. in February, 2003; Table 6.2). After the installation of the two additional dams, notable runoff has been measured behind the dam at the outlet (dam 3; Fig. 1.3) during only 13 events. These events correspond to: (i) prolonged periods of rain in winter ($\geq 30 \text{ mm}$ in 48 hours) or (ii) to heavy thunderstorms between May and August ($\geq 20 \text{ mm}$ in a few hours). All runoff parameters are significantly different between both extremities of the GWW at the 95% confidence interval (Table 6.3).

An important and significant decrease of the peak discharge per unit area (mean of 69%) was observed between the San Dimas flume (just upslope of the GWW) and the catchment outlet. Loss of runoff, probably due to infiltration in the GWW and behind the dams, has also been observed, but almost exclusively during low intensity rainfall ($I_{max} < 40 \text{ mm h}^{-1}$ and total precipitation $< 15 \text{ mm}$). Mean runoff coefficients during these events decreased by 40% between both extremities of the GWW (Table 6.3). The reduction was, however, very limited during intense thunderstorms (mean of 8% for events with an $I_{max} > 40 \text{ mm h}^{-1}$ and total precipitation $> 15 \text{ mm}$; Table 6.2).

Runoff was buffered during 5 to 12 hours behind the three successive dams. The mean duration of runoff was 38% longer at the outlet than just upstream of the GWW. A long hydrograph recession limb, corresponding to the progressive outflow of runoff buffered behind the dams through the pipes, was observed. The lag time increased by a mean of 75% after the installation of the control measures.

Peak flow left the San Dimas flume and reached the outlet of the first dam in a mean of 2 hours 25 minutes (mean propagation velocity of the peak discharge of 0.04 m s^{-1}). Peak outflow from the first dam reached the outlet of the second pond in a mean of 32 minutes (mean propagation velocity of 0.09 m s^{-1}). Some 64 minutes were then needed for peak runoff to reach the outlet of the third dam (mean propagation velocity of 0.14 m s^{-1}). The propagation of the peak discharge was hence slowed down in the GWW, but the decrease was not linear between the dams (Table 6.2).

Table 6.3: Summary of *t*-test results to detect significant differences in the flume (upstream of GWW) and at the outlet. SD is the standard deviation.

Parameter	Peak discharge per ha ($l\ s^{-1}$)		Runoff coefficient (%)		Flow duration (h)		Lag time (h)		Sediment discharge ($kg\ s^{-1}$)	
	Flume	Outlet	Flume	Outlet	Flume	Outlet	Flume	Outlet	Flume	Outlet
Mean	0.8	0.2	7.5	4.4	9.6	15.5	1.2	5	3.2	0.2
SD	1.2	0.3	5.9	3.5	5	6	1.1	1.4	8	0.6
Observations	30	30	30	30	15	15	15	15	10	10
<i>t</i> stat		2.4		2.5		-2.8		-8.1		1.9
<i>P</i> ($T \leq t$)		<0.01		<0.05		<0.01		<0.0001		0.064 (NS)

NS = not significant.

6.3.2 Impact of control measures on specific sediment yield

According to Eq. 6.2, the specific sediment yield for a catchment of the size of the Heulen Gracht should be $3.5 \text{ t ha}^{-1} \text{ yr}^{-1}$. The gullies observed since the 1950s and draining to Velm are mapped in section 1.2.2 (Fig. 1.2).

Six major erosion events have been documented between April and September 2002 (Table 6.4). The first erosion event occurred in May 2002. The summer crops were already sown at that time, and tillage erased erosion features remaining from the winter period. Total volume of the rills and gullies reached *ca.* 1500 m^3 in September 2002, corresponding to a soil loss due to rill and gully erosion of 2175 t . Rill and gully cross-section was very variable (0.2 to 2.5 m^2), both between and within fields. Erosion rate reached a mean value of 7.25 t ha^{-1} at the catchment scale in 2002, without taking sheet erosion into account.

Table 6.4: Muddy flood events requiring fire brigade interventions in Velm village between 1977 and 2002 and associated rainfall depth. Return periods after Delbeke (2001).

Date	Daily rainfall (mm)	Duration (h)	Return period (yr)
20/07/1980	38	< 24	> 5
10/08/1992	44.5	< 24	> 5
08/06/1996	21	< 24	
13/08/1996	47	< 24	> 10
30/05/1999	n/a	n/a	n/a
08/05/2000	n/a	n/a	n/a
03/06/2000	18.2	< 24	
14/07/2000	13.6	< 24	
25/07/2000	66.5	< 24	> 100
29/07/2000	23.2	< 24	
02/08/2001	40	< 24	> 5
09/05/2002	20	1	5
20/06/2002	25	1	10
20/07/2002	30	8	5
03/08/2002	25	0.5	20
20/08/2002	50	3	100
27/08/2002	70	1	> 200

Measurements of sediment concentrations in the flume as well as in the outflow of the dams are available for 13 events recorded in 2006 and 2007 (Table 6.5). Much of the sediment was trapped behind the first dam. Sediment concentration in the first dam's outflow decreased by a mean of 86% compared to the concentration measured in the San Dimas flume. It further decreased by 16% due to trapping behind the second dam. In contrast, an increase of sediment concentration (+38%) was generally measured at the catchment outlet compared to the second dam outflow. This is due to the inflow of runoff loaded with sediments, flowing from row crop fields located along this part of the GWW. However, sediment concentration at the outlet was reduced by a mean of 88% (0.9 g l^{-1}) compared to the one measured in the flume (mean of 5.4 g l^{-1}). Sediment discharge is

reduced by 93% on average, decreasing from 3.2 kg s^{-1} in the flume to 0.2 kg s^{-1} at the outlet. However, this difference was not statistically significant at 95% confidence interval (Table 6.3). This is probably due to the rather low number of events for which sediment data are available, as well as to the important seasonal variation of runoff and sediment production on cropland in the Belgian loess belt (Chapters 3 and 4). During the extreme event of June 11, 2007, 84 t

Table 6.5: Results of soil loss measurements in the San Dimas flume and sediment concentrations in the outflow of the dams. N is the number of water samples taken in the flume. Two water samples have systematically been taken behind the dams.

Date (d/m/y)	San Dimas Flume			Dam 1	Dam 2	Dam 3
	Soil loss (t)	Mean sediment conc.(g l ⁻¹)	N	Sediment conc.(g l ⁻¹)	Sediment conc.(g.l-1)	Sediment conc.(g l ⁻¹)
26/05/2006	1	0.9	2	0.4	0.2	n/a
29/05/2006	20	10	10	0.2	0.1	n/a
14/06/2006	120	30.9	24	1.7	1.3	1.9
21/08/2006	19	3.8	24	1.1	1.1	0.6
08/12/2006	5	0.7	2	0.4	0.4	0.3
26/02/2007	13	3.2	2	0.3	0.3	0.3
28/02/2007	4	1.2	2	0.3	n/a	n/a
07/03/2007	2	1.1	2	0.9	0.3	n/a
25/05/2007	2	2.1	2	0.7	n/a	n/a
11/06/2007	117	5	24	1.6	1.9	2.2
18/06/2007	10	4.4	4	0.3	0.2	n/a
02/08/2007	5	1.2	2	0.6	0.5	0.5
09/08/2007	16	0.9	3	0.9	0.2	0.3

of sediments were trapped behind the three successive dams. It represents 72% of soil loss measured in the San Dimas flume. No more rills nor (ephemeral) gullies have been observed in the thalweg since the sowing of the GWW and the construction of the dams, despite the occurrence of several extreme events.

6.3.3 Impact of control measures on muddy floods

Soil erosion and flooding are ancient problems in the area. Flooding of the nearby Gingelom village was already very frequent during the 18th century (Aumann and Vandenghoer, 1989). Intense soil erosion was explicitly mentioned in the 1960s for the nearby Gingelom village (section 1.2.2, Fig. 1.2; T'Jonck, 1967). However, the off-site consequences have become more severe since the beginning of the 1990s (Chapter 2). Fire brigade interventions due to muddy floods in the Velm village have dramatically increased since 1980 (Table 6.4). All muddy floods were triggered by heavy thunderstorms (between 14 and 70 mm of rainfall, with a mean of 35.5 mm) and occurred between May and August (Table 6.4). Six heavy storms (20 to 70 mm precipitation) occurred in 2002, each leading to the flooding of the village. The three events in August 2002 were rather extreme, having a return period between 20 and >200 years (after

Delbeke, 2001).

Since the installation of the GWW and the two additional earthen dams in 2004, no muddy flood has been recorded in Velm village, despite the occurrence of several extreme events (Table 6.2). The measures have particularly served their purpose during the extreme event of June 11, 2007 (having a return period of 150 years, according to Delbeke, 2001), buffering runoff during 17 hours and preventing any flood in Velm village (Fig. 6.2). Peak discharge per unit area decreased by 79% and the lag time dramatically increased (from 10 minutes in the flume to 5 hours 30 minutes at the outlet).

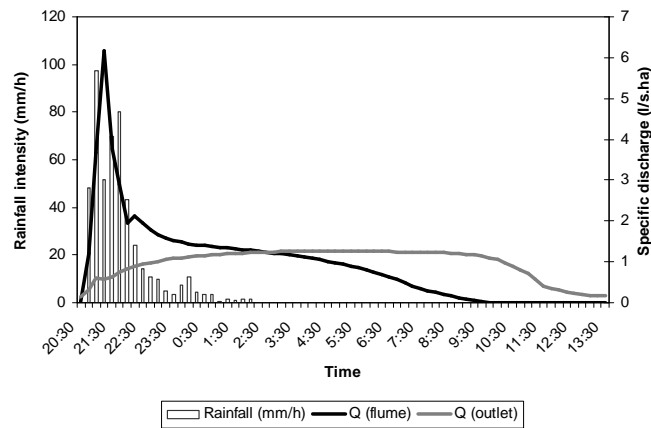


Figure 6.2: Rainfall, inflow and outflow hydrographs measured during the thunderstorm of June 11, 2007.

6.4 Discussion

6.4.1 Effectiveness of the grassed waterway and earthen dams

The propagation of the peak discharge was drastically slowed down within the section with the GWW and the earthen dams. However, there was no important infiltration in GWW for moderate and extreme storms. This is due to a high soil compaction (bulk density of 1.59 g cm^{-3} in the GWW compared to a mean of 1.43 g cm^{-3} for cropland in the Belgian loess belt according to Goidts and van Wesemael, 2007). This confirms the results of rainfall simulations carried out in the Belgian loess belt showing that grass strips and GWW have a higher runoff coefficient (62-73%) than most cultivated soils (13-58%; chapter 3). The rather

low infiltration in the GWW is in contradiction with most studies reported in the literature. The reduction of runoff due to infiltration in grassed areas can reach *ca.* 90% in certain studies (e.g. Schmitt et al., 1999). However, these findings were derived from experimental set-ups whereas we monitored a GWW in the middle of farmers' fields. Furthermore, the runoff reductions reported in the literature are highly variable (6-89%), depending the experimental setup, the precipitation and the physical characteristics of the grassed areas (e.g. slope, width, soil type, grass species and density; Chaubey et al., 1994; Prosser et al., 1995; Van Dijk et al., 1996a; Fiener and Auerswald, 2003b; Mersie et al., 2003; Le Bissonnais et al., 2004; Vianello et al., 2005).

Sediment trapping is very high and occurs mainly behind the first dam, except during extreme events. These observations confirm the main results of a modelling case-study (Chapter 5). The model simulated that the GWW led to a 50% decrease of peak discharge, which is consistent with the field observations. Our findings also agree with the results of a similar study analysing the impact of a GWW on runoff and erosion in a micro-catchment (8 ha) in southern Germany (Fiener and Auerswald, 2005a; Fiener et al., 2005). The German ponds were very efficient in trapping sediments (between 50% and 80% of sediments were trapped) and reducing peak runoff rates. However, two main differences with our study can be outlined, besides the different catchment sizes. In Germany, no event having a return period of > 5 years occurred during the 9-year experiment, while we observed that the dams particularly served their purpose during extreme events. Furthermore, an intensive soil and water conservation scheme was implemented in the German catchments draining to the ponds, limiting sediment and runoff inputs (Auerswald et al., 2000). Our study shows that even without widespread implementation of alternative farming practices, the measures are effective in controlling muddy floods. They offer, therefore, a solution that can be implemented in the short term to protect the most endangered villages against muddy floods.

6.4.2 Evaluation of erosion rates and sediment delivery

Based on field measurements in 2002, rill and gully erosion rates reached 7.25 t ha^{-1} for that specific year. This figure does not take sheet erosion into account. Often, interrill erosion has been estimated as a fraction of total soil loss. This fraction ranges between 10 and 20% of the total soil loss in the Belgian loess belt (Govers and Poesen, 1988; Takken et al., 1999; Steegen et al., 2000). Total erosion was hence underestimated in our study and should be close to 8.3 t

ha⁻¹. This figure is consistent with the range of annual erosion rates measured in central Belgium (6.5 - 12.3 t ha⁻¹ yr⁻¹; Verstraeten et al., 2006).

Nachtergaele and Poesen (1999) calculated a mean ephemeral gully erosion rate of 2.33 t ha⁻¹ yr⁻¹ (over a six months period during which summer ephemeral gullies remain active). The ephemeral gully in the thalweg of the Heulen Gracht catchment was observed on all aerial photographs available for the study area, always appearing at the same location (section 1.2.2; Fig. 1.2). Hence, no increase of gully erosion throughout the study period was found. The highest erosion rate was even observed in 1947 (3.43 t ha⁻¹ yr⁻¹; Nachtergaele and Poesen, 1999), which shows that erosion is not a recent phenomenon in the study area.

Steegeen (2001) showed that summer extreme events have a particularly important effect on long-term landscape evolution. For instance, a summer rainfall with a 10 year-return period that occurred in a 250 ha-catchment in the Belgian loess belt exported several times the mean long-term erosion rate (7 t ha⁻¹ yr⁻¹ for the extreme event after Steegeen et al., 2000; vs. 2.6 t ha⁻¹ yr⁻¹ for the long-term mean, after Vandaele, 1997).

During the extreme event of June 2007, the three ponds trapped sediments (84 t in total). **Since the control measures prevent the formation of gullies in the catchment, erosion rates are dramatically reduced. Only interrill erosion is still observed at a mean rate of 0.5 t ha⁻¹ yr⁻¹ (2006-2007), thereby drastically decreasing sediment delivery to the alluvial plain.** The sediments trapped behind the dams (and mainly behind dam 1) must be evacuated each year (*ca.* 150 t yr⁻¹) by the municipal services. However, it is more convenient for them to excavate the mud behind the dams than to remove it from the streets and private properties of the downstream village ³.

6.4.3 Cost-efficiency of control measures

Immediately after thunderstorms, people need assistance from the fire brigade and municipal services to pump water from cellars and clean up the roads. Fire brigade interventions after the thunderstorms of August 2002 in the Melsterbeek catchment (section 1.1; Fig. 1.1) costed *ca.* €25,000 (i.e. €125 km⁻²). Muddy floods also led to numerous damages to private property. According to 1601 records submitted by Belgian households to the Disaster Fund, mean damage

³The mud is then transported to a field owned by the local water agency which plans to reforest it when its storage capacity will be filled.

amount was €4,436 (SD= €3,406 ; Chapter 2). The villages of Velm and Ginkelom were particularly affected by the thunderstorms of May and August 2002 (Table 6.4). Households from these two villages submitted 268 records to the Belgian Disaster Fund. They received €636,967 (mean of €2,377 per record).

Overall, muddy floods lead to a damage cost of €54 ha⁻¹ yr⁻¹ in the region of Velm. Total cost of the control measures installed in the area reached €126 ha⁻¹. The measures are built for a 20 year-period according to the Soil Erosion Decree. Farmers receive additional subsidies each year for the maintenance of grass strips (€21 ha⁻¹ yr⁻¹). Compared to the damage cost of muddy floods (€54 ha⁻¹ yr⁻¹), the investments would be cost-efficient very rapidly if the measures are effective and no muddy flood occurs. Our results prove that the measures serve their purpose. In Velm village, total investment (€351,528) represents the damage cost to private properties caused by the single August 2002 flood.

The Flemish authorities calculated that the construction of all the control measures proposed in the municipal erosion mitigation schemes that were approved by their administration would cost between €7.7 and 9.6 million yr⁻¹ during the period 2006-2025, which is not disproportionate compared with the total damage cost associated with muddy floods in the Flemish municipalities of the Belgian loess belt (between €8 and 86 million yr⁻¹; Chapter 2).

6.5 Conclusions

A 12 ha-grassed waterway and three earthen dams were installed in a 300 ha-cultivated catchment in central Belgium, in order to prevent muddy floods in the downstream village. These measures served their purpose by preventing muddy floods in the village, even during extreme events (with a maximal return period of 150 years). Peak discharge per unit area was reduced by a mean of 69% between both extremities of the GWW. Furthermore, runoff was buffered during 5 to 12 hours, due to the combined effect of the GWW and the earthen dams. The lag time increased by 75% after the installation of the control measures. Sediment discharge at the catchment outlet is decreased by a mean of 93% compared to the one measured in the GWW's runoff inflow. The measures also prevented any gully formation in the thalweg, thereby reducing erosion to an interrill phenomenon which occurs at a mean rate of 0.5 t ha⁻¹ yr⁻¹ (2006-2007), whereas the specific sediment yield of a catchment of similar size without control measures in the Belgian loess belt should reach 3.5 t ha⁻¹ yr⁻¹. This

would dramatically decrease sediment transfer from the cultivated dry valley to the alluvial plain. Given they prevent muddy floods and remain cost-efficient, similar control measures can be installed to protect other flood prone areas in the Belgian loess belt.

Chapter 7

Evaluating and implementing measures to control runoff and muddy floods from cultivated catchments

This last chapter aims at proposing simple methods to evaluate the effectiveness of grassed waterways and earthen dams in gauged and ungauged catchments. Scenarios are also simulated with the STREAM model to evaluate the potential of conservation tillage to reduce runoff at the catchment scale. In conclusion, a methodology is proposed to implement similar measures to protect other flood prone areas in the Belgian loess belt and comparable environments.

Outline

Simple methods are needed to guide the implementation and evaluate the effectiveness of control measures (i.e. conservation tillage, grassed waterways and earthen dams) to protect flood prone areas. This study is carried out in the gauged Heulen Gracht catchment as well as in the ungauged Gelinden catchment. The STREAM model validated in the Belgian loess belt is first used to estimate the runoff volume to be controlled from these two 300 ha-cultivated catchments. Then, a methodology providing the runoff discharge and allowing to evaluate the effectiveness of grassed waterways and dams to convey runoff at a non-erosive velocity is applied. Simulations carried out with the STREAM model show that runoff volume would be reduced by 80% in the Heulen Gracht catchment if conservation tillage was applied on one third of the cropland surface. Based on field measurements during an extreme storm (50

mm rainfall in one hour), it is then demonstrated that the three detention ponds installed in the Heulen Gracht catchment served their purpose by buffering runoff temporarily. A worst-case scenario (50 mm rainfall in one hour with a heterogeneous pattern of winter cereals and spring crops in June) has been constructed to evaluate the effectiveness of the measures implemented in the ungauged Gelinden catchment. It is shown that the buffer capacity of two dams would be exceeded for the worst-case scenario. In conclusion, a methodology is proposed to implement similar control measures to protect flood prone areas in the Belgian loess belt and comparable environments.

7.1 Introduction

A muddy flood occurs when large quantities of runoff are generated on cultivated soils (Boardman et al., 2006). This large runoff volume is generally produced over a short period (a few hours; see chapter 3). For a given soil type, the 'muddy' character of the flood depends on the soil surface characteristics (crusting state, roughness and cover) and on the occurrence of concentrated erosion. We will focus on runoff in this chapter.

The control of muddy floods is best achieved by preventing runoff generation directly at the source, i.e. cropland in most cases. Various measures, among which conservation tillage, can be implemented to this end. Most studies showing that conservation tillage mitigates runoff and erosion have been carried out in the United States (e.g. Uri et al., 1998), but paired conventional tillage vs. reduced tillage experiments on fields in the Belgium loess belt recently demonstrated the potential of reduced tillage for soil and water conservation (Leys et al., 2007). However, its adoption remains rather limited in Europe (Holland, 2004). Leys et al. (2007) conducted 184 rainfall simulations on maize and sugarbeet fields in the Belgian loess belt. They observed a reduction of interrill runoff (mean of 63%) on plots under conservation tillage compared to plots where conventional mouldboard ploughing was carried out. However, their results were highly variable. Runoff reduction on plots where conservation tillage is applied is mainly explained by the modifications of the soil surface characteristics. Residues from the previous crop are left on the surface, which protects the soil against crusting. Even though conservation tillage limits runoff generation at the plot scale, the widespread adoption of this technique by farmers in the loess belt will likely take several years or decades. The potential impact of the progressive application of conservation tillage on runoff generation at the catchment scale should therefore be evaluated.

Besides measures controlling runoff at the source, numerous 'curative' measures have been taken by local authorities of central Belgium to control runoff and erosion at the scale of small and medium catchments (typically 30 - 300 ha; see chapter 5). The most widespread measures are grass buffer strips (GBS), grassed waterways (GWW) and small-scale detention ponds.

GBS are typically installed along field borders, parallel to the contour lines, to slow down runoff, trap sediments and pesticides originating from adjacent fields. However, their effectiveness is highly variable. Runoff infiltration in GBS varies for instance between 10 and 91%, depending on the experimental

conditions and the rainfall characteristics (Mersie et al., 2003; Le Bissonnais et al., 2004; Vianello et al., 2005). The rainfall simulations described in chapter 3 showed that grassed areas had a higher runoff coefficient ($62 \pm 5\%$) than most cultivated soils (between 13 ± 5 and $58 \pm 8\%$). On average, runoff from adjacent fields only reinfilters in the strip when rainfall intensity does not exceed 23 mm h^{-1} . Given their rather low infiltration capacity, contribution of GBS to control muddy floods generated by intense storms will be rather limited. However, they can trap sediments and thereby decrease the sediment load carried by runoff.

GWW are installed in the catchment thalwegs to convey runoff at a non-erosive velocity up to the outlet (Morgan, 2005). According to a study conducted in a 8-ha hillslope between 1994 and 2001 on a 290 m long and 37 m wide GWW in Germany, runoff was reduced by 87% and sediment delivery by 93% (Fiener and Auerswald, 2005a). In the 300-ha Heulen Gracht catchment, runoff coefficient was reduced by a mean of 50% between upslope and downslope extremities of a 12 ha-GWW. Sediment delivery was reduced by 93% (chapter 7). However, when the analysis was restricted to the most intense storms (maximum rainfall intensity during 5 minutes $> 35 \text{ mm h}^{-1}$ and total precipitation $> 15 \text{ mm}$), reduction in runoff coefficient was much lower (mean of 8%). Since an important reinfiltration of runoff is unlikely to occur in GWWs during intense storms, they must be designed in such a way that runoff velocity remains non-erosive. To this end, a GWW can be combined with small-scale detention ponds that buffer runoff temporarily. In the Heulen Gracht catchment (chapter 6), this combination of measures served its purpose by preventing muddy floods in the village of Velm despite the occurrence of extreme storms.

A simple methodology based on these experimental results is required to evaluate the effectiveness and implement similar measures in other ungauged flood prone areas in the Belgian loess belt. For a given area, runoff volume and peak discharge must be estimated for a given storm to allow the design of these measures. The STREAM model (Cerdan et al., 2002a) was calibrated and validated for the context of the silt-loam soils of central Belgium (chapter 4). It has already been used to simulate the impact of agri-environmental scenarios on runoff in Normandy (Souchère et al., 2005) and to model the response of runoff and erosion to changes in precipitation and land cover (Nearing et al., 2005). STREAM can therefore be used to evaluate the runoff volume from cultivated catchments for given scenarios. However, since STREAM does not provide the hydrograph, this expert approach should be combined with empirical methods to obtain this information.

This chapter evaluates the potential of conservation tillage to reduce runoff at the catchment scale. Furthermore, it proposes simple methods to evaluate the effectiveness and implement GWs and earthen dams to control muddy floods at the scale of small and medium size cultivated catchments (*ca.* 30 - 300 ha). The proposed measures are constrained by the requirements that they protect the downstream villages for a given safety level and remain cost-efficient.

7.2 Materials and methods

This study is carried out in both the Heulen Gracht (gauged) and Gelinden (ungauged) catchments described in sections 1.2.2.1 and 1.2.2.2.

7.2.1 Estimation of runoff volume to control

Runoff generation within a catchment is mainly controlled by the land cover pattern as well as by the precipitation (Chapter 3). We choose to simulate a land cover scenario with a random heterogeneous distribution of winter cereals and summer crops (sugar beets, maize and potatoes) within the catchment. We hypothesise that this scenario is the most likely to occur, because of the crop rotation and the high number of farmers cultivating fields in the same catchment without any coordination on crop location (Chapter 5). The effectiveness of conservation measures is best estimated for the period of the year when the overall runoff risk is highest at the catchment scale. To identify the most critical month, the runoff risk index ($I_{CATCHMENT}$) in the Heulen Gracht catchment is calculated for each month of the period 2002-2007 based on land cover derived from field surveys (Eq. 7.1).

$$I_{CATCHMENT} = 1/A \sum_i I_{RUNOFF_i} \cdot A_i \quad (7.1)$$

Where $I_{CATCHMENT}$ is the runoff risk index at the catchment scale, A is the catchment area (ha), I_{RUNOFF_i} is the runoff risk of the crop i given in Table 3.5b, A_i is the area of catchment cropland surface (ha) covered by the crop i . Runoff risk classification at the catchment scale is given in Table 3.5b.

For a given month, the runoff risk index in the Heulen Gracht catchment remains stable throughout the study period (Table 7.1). A high runoff risk is observed each year in February, May, June and August. We choose to simulate a land cover scenario with the soil surface characteristics observed in June (Chapter 3).

Conservation Service, 1972).

$$Q_{ip} = 0.208 \times \frac{V_{in} \times A}{T_c} \quad (7.3)$$

where V_{in} is the total runoff volume provided by STREAM (mm); A is the catchment area (km²).

7.2.2 Potential of conservation tillage to reduce runoff

The worst-case scenario described in section 7.2.1 is simulated in the Heulen Gracht catchment to evaluate the impact of conservation tillage on runoff. We hypothesise that this technique is only applied to a certain percentage of cropland. Steady-state infiltration rate of these fields is calculated based on Eq. 7.4 which was proposed by Leys et al. (2007) to estimate the final runoff rate (FRR ; mm h⁻¹) of a plot. Unfortunately, we could not use the data derived from our rainfall simulations (see Chapter 3), given that we focused on fields under conventional farming¹. We hypothesise that the data from Leys et al. (2007) are valid for the study sites, given that their rainfall simulations were carried out in the Belgian loess belt, around the towns of Sint-Truiden and Leuven.

$$FRR = -23.00 + 0.21ISC + 0.71RIN - 0.40COV \quad (7.4)$$

where ISC is the extent of surface crusting prior to the rainfall (%); RIN is the mean rainfall intensity (mm h⁻¹) and COV is the total vegetation cover (%).

We have selected a rainfall intensity similar to the one used for the worst-case scenario (50 mm h⁻¹). ISC and COV parameters are estimated based on a study investigating the variability of soil surface characteristics under conservation tillage ($ISC=53\%$; $COV=60\%$; values for the month of June; Armand et al., 2007). FRR is directly introduced in STREAM, bypassing the classification system.

7.2.3 Effectiveness of control measures

The effectiveness of the control measures is first evaluated in the Heulen Gracht catchment. A storm of 50 mm in one hour (similar to the worst-case scenario) was recorded in this catchment on June 11, 2007 (Chapter 7). The effectiveness of these measures is then investigated in the ungauged Gelinden catchment.

¹Traditional and conservation farming lead to a different evolution of soil surface characteristics (Leys et al., 2007). The presence of residues of the previous crop on fields under conservation tillage limits soil surface crusting for instance.

7.2.3.1 Grassed waterways

GWWs are usually installed in areas where concentrated flow of surface runoff occurs. This is typically the case in the thalweg of dry valleys (Tomer et al., 2003). Such areas are characterised by a high topographic index I (Beven and Kirkby, 1979; Moore et al., 1988, ; Eq. 7.5).

$$I = \ln \left(\frac{\alpha}{\tan \beta} \right) \quad (7.5)$$

where α is the upslope contributing area per unit grid cell width ($\text{m}^2 \text{m}^{-1}$) and β is the slope. In the literature, values of I index are considered to be high when they exceed 15 (e.g. Beven and Wood, 1983; Rodhe and Seibert, 1999).

Fiener (2003) recommends the installation of wide, flat-bottomed and long GWWs to improve their effectiveness to control runoff. A key issue for the design of GWWs consists in maintaining a maximum safe flow velocity in the channel, which depends on the grass cover density of the soil and the soil material (Temple, 1991; Morgan, 2005). Flow velocity (v ; m s^{-1}) can be calculated according to Manning's equation (Eq. 7.6).

$$v = \frac{1}{n} S_0^{1/2} R^{2/3} \quad (7.6)$$

where n is the roughness coefficient ($\text{s m}^{-1/3}$), S_0 is the slope ($\tan \alpha$) and R is the hydraulic radius (m). Fiener and Auerswald (2003a) measured a Manning's n of $0.3 \text{ s m}^{-1/3}$ in the GWW of two micro-catchments in Germany. For loamy soils with a very dense grass cover, maximum safe velocity in the channel reaches *ca.* 2 m s^{-1} (Temple, 1991; Morgan, 2005). Furthermore, we hypothesise that outflow discharge from the cultivated catchment should not exceed a fixed safe value, depending on bankfull discharge of the downstream river.

For a given safe velocity in the GWW and a given safe discharge at the outlet (Q ; $\text{m}^3 \text{s}^{-1}$), the flow cross-section (C ; m^2) can be estimated from Eq. 7.7.

$$C = \frac{Q}{v} \quad (7.7)$$

For a triangular channel, the cross-section is given by Eq. 7.8.

$$C = \frac{1}{2} \times d \times w \quad (7.8)$$

where d is the channel depth (m) and w is the channel width (m). Fiener (2003) proposed to maintain a shallow flow in the channel (under 0.1 m). Knowing C and for $d = 0.1 \text{ m}$, the width of the channel can be estimated.

7.2.3.2 Dams and detention ponds

Hong et al. (2006) proposed a simplified method to evaluate detention storage volumes from small catchments. Detention storage volume (S_p ; m³) can be calculated with Eq 7.9.

$$S_p = V_{in} \times \left[\left(1 - \frac{Q_{Op}}{Q_{Ip}} \right)^2 + \frac{T_c}{T_c + T_r} \left(\frac{Q_{Op}}{Q_{Ip}} \right)^2 \right] \quad (7.9)$$

where V_{in} is the runoff volume to be controlled estimated by the STREAM model; Q_{Op} is the outflow peak discharge (m³ h⁻¹); Q_{Ip} is the inflow peak discharge (m³ h⁻¹); T_r is the total runoff duration (h); T_c is the time of concentration of the catchment (h).

Based on runoff monitoring in the Heulen Gracht catchment (Chapter 6), total runoff duration (T_r) can be estimated with Eq. 7.10.

$$T_r = 4 \times T_c \quad (7.10)$$

The relative storage volume (S_p^*) can also be calculated for the design storm (Eq. 7.11).

$$S_p^* = \frac{S_p}{V_{in}} \quad (7.11)$$

A detention pond can also be designed using the 'rainstorms method' ('*méthode des pluies*') proposed by the French administration (Instruction Technique, 1977). It calculates the storage volume as the largest difference between the runoff inflow curve ² and the runoff outflow line, runoff being evacuated from the pond at a constant rate.

Topographic surveys were carried out to determine the volume-depth curves of the detention ponds at both study sites. Water temporarily stored in the detention ponds drains through a pipe at the bottom of the dams (Table 7.2). Water levels are converted to outflow discharges using Eq. 7.12 (Ilaco, 1985, Table 7.2):

$$Q = mc\sqrt{2gh} \quad (7.12)$$

where Q is the discharge (m³ s⁻¹); m is the discharge coefficient (0.62); c is the cross-section of the drain (m²); g is the gravity acceleration (9.81 m s⁻²) and h is the hydraulic head (m).

²The runoff inflow curve is calculated as the polynomial trend curve fitting runoff volume calculations at several times (e.g. $T = 0$; T_c ; T_r).

Table 7.2: Characteristics of the dams in the two study sites. Location of the dams is given in section 1.2.2 (Fig. 1.3 and 1.4).

Dam	Characteristics		
	Height (m)	Capacity (m ³)	Q_{Op} (m ³ s ⁻¹) ^a
Velm 1	2.1	3500	0.45
Velm 2	2.2	3500	0.45
Velm 3	0.95	2000	0.45
Gelinden 1	1.6	2050	0.2
Gelinden 2	1.2	730	0.2
Gelinden 3	0.6	730	0.11

^a Discharge calculated with Eq. 7.12.

7.3 Results

7.3.1 Potential of conservation tillage to reduce runoff in the Heulen Gracht catchment

STREAM simulates a drastic reduction (80%) of runoff volume when conservation tillage is carried out on one third of the total catchment surface (Table 7.3). Runoff reduction when using conservation tillage on 10% of the catchment fields varies between 25 and 34%, depending on the spatial distribution of the fields within the catchment. The highest runoff reduction is observed when conservation tillage is applied to the fields located the farthest from the outlet.

Table 7.3: Impact of conservation tillage (CT) on total runoff volume for the worst-case scenario in the Heulen Gracht catchment.

Area of fields under CT (ha)	Location in the catchment	Runoff volume (m ³)	Difference (%)
0	n/a	26,981	Reference
33	Random	18,602	- 31
33	Close to the outlet	20,049	- 26
33	In the middle part	20,114	- 25
33	Far from the outlet	17,901	- 34
66	Random	11,232	- 58
100	Random	4726	- 82

n/a: not applicable.

7.3.2 Evaluation of measures to control runoff in the gauged Heulen Gracht catchment

The GWW is well located in the area of runoff concentration, which is confirmed by high values of the topographic index ($16.1 < I < 16.7$; Table 7.4). Given the limited bankfull discharge of the downstream river, peak outflow discharge from the catchment should not exceed $0.5 \text{ m}^3 \text{ s}^{-1}$. Since we want to maintain a safe runoff velocity in the channel (2 m s^{-1}) and a shallow flow depth (max. 0.1 m), the GWW must be at least 4.5 m-wide (Eq. 7.7 and 7.8), which is already the case. However, runoff arrives as concentrated flow in the GWW (peak discharge of $1.5 \text{ m}^3 \text{ s}^{-1}$ on June 11, 2007). Detention ponds are therefore needed to buffer runoff temporarily and limit outflow discharge. Buffer capacity of the three detention ponds proved to be sufficient during the extreme storm of June 11, 2007 (e.g. for upstream dam; Fig. 7.2).

Peak outflow discharge from the dams varied between 0.4 and $0.45 \text{ m}^3 \text{ s}^{-1}$ (Fig. 7.1). The first dam had the highest impact, whereas it was more limited for the other two dams. However, they did increase the lag time (Fig. 7.1).

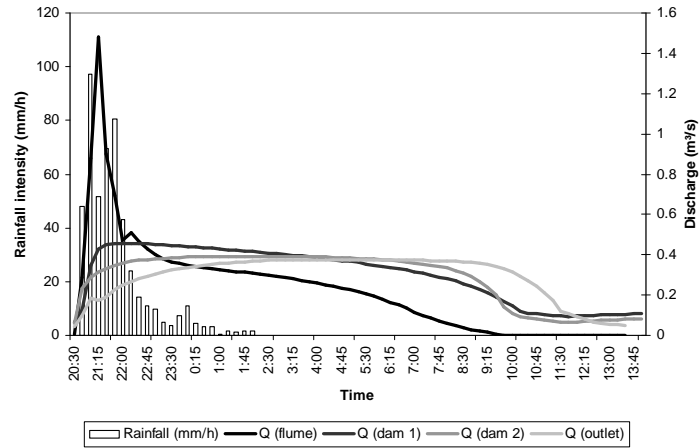


Figure 7.1: Inflow discharge (in the flume just upslope of the GWW) and measured outflow discharge from the three successive dams for the event of June 11 2007 in the Heulen Gracht catchment.

A reduction of the pipe diameter could therefore be envisaged. However, an enlargement of the dams should then be carried out to prevent overflow. A planning permission is needed to built such dams and the local authorities will not deliver it if the height of the dams exceeds 1.5 m or 2 m, which is already the current height of the dams.

Consequently, it is very likely that the buffer capacity of the ponds will be exceeded if a more intense storm occurs in the future.

Table 7.4: Evaluation of runoff control measures in the two study sites. Characteristics for the three dams of the Heulen Gracht catchment are similar.

Characteristics	Catchment			
	Heulen Gracht	Gelinden 1	Gelinden 2	Gelinden 3
(a) GWW				
T index	16.1 - 16.7	18 - 18.3	18.1 - 18.6	n/a
C (m^2)	0.25	0.15	0.15	n/a
w (m)	4.5	3	3	n/a
(b) Detention ponds				
T_c (h)	3	1.6	1.1	1.2
T_r (h)	12	5.4	4.4	4.8
Q_{IP} ($m^3 s^{-1}$)	1.5	1.4	0.3	0.8
Q_{OP} ($m^3 s^{-1}$)	0.45	0.2	0.2	0.11
S_p (m^3)	21,620	8,480	1525	1340
S_p^* (%)	94	73	20	74

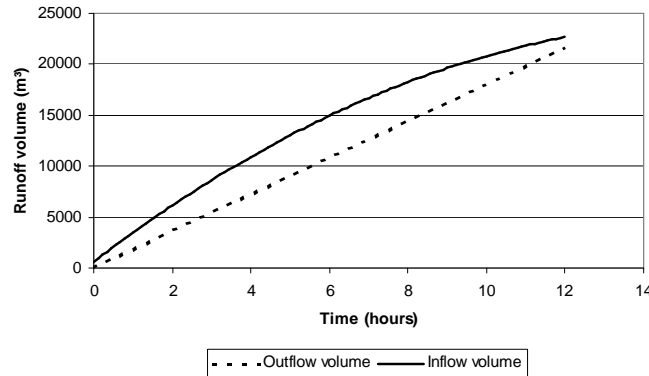


Figure 7.2: Cumulative runoff inflow and outflow volume in the upstream detention pond of the Heulen Gracht catchment for the worst-case scenario. Runoff volume to store is defined as the largest difference between the inflow and outflow curves.

7.3.3 Evaluation of measures to control runoff in the ungauged Gelinden catchment

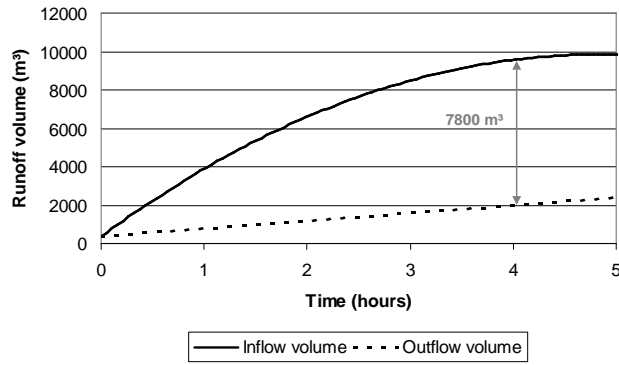
STREAM provides total runoff volume for the simulated worst-case scenario (Table 7.5). As expected during an intense storm, GBS generate between 0.4 and 19% more runoff than would be generated without grass, proportionally to their surface.

Table 7.5: Impact of grass buffer strips (GBS) on total runoff volume for the worst-case scenario in Gelinden catchment.

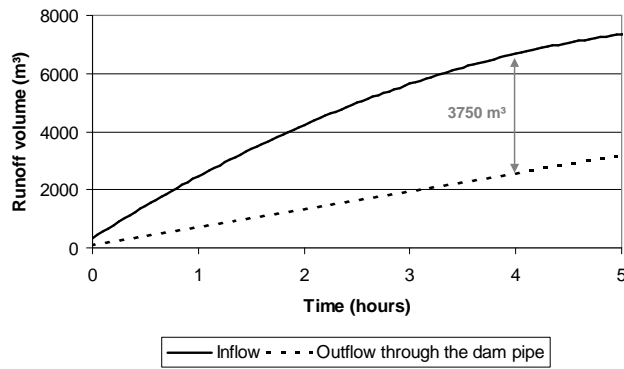
Catchment	Runoff volume		Difference (%)
	without GBS (m ³)	with GBS (m ³)	
Gelinden (dam 1)	10,570	12,610	+ 19
Gelinden (dam 2)	7,368	7,625	+ 3.5
Gelinden (dam 3)	1,794	1,801	+ 0.4

The Steernboornbeek river can evacuate a maximum peak discharge of $0.5 \text{ m}^3 \text{ s}^{-1}$. The two GWWs in the catchment are wide enough (30 m) to convey runoff up to the detention pond with a safe velocity (max. 2 m s^{-1}). However, peak discharges reconstructed for the worst-case scenario are much higher (0.8 to $1.4 \text{ m}^3 \text{ s}^{-1}$) than $0.5 \text{ m}^3 \text{ s}^{-1}$ (except for dam 2; Table 7.4) and detention ponds are therefore needed. Buffer capacity of the ponds for the worst-case scenario will be exceeded for dams 1 and 2 and an important overflow will occur as shown by the fact that the inflow and outflow curves do not converge within each other over a reasonable period of time (Fig. 7.3a-b; Table 7.4). However, it is sufficient for dam 3 (Fig. 7.3c; Table 7.4). The capacity of the smaller ponds located upslope

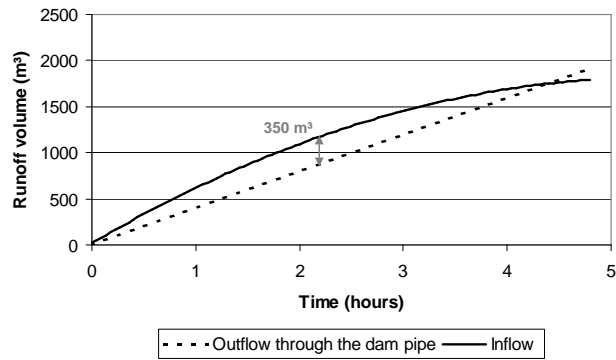
(630 m³ in total; section 1.2.2.2, Fig. 1.4) is not sufficient to compensate this lack of buffer capacity.



(a) Dam 1



(b) Dam 2



(c) Dam 3

Figure 7.3: Cumulative runoff inflow and outflow volume from dams 1 (a), 2 (b) and (3) of Gelinden study site for the worst-case scenario. Runoff volume to store is defined as the largest difference between the inflow and outflow curves.

7.4 Discussion

7.4.1 Conservation tillage

The largest reduction of runoff at the catchment scale (80%) has been simulated for the application of conservation tillage to fields located the farthest from the outlet. A possible explanation is that runoff arrives less concentrated at the outlet in such situation given that it reinfilters in fields with a higher infiltration capacity when flowing up to the outlet.

Farmers' conversion to conservation tillage should be envisaged over the medium to long term. Adoption of new tillage practices appears to be related to practical and economic considerations, and proved to be more profitable after a considerable period of research and development (see e.g. Silburn et al., 2007).

7.4.2 Effectiveness of the measures and cost-efficiency

The measures installed in the Heulen Gracht catchment proved to serve their purpose for the considered worst-case scenario. However, the capacity of the dams to control runoff in the case of a more intense event is unlikely. Costs of the individual measures are summarised in Table 7.6.

Table 7.6: Costs of dams and GBS.

Type of measure	Cost	Remark
Earthen dam (catchment 10 -200 ha)	€32.50 m ⁻¹	€8,400 for overflow
Earthen dam (catchment > 200 ha)	€64.30 m ⁻¹	€20,500 for overflow
GBS	€0.13 m ⁻² yr ⁻¹	For sowing only
GWW	€0.16 m ⁻² yr ⁻¹	For sowing and reprofiling

The measures implemented in the Heulen Gracht catchment induced high costs (*ca.* €350,000). This amount is justified by the important damages caused routinely by muddy floods in the downstream village (e.g. *ca.* €250,000 for the single August 2002 flood in Velm).

Gelinden village, in contrast, would have been flooded again if the selected worst-case scenario occurred. An extension of the existing dams could usefully be envisaged. A widening of the drain pipes of dams 1 and 2 should also be carried out to increase the outflow which is currently rather low compared to the discharge that the Steernboornbeek river can evacuate. Buffer capacity of the upslope dams could also be increased.

It is impossible to protect a village against all potential floods at reasonable cost. It was for instance demonstrated in chapter 2 that very intense storms (i.e. more than 85 mm rainfall in one day) led to large-scale floods inducing huge damage costs (Fig. 2.9). In natural hazard management, several cost-benefit analyses must be carried out to evaluate the implementation of protection measures. However, these evaluations are only valid for a given safety level (Gamper et al., 2006). In Belgium, public authorities fund the implementation of control measures. This is justified by the fact that runoff and erosion harm the vital interests of society (Schuler et al., 2006). However, soil is a private good and according to the 'polluter pays' principle, certain economists propose to set up an 'environmental tax' paid by the farmers. Tax income would be used to compensate victims for the damage induced by muddy floods. However, farmers would have the opportunity to reduce their tax payment by implementing alternative practices reducing runoff and erosion (Spaeter et al., 2006).

7.4.3 Implementation of control measures in other flood prone areas

Consulting firms need simple and comprehensive models that require limited efforts and data input to compute runoff predictions. Two methods are mainly used to this end:

- the 'Rational method' designed by Mulvaney (1851) and Kuichling (1889) and its European equivalents (Lloyd-Davies, 1906; Caquot, 1941) which were improved by Chow et al. (1988);
- the USDA-SCS Curve Number method (USDA-SCS, 1973).

Even though these methods provide satisfactory results (i.e. for urban catchments; Hong et al., 2006; Crobeddu et al., 2007), the heterogeneity of runoff response in cropland and its seasonal variation (see Chapter 3) is hardly taken into account by these methods.

Besides these methods, numerous hydrological models have been developed (see e.g. Jetten and Favis-Mortlock, 2006, for a review of models). However, the ability of empirical models (e.g. Curve Number) to integrate the dominant processes at the catchment scale is uncertain (Imeson and Kirkby, 1996), whereas process-based models require numerous input data that are generally not available and difficult to measure (Takken et al., 1999).

A simple methodology is hence proposed to control muddy floods from small and medium size cultivated catchments based on the main findings of this thesis (Fig. 7.4). First, the STREAM model is used to evaluate runoff at the catchment outlet for a given scenario. We suggest to construct a scenario similar to the one described in section 7.2.1. Peak discharge can then be obtained based on the methodology proposed by the Soil Conservation Service (Eq. 7.2 and 7.3). We suggest to locate a GWW in thalweg areas with $I > 15$ (Eq. 7.5) to prevent gully erosion. The width of the GWW can be estimated using Eq. 7.7 and 7.8. Furthermore, a dam (or several dams) can also be built so that runoff can be conveyed downstream at safe velocity and discharge. This value of safe discharge should be determined based on the safe river discharge that can be evacuated downstream.

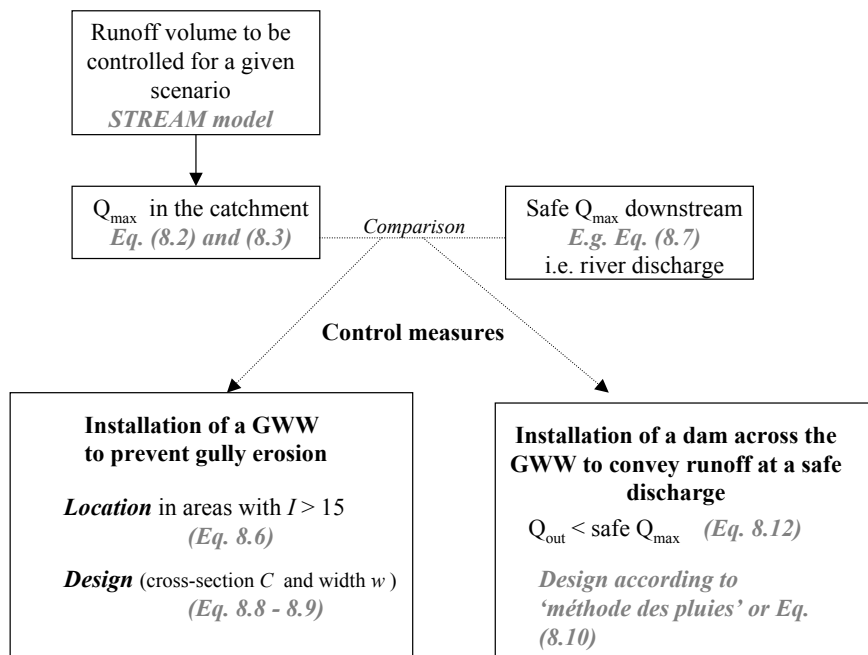


Figure 7.4: Proposed methodology to implement measures to control muddy floods from small and medium cultivated catchments. Q_{max} is the runoff peak discharge.

7.5 Conclusions

Muddy floods are triggered when large quantities of runoff are produced on cultivated land over a period of a few hours. A worst-case scenario (50 mm rainfall in one hour during the month of June, i.e. a heterogeneous pattern of winter cereals and spring crops) was constructed to evaluate the effectiveness of measures to control muddy floods from a gauged and an ungauged catchment. Scenarios simulated with the STREAM model show that the application of conservation tillage to one third of the catchment surface reduces runoff from the entire 300 ha-catchment by 80%. An alternative solution to prevent muddy floods consists in installing GWWs and detention ponds to buffer runoff temporarily within the catchment and evacuating runoff downstream at a safe discharge. The effectiveness of this combination of measures was demonstrated for the 300 ha-Heulen Gracht catchment. The village of Gelinden, in contrast, would be flooded again if the selected worst-case scenario occurred. An enlargement of the dams as well as the widening of the dam pipes could usefully be envisaged to prevent flooding. In the future, the application of conservation tillage and the installation of GWWs and detention ponds should be combined. It must nevertheless be underlined that protection against floods produced by very intense storms (e.g. more than 85 mm rainfall in one day) can probably not be achieved at reasonable cost.

Conclusions

Main findings of the thesis

The first part of the thesis aimed at defining the **conditions triggering muddy floods** in the Belgian loess belt. It was shown that muddy floods are not only widespread (79% of the municipalities were affected by at least one muddy flood over a 10 yr-period) but also very frequent (among the flooded municipalities, 22% were affected more than 10 times throughout a decade). On average, each municipality is confronted with 3.6 muddy floods each year. The connection between cultivated and inhabited areas is achieved by erosion features (i.e. rills and ephemeral gullies) in 36% of the cases, whereas roads and ditches ensure the connectivity in the remaining 64% of cases. Annual costs associated with their off-site impacts are estimated at €16-172 millions for the entire Belgian loess belt.

A topographic threshold was derived to predict the location in the landscape where muddy floods are likely to be triggered. For a given slope, there is a critical drainage area required to produce sufficient runoff for a muddy flood. Larger hydrological units such as (zero order) catchments intrinsically have the topographic characteristics allowing the triggering of a muddy flood. Catchment hence generate floods as soon as a rainfall threshold is reached. The storms required to produce a flood are on average smaller in May and June (25 mm) than between July and September (46 mm).

This difference is explained by the variability of soil surface characteristics that determine the runoff potential of cultivated soils (soil cover by crops and residues, soil surface crusting and roughness). These characteristics were documented for common crops in central Belgium. The steady state infiltration rates of the most commonly observed combinations of soil surface characteristics were determined in the field using a 0.5 m²-portable rainfall simulator. Overall, the steady state infiltration rates (mean of 25-52 mm h⁻¹) are rather high compared to the ones measured in other regions (e.g. 2-50 mm h⁻¹ in Normandy; Cerdan et al., 2002a). Runoff has also been observed on maize lines as well as on

wheel tracks, for which steady state infiltration rates are very low (mean of 3-6 mm h⁻¹). Even though the processes governing the temporal dynamics of soil hydraulic properties are rather complex as demonstrated by several laboratory experiments (see e.g. Fohrer et al., 1999), the cultivated soils in the Belgian loess belt can be characterised by a decrease in infiltration rate following tillage and sowing, which is mainly driven by surface crusting. The only exceptions to this rule were observed when cracks developed at the soil surface because of shrinkage as the result of the action of burrowing animals.

The literature generally reports that grass buffer strips and grassed waterways lead to runoff re-infiltration. In contrast, our study shows that grassed areas are characterised by a higher mean runoff coefficient (62-73%) than cultivated soils (13-58%). Runoff generation in orchards is very heterogeneous, runoff coefficients ranging from zero on tilled soil under the trees to 78% on wheel tracks. A classification of runoff risk applied to the common crops in central Belgium showed that February as well as the period from May to September were the most critical for runoff at the field scale. However, it appeared from monitoring a 16 ha-catchment that the highest runoff volumes and peak discharges were recorded between May and August during heavy storms, explaining why 85% of muddy floods in central Belgium occur during this period.

After an adaptation of its decision rules to the local conditions, the STREAM expert-based model (Cerdan et al., 2002a) provided good runoff/erosion predictions at the catchment scale. Field surveys were carried out according to the methodology developed by Le Bissonnais et al. (2005) to document the soil surface characteristics determining the runoff potential of cultivated soils. It was demonstrated that the translation into final infiltration rates is only valid for local conditions. A same combination of characteristics may indeed correspond to very different crops and development stages in the field, depending on the interaction of the local climate conditions and the crops grown in each region. STREAM only provides good runoff/erosion predictions for events dominated by processes of hortonian overland flow. In contrast, the model poorly predicts runoff/erosion in areas or during events dominated by saturation flow processes. The model is also much more efficient to predict runoff during intense summer rainfall than during low intensity events in winter. As shown in this thesis, expert-based models can perform satisfactorily if (i) a good concept lies behind the model rules (i.e. decrease in infiltration rate of cultivated soils after sowing/tillage, mainly driven by surface crusting processes) and (ii) if the rules are adapted to the local context (e.g. by assigning a measured final infiltration rate to the classes).

The second part of the thesis aimed at **evaluating the effectiveness of measures to control muddy floods**. To date, the most widespread control measures are grass buffer strips, grassed waterways and, in certain pilot areas as in the 200 km²-Melsterbeek catchment, earthen dams and detention ponds. A modelling case-study evaluating the runoff control potential of a grassed waterway and a dam at the outlet of a 300 ha-catchment showed that peak discharge was reduced by more than 40%. It was also demonstrated that land consolidation carried out in the 1970s led to an increase in peak discharge by 33% and in runoff volume by 19%. The major role played by a new consolidation road in the thalweg on runoff concentration was highlighted. Given the high values of peak discharge provided by the model, two additional dams across the GWW were installed by the local water board to increase protection of the downstream village.

The grassed waterway as well as three earthen dams served their purpose by preventing any muddy flood in the downstream village despite the occurrence of several extreme rainfall events (with a maximum return period of 150 years). Peak discharge (per ha) was reduced by 69% between the upstream and downstream extremities of the grassed waterway. However, reinfiltration of runoff in the waterway was mostly observed during low to moderate intensity storms. No (ephemeral) gully has formed in the catchment since the installation of the control measures, thereby reducing erosion to an interrill phenomenon. Specific sediment yield dropped from 3.5 t ha⁻¹ yr⁻¹ to a mean of 0.5 t ha⁻¹ yr⁻¹ after the installation of the control measures. Hence, sediment transfer from the cultivated dry valley to the alluvial plain should dramatically decrease. It was also underlined that these control measures are cost-efficient to protect flood prone areas. Even without widespread implementation of alternative farming practices, the measures are effective in controlling muddy floods. They offer, therefore, a solution that can be implemented in the short term to protect the most endangered villages against muddy floods.

A worst-case scenario consisting in the occurrence of a heavy storm in June when runoff potential of cropland is at its highest was simulated with STREAM to estimate the runoff volume to control from two dry valleys. According to these simulations, the application of conservation tillage on one-third of the cropland surface could potentially lead to an 80% decrease of runoff in the 300 ha-catchment. A methodology was provided to implement grassed waterways in such a way that they convey runoff at a non-erosive velocity, thereby preventing the formation of (ephemeral) gullies in dry valley bottoms. However, dams are necessary to temporarily buffer concentrated runoff in the thalweg. It was finally

reminded that protecting a village against floods produced by extreme storms (i.e. > 85 mm in one day) can probably not be achieved at reasonable cost.

General discussion

This thesis shows that a grassed waterway and earthen dams prevent ephemeral gully erosion in the thalweg of a 300 ha-dry cultivated valley and muddy floods in the downstream village. Sediment transfer to the alluvial plain would thereby be dramatically decreased. However, these results are mostly based on the monitoring of a single dry valley during the period 2002-2007. The question remains whether we can confidently extrapolate the results (i) to other dry valleys of the Belgian loess belt (ca. 9000 km²) and (ii) to longer time periods.

(i) The physical characteristics of the Belgian loess belt are rather homogeneous in terms of topography, soil texture, land cover, temperature and precipitation. A topographic threshold for muddy flood triggering was derived based on a database of ca. 300 zones affected by muddy floods throughout the Belgian loess belt. Erosion rate before the installation of control measures derived from our detailed catchment monitoring (8.3 t ha⁻¹ in 2002) is consistent with the range of annual erosion rates measured in central Belgium (6.5 - 12.3 t ha⁻¹ yr⁻¹; Verstraeten et al., 2006). However, the proposed control measures will only be effective in areas where erosion features connect cultivated and inhabited sites. Still this connection was achieved by ditch and road networks in 64% of the areas affected by muddy floods that we studied in detail in Chapter 2. The control measures that we monitored are hence not applicable in these latter situations and more classical engineering approaches (e.g. construction of traditional retention ponds in concrete) are still needed to protect the endangered areas against muddy floods.

(ii) Boardman and Favis-Mortlock (1999) state that if we monitor the moderate to large storms over long periods of time, we are likely to be able to account for most erosion in the study area. We collected numerous runoff and erosion data (2002-2007). They cover a wide range of rainfall return periods (0-200 yrs), which is rather surprising over such a short period of time (6 yrs)³. This finding was also reported by other researchers in central Belgium during the last decade (e.g. Vandaele, 1997; Takken et al., 1999; Steegen, 2001). This

³Return periods are only another way to express the probability (p) of occurrence of a storm at a given time. It does not refer to a periodicity. A 1000 yrs-storm has for instance a $p=0.001$ to occur during a given year (Hubert, 2005).

observation outlines the question of the relevance of the rainfall return periods we use. Indeed, this concept is only valid if these periods are computed based on rainfall data characterised by stationarity throughout time.

Main recommendations for policy

Muddy floods are a hillslope process occurring in dry valleys planted with crops showing a high runoff risk during heavy storms. Their occurrence will therefore be highly influenced by land use, land cover and climate changes that may occur in the future. In a global context of increasing demand for food products and bioenergy crops, distribution of the different crops within the landscape will considerably affect the runoff risk of cultivated land and, thereby, the risk of muddy flood.

The best solution consists in preventing runoff/erosion generation directly at the source. This could for instance be achieved by stimulating the widespread application of conservation tillage. Moreover, hydrological transfers need to be taken into account when designing land consolidation schemes. The construction of new buildings in areas affected by runoff from cropland should also be avoided. Approaches like the Water Ordinance ('*Watertoets*') in the Flemish Region of Belgium should be systematically applied before granting planning permission.

Given that the frequency of heavy storms is very likely to increase in future because of climate change, additional control measures must be implemented to protect the flood prone areas. Largest problems are caused by heavy storms (typically > 40 mm in a few hours). To date, the most widespread measures are grass buffer strips and grassed waterways. Designing a grass buffer strip depends on the objective pursued. The width of grass strips is typically designed to trap a given proportion of eroded sediments during a storm having a low return period. Given their limited steady infiltration rate (mean of 23 mm h⁻¹), grass buffer strips lead to the generation of additional runoff during heavy storms. It is hence important to convey runoff at a non-erosive velocity up to the outlet in order to prevent the formation of (ephemeral) gullies in dry valley bottoms. Earthen dams and detention ponds across a GWW can serve this purpose. The storms used to dimension these measures must have a high return period. Flood control schemes should be implemented at the scale of small and medium catchments. A 'catchment authority' is needed to coordinate these actions. A compromise has to be found between the municipal (*ca.* 10-50 km²) and the regional (*ca.* 4,000 - 10,000 km²) scales. Catchment agencies (100-1,000 km²)

should be set up for groupings of municipalities. These agencies would provide technical assistance to equip the flood prone areas and ensure the maintenance of the implemented control measures.

Perspectives for future research

An annual estimate of the costs associated with the off-site impacts of runoff and erosion was provided for central Belgium. Compared to this estimate and given the effectiveness of the monitored control measures to prevent muddy floods, the cost-efficiency of these measures was demonstrated in this thesis. However, an estimation of the costs associated with the on-site impacts of erosion (e.g. production loss over the long term, gulying, yield losses) is still lacking. This estimate would probably contribute to raise farmers' consciousness about the necessity to control erosion in their fields.

We have also mentioned on several occasions throughout this thesis that the application of conservation tillage should be further stimulated among the farmers to control runoff and erosion directly at the source. The potential of conservation tillage techniques to reduce runoff and erosion in the Belgian loess belt was demonstrated by Leys et al. (2007). They conducted rainfall simulations on numerous 0.7 m²-plots and observed an 88%- mean reduction of interrill erosion on the fields where conservation tillage was applied. They showed that conservation tillage reduced runoff with a mean of 63% but that the variability between plots was high. Runoff response is indeed mainly controlled by the soil surface characteristics such as the soil cover by crops and residues and the development of a surface crust. Conservation tillage techniques induce significant changes to these characteristics and, under certain circumstances (e.g. absence of crop residues during the first years of direct drilling application), runoff generation may be higher under conservation than under conventional tillage. Consequently, future research projects should investigate the runoff transfer issue at the field and catchment scales, monitoring several plots covering a wide range of tillage techniques, from conventional mouldboard ploughing to direct drilling. These investigations at the catchment scale are needed since the results obtained on 0.7 m²-plots can probably not be extrapolated to the field scale. The potential of conservation tillage techniques to reduce runoff generation at the field- and catchment- scales remains to be proven.

This thesis also demonstrated that evacuating runoff peak flow from a cultivated catchment at a safe discharge is crucial to prevent muddy floods. In the future,

the STREAM model could usefully be improved to simulate directly the impact of measures slowing down runoff up to the outlet. Such scenario analyses are typically demanded by policymakers who work at the river (sub-)basin scale in the framework of the EU Water Framework Directive. New approaches would also need to be tested to give accurate runoff/erosion estimates at that scale.

Finally, this thesis showed that the combined implementation of a grassed waterway and earthen dams in the thalweg of a dry valley reduced drastically sediment transfers from cultivated land to the river valleys. The impact of a widespread implementation of similar measures on the transfer of sediments and associated substances from cultivated land to the river valleys should therefore be investigated at the river basin or even the continental scale.

Les inondations boueuses dans la région limoneuse belge: Problèmes et solutions

Résumé

Introduction

L'érosion des sols et le ruissellement représentent l'une des principales menaces liées à l'agriculture en Europe. Ces phénomènes conduisent, entre autres, à des inondations boueuses. Celles-ci consistent en des écoulements d'eau provenant des terres agricoles et transportant des quantités importantes de sédiments érodés. L'objectif principal de cette thèse est de caractériser la variation spatiale et temporelle des inondations boueuses dans la région limoneuse belge, de préciser leurs conditions de déclenchement et d'évaluer l'efficacité de mesures de lutte contre ces inondations. L'accent est mis sur les mesures mises en place à l'échelle de bassins versants cultivés de taille moyenne (30-300 ha). Cette thèse consiste en une compilation d'articles scientifiques révisés par des pairs, soumis ou acceptés dans des revues internationales.

Zone d'étude

Les recherches sont réalisées dans la région limoneuse belge (8867 km²) qui consiste en un plateau ondulé largement cultivé au centre du pays (Fig. 1.1). Les principaux sites d'étude sont la parcelle expérimentale de Corbais (6 ha), le micro bassin-versant de Walhain (16 ha; 5 parcelles) ainsi que deux bassins versants situés dans le bassin hydrographique du Melsterbeek (200 km²). Ces deux bassins versants (Heulen Gracht, 300 ha, Fig. 1.3; Gelinden, 200 ha, Fig. 1.4) ont été équipés de mesures de lutte contre l'érosion et les inondations boueuses dans le cadre de projets pilotes.

Variation spatiale et temporelle des inondations boueuses

79% des communes du centre de la Belgique ont été touchées par au moins une inondation boueuse au cours d'une période de dix ans (1991-2000 en Wallonie; 1995-2004 en Flandre). Parmi les communes inondées, 22% l'ont été plus de 10 fois. Vingt communes ont été sélectionnées pour une analyse plus détaillée. Une base de données reprenant 367 sites touchés par des inondations boueuses a été compilée, et la connectivité entre les zones cultivées et les zones habitées a pu être évaluée pour 100 sites. Les routes (notamment les routes construites dans le cadre des opérations de remembrement) et le réseau de drainage (des fossés par exemple) facilitent le transfert du ruissellement entre les zones cultivées et habitées dans 64% des cas. Trois types de surfaces générant des inondations boueuses ont été identifiées: (i) les versants (1-30 ha) sans thalweg, où le ruissellement est généralement diffus; (ii) les petits bassins versants (10-300 ha) caractérisés par une concentration du ruissellement dans le thalweg et (iii) les bassins versants moyens (100-300 ha) où plusieurs vallées sèches concentrent le ruissellement. Environ 90% des inondations boueuses sont générées sur les versants et dans les petits bassins versants. Un seuil topographique critique pour le déclenchement des inondations a été calculé pour la relation entre la surface et la pente des versants et des bassins-versants. Il ressort d'une analyse statistique que les inondations boueuses sont générées dans les bassins versants avec 99% de probabilité après 43 mm de pluie (en un jour). Les quantités de précipitations requises pour déclencher les inondations boueuses sont plus faibles en mai et en juin (25 ± 12 mm) qu'entre juillet et septembre (46 ± 20 mm). Cette différence s'explique par des conditions de surface différentes des sols (stade d'encroûtement, rugosité du sol et couvert par les cultures). Chaque année, les inondations boueuses affectent 738 sites du centre de la Belgique. Les dégâts causés aux infrastructures et aux habitations peuvent atteindre entre 16 et 172 millions d'€ chaque année. Des données disponibles pour les dernières décennies suggèrent une recrudescence du phénomène depuis le début des années 1990. Plusieurs raisons peuvent expliquer la fréquence accrue des inondations: le remembrement des terres agricoles, l'expansion des zones d'habitat et l'expansion des cultures sarclées, semées au printemps, au détriment des céréales d'hiver. Les coûts énormes engendrés par les inondations boueuses justifient l'installation rapide de mesures permettant de lutter contre celles-ci.

Evolution saisonnière de la génération de ruissellement sur les terres agricoles et implications pour le déclenchement des inondations boueuses

Les inondations boueuses sont déclenchées lorsque d'importantes quantités de ruissellement sont générées sur des terres agricoles où elles causent une érosion importante. Trois caractéristiques de surface des sols sont pertinentes pour déterminer le potentiel de ruissellement des sols cultivés: (1) la couverture du sol par les cultures et leurs résidus; (2) la formation d'une croûte de battance à la surface du sol et (3) la rugosité de surface des sols. Ces caractéristiques ont été observées sur 65 parcelles tout au long de l'année 2005. Un orage intense représentatif des événements déclenchant les inondations boueuses dans le centre de la Belgique (60 mm h^{-1} pendant 30 minutes) a été simulé en utilisant un simulateur portable couvrant une surface de 0.5 m^2 sur des parcelles présentant les 17 combinaisons de caractéristiques de surface les plus fréquemment observées dans le centre de la Belgique.

Aucun ruissellement n'a été observé dans le cas de sols nus non encroûtés (labourés ou non), ni dans le cas de sols couverts par les cultures et présentant une croûte de transition et une rugosité de surface modérée (1-2 cm). Dans les cas où du ruissellement a été observé, les coefficients de ruissellement moyens (à savoir le rapport entre le volume de ruissellement et le volume de pluie) oscillaient entre 13% (blé en juillet) et 58% (betteraves ou maïs en mai et en juin). Les bandes enherbées et chenaux enherbés présentent un coefficient de ruissellement moyen plus élevé (62 et 73% respectivement) que les sols cultivés (13-58%). De plus, il a pu être démontré que les mesures sur des micro-placettes (0.5 m^2 dans ce cas) peuvent être utilisées pour estimer la génération de ruissellement à l'échelle de toute une parcelle. Une méthode de classification du risque de génération de ruissellement basée sur les relevés des caractéristiques de surface du sol a été appliquée aux cultures les plus fréquemment observées dans le centre de la Belgique. Il en ressort que le mois de février ainsi que la période de mai à septembre sont les plus critiques pour la génération de ruissellement à l'échelle parcellaire. Cependant, le suivi du micro bassin-versant de Walhain (16 ha) montre que les volumes de ruissellement et les débits de pointe les plus élevés sont généralement observés entre mai et août durant des orages intenses, ce qui explique pourquoi 85% des inondations boueuses sont enregistrées au cours de cette période dans le centre de la Belgique.

Fiabilité des modèles experts de ruissellement et d'érosion: Application de 'STREAM' dans différents environnements

Au cours des dernières décennies, la ceinture loessique européenne a connu une hausse significative des problèmes environnementaux résultant de l'érosion des sols cultivés. Face à ce constat, la demande de solutions se fait de plus en plus pressante. A cette fin, les modèles d'érosion et de ruissellement distribués spatialement et s'appliquant à l'échelle du bassin versant permettent d'évaluer l'impact de différentes mesures de lutte et/ou de différents scénarios. Les modèles de type expert fournissent de bons résultats mais leurs règles de décision ne sont valides que dans les conditions locales pour lesquelles elles ont été dérivées. Le modèle STREAM, conçu en Normandie (France), a dès lors été appliqué (1) dans deux bassins versants belges présentant des caractéristiques pédologiques, climatiques et d'utilisation du sol similaires à celles observées en Normandie ainsi que (2) dans un bassin versant du sud de la France présentant des caractéristiques pédologiques, climatiques et d'utilisation du sol différentes. Sans adaptation des règles de décision du modèle, les résultats obtenus pour les bassins versants belges sont peu satisfaisants. Après une telle adaptation, les prédictions du modèle sont fortement améliorées, tant en ce qui concerne l'érosion que le ruissellement. Dans le cas du bassin versant du sud de la France, les règles ont été adaptées dès le départ au vu des différences environnementales avec la Normandie. Cependant, les résultats se sont révélés peu satisfaisants, à cause de l'importance du phénomène de remontée de nappe dans ce bassin complexe dont STREAM ne peut tenir compte. En conclusion, STREAM est un modèle fiable permettant de simuler le ruissellement et l'érosion ainsi que leur distribution spatiale de manière très satisfaisante dans les environnements où le processus de ruissellement hortonien est dominant. Une adaptation préalable des règles de décision du modèle est néanmoins nécessaire, à partir de bases de données locales (placette, parcelle, bassin versant).

Efficacité d'un chenal enherbé pour lutter contre les inondations boueuses: Etude de cas

Les inondations boueuses posent particulièrement problème dans le village de Velm (commune de Saint-Trond, province du Limbourg) où un cours d'eau permanent traverse le village par le biais d'un pertuis. Celui-ci a été dimensionné à partir du débit de plein bord de la rivière, mais sans tenir compte du ruissellement provenant de sept vallées sèches situées en amont du village. L'étude de cas se focalise sur l'une de ces vallées sèches (Heulen Gracht, 300 ha). Le 'Mod-

èle *Hydrologique Maillé*' (MHM) est utilisé pour évaluer l'impact de plusieurs scénarios sur la génération du ruissellement. Ces scénarios peuvent être résumés comme suit: (i) implantation de mesures de lutte contre les inondations, (ii) variation saisonnière de la couverture du sol par les cultures et (iii) changements apportés au parcellaire et au réseau routier suite au remembrement. La distribution spatiale de la couverture du sol a été cartographiée à intervalles réguliers tout au long de l'année 2003. La situation hivernale présentait un potentiel de génération de ruissellement particulièrement élevé et a de ce fait été sélectionnée comme 'scénario du pire'. Les mesures de lutte mises en place après l'orage exceptionnel d'août 2002 (à savoir un chenal enherbé de 12 ha ainsi qu'une digue de rétention à l'exutoire du bassin versant) réduisent le risque d'inondation dans le village de Velm. Le modèle MHM simule une réduction du débit de pointe et du volume de ruissellement de plus de 40%. Dans le cas du scénario simulé, la digue de rétention permettrait de retenir temporairement la totalité du ruissellement. Enfin, le modèle MHM montre que le remembrement réalisé dans les années 1970 a conduit à une augmentation du débit de pointe de 33% et à une augmentation du volume de ruissellement de 19%. L'influence d'une nouvelle route construite dans le thalweg en tant qu'axe privilégié de concentration du ruissellement est particulièrement mise en évidence. Afin de limiter davantage l'apport de ruissellement et de sédiments provenant de cette vallée sèche, deux digues supplémentaires ont été installées dans le thalweg.

Suivi systématique d'un chenal enherbé et de digues en terre visant à lutter contre les inondations boueuses provenant d'un bassin versant cultivé

Les inondations boueuses sont principalement générées dans des vallées sèches. De nos jours, elles sont considérées comme l'un des processus permettant le transfert des sédiments accumulés au niveau des versants cultivés vers les plaines alluviales. Les coûts énormes induits par les inondations boueuses justifient l'installation urgente de mesures de lutte. Dans le cadre du décret 'érosion' de la Région Flamande de Belgique, un chenal enherbé de 12 ha de même que trois digues en terre ont été installées entre 2002 et 2004 dans le thalweg d'une vallée sèche cultivée de 300 ha. Ces mesures ont permis d'éviter que des inondations boueuses ne se produisent à nouveau dans le village de Velm, en dépit de l'occurrence de plusieurs orages extrêmes (ayant une période de retour allant jusqu'à 150 ans). Le bassin versant a fait l'objet d'un suivi intensif entre 2005 et 2007 au cours duquel 39 événements de ruissellement ont été enregistrés. Le débit de pointe (par ha) a été réduit de 69% entre les extrémités

amont et aval du chenal. De plus, le ruissellement a été retenu entre 5 et 12 heures derrière les digues, augmentant de ce fait de 75% le délai de transfert du débit de pointe jusqu'à l'exutoire. Le ruissellement s'est également partiellement réinfiltré dans le chenal, le coefficient de ruissellement moyen diminuant de 50% entre l'amont et l'aval du chenal. Le débit des sédiments a enfin été réduit de 93% de part et d'autre de ce même chenal. Avant l'installation des mesures de lutte, la production spécifique de sédiments (PSS) du bassin versant atteignait $3.5 \text{ t ha}^{-1} \text{ an}^{-1}$ et une ravine éphémère se formait chaque année dans le thalweg. Depuis leur installation, plus aucune ravine ne s'est formée et la PSS du bassin a fortement diminué et n'atteint désormais plus que $0.5 \text{ t ha}^{-1} \text{ an}^{-1}$. Le transfert de sédiments de la vallée sèche vers la plaine alluviale devrait dès lors diminuer considérablement. Le coût total des mesures installées pour une période de 20 ans est faible (126 € ha^{-1}) si on le compare au coût moyen des dégâts engendrés par les inondations boueuses dans la zone d'étude ($54 \text{ € ha}^{-1} \text{ an}^{-1}$). Des mesures similaires pourraient dès lors être implantées pour protéger d'autres villages fréquemment inondés de la région limoneuse belge.

Dimensionnement des mesures de lutte contre les inondations boueuses dans les bassins versants cultivés

Des méthodes simples sont nécessaires pour dimensionner les mesures de lutte contre les inondations boueuses. Le modèle STREAM validé pour la région limoneuse belge est utilisé pour évaluer le volume de ruissellement produit dans deux bassins versants cultivés (Heulen Gracht, 300 ha et Gelinden, 200 ha) pour un scénario donné. Celui-ci consiste en un orage intense de juin (50 mm de pluie en une heure) et une occupation du sol hétérogène, présentant une alternance de céréales d'hiver et de cultures de printemps. Le modèle simule tout d'abord une réduction du volume de ruissellement de 80% lorsque les techniques de labour simplifié sont appliquées sur un tiers de la surface totale du bassin versant du Heulen Gracht. Ensuite, une méthodologie permettant de dimensionner les chenaux enherbés de telle sorte qu'ils puissent acheminer le ruissellement à une vitesse non-érosive (évitant de ce fait la formation d'une ravine éphémère) est proposée. L'installation de digues est nécessaire pour retenir temporairement le ruissellement lorsque l'écoulement arrive sous une forme concentrée dans le chenal. Il faut néanmoins souligner que la protection contre les inondations boueuses ne peut être assurée à un coût raisonnable que pour un niveau de sécurité donné.

Conclusion

Cette thèse a permis de caractériser la variation spatiale et temporelle des inondations boueuses dans la région limoneuse belge et d'en affiner les conditions de déclenchement. Elle a également permis de démontrer l'efficacité de mesures de lutte contre ces inondations implantées dans le cadre de projets pilotes.

En conséquence, plusieurs recommandations peuvent être formulées à l'attention des décideurs politiques. L'occurrence d'inondations boueuses à l'avenir sera fortement influencée par d'éventuels changements d'affectation des sols. La meilleure solution pour lutter contre ces inondations consiste dès lors à limiter le ruissellement et l'érosion à la source, en stimulant par exemple l'application des techniques de labour simplifié par les agriculteurs. Il s'agit également d'éviter l'implantation de nouvelles constructions dans des zones à risque. Cependant, étant donné la recrudescence prévue des pluies intenses à l'avenir à cause du changement climatique, des mesures 'palliatives' supplémentaires doivent être mises en place pour protéger les zones fréquemment inondées. Les bandes enherbées ne permettent d'assurer une telle protection que lors d'événements pluvieux d'intensité faible ou moyenne ($< 23 \text{ mm h}^{-1}$ en moyenne). Il convient dès lors d'installer des chenaux enherbés et des digues pour éviter la formation de ravines éphémères, piéger une part importante des sédiments érodés et retenir temporairement le ruissellement. Ces aménagements devront être dimensionnés en tenant compte de pluies de projet présentant des périodes de retour élevées. L'ensemble de ces mesures devront être gérées par des agences de bassin versant (100-1000 km²).

À l'avenir, la modélisation dynamique du ruissellement à l'échelle du bassin versant (100-300 ha) devrait être développée. De même, l'impact des mesures agri-environnementales sur le transfert du ruissellement, des sédiments et des substances associées devrait être évalué à l'échelle du bassin versant hydrographique (100-1000 km²).

Modderoverlast in de Belgische Leemstreek: Problemen en oplossingen

Samenvatting

Inleiding

Intense bodemerosie en overmatige waterafvoer vormen een belangrijke bedreiging voor de landbouw in Europa. Deze fenomenen leiden o.a. tot modderstromen die in de stroomafwaartse gebieden aanleiding kunnen geven tot water- en modderoverlast. Modderstromen zijn in feite grote hoeveelheden afstromend water, afkomstig van agrarische gebieden, en beladen met belangrijke hoeveelheden geërodeerd sediment. Het doel van deze thesis is de ruimtelijke en tijdelijke variabiliteit van de modderoverlast in de Belgische Leemstreek te karakteriseren, de kennis m.b.t. de oorzaken te verfijnen en de doeltreffendheid van bestrijdingsmaatregelen te evalueren. De nadruk ligt hierbij op de maatregelen die genomen worden op schaal van kleine stroomgebieden (30-300 ha). Deze thesis bestaat uit een bundeling van een aantal wetenschappelijke artikels die in internationale tijdschriften (met *peer-review*) werden ingediend/gepubliceerd.

Studiegebied

Het onderzoek wordt uitgevoerd in de Belgische Leemstreek, een golvend plateau in het midden van het land (Fig. 1.1). De belangrijkste studiegebieden zijn het experimentele perceel van Corbais (6 ha), het stroomgebiedje van Walhain (16 ha; 5 percelen) en twee grotere stroomgebieden die gelegen zijn in het deelbekken van de Melsterbeek (200 km²). In beide stroomgebieden (Heulen Gracht, 300 ha, Fig. 1.3; Gelinden, 200 ha, Fig. 1.4) werden in het kader van pilootprojecten bestrijdingsmaatregelen uitgevoerd om de bodemerosie en de daarmee gepaard gaande modderoverlast te beperken.

Ruimtelijke en temporele variabiliteit van modderoverlast

In een periode van 10 jaar (1991-2000 in Wallonië en 1995-2004 in Vlaanderen) werden 79% van de gemeenten in Midden-België tenminste één keer geconfronteerd met modderoverlast. 22% van de getroffen gemeenten werd in deze periode meer dan 10 keer geconfronteerd met modderoverlast. Twintig gemeenten werden geselecteerd voor een meer gedetailleerde studie. Deze studie leverde een databank op met 367 geteisterde zones. Voor 100 van deze zones kon de aanvoerroute van water en modder tussen het agrarische gebied en de woongebieden geïdentificeerd worden. In 64% van de gevallen fungeren wegen (o.a. ruilverkavelingswegen) en drainagenetwerken (zoals grachten en beken) als aanvoerroute. Drie types van oppervlakken die tot modderoverlast leiden kunnen geïdentificeerd worden: (i) hellingen (1-30 ha) zonder thalweg, met diffuse waterafvoer; (ii) kleine stroomgebiedjes (10-300 ha) met afvoerconcentratie in de thalweg en (iii) middelgrote stroomgebieden (100-300 ha) met meerdere droge valleien. Ongeveer 90% van de modderoverlast gebeurt stroomafwaarts van hellingen en stroomgebieden. Op basis van de relatie tussen oppervlakte van de helling enerzijds en de hellingsgraad anderzijds kan een kritische topografische drempel voor het optreden van modderoverlast worden opgesteld. Uit een statistische analyse blijkt dat modderoverlast in kleine en middelgrote gebieden, optreedt met een 99% probabiliteit na 43 mm neerslag op één dag. Neerslaghoeveelheden die aanleiding geven tot overlast zijn lager in mei en juni (25 ± 12 mm) dan in de periode juli-september (46 ± 20 mm). Dit kan verklaard worden door waargenomen verschillen in de toestand van het bodemoppervlak (zoals verslempingsgraad, ruwheid en gewasbedekking). Elk jaar worden 738 locaties in Midden-België geconfronteerd met modderoverlast. De schade aan woningen en infrastructuur kan worden begroot op 16 tot 172 miljoen €. Gegevens van de voorbije decennia suggereren een toename van het fenomeen vanaf het begin van de jaren negentig van de vorige eeuw. Er zijn verschillende redenen voor deze toename: de ruilverkavelingen van landbouwgebieden, de uitbreiding van de bebouwde zones en de toename van het areaal rijgewassen (tijdens de lente ingezaaid) ten nadele van wintergewassen.

Seizoens evolutie van waterafvoer in agrarische gebieden en gevolgen voor het optreden van modderoverlast

Modderoverlast treedt op als grote hoeveelheden water afstromen in agrarische gebieden en intense bodemerosie veroorzaken. Drie karakteristieken van de bodemtoplaag zijn relevant om het afvoerpotentieel van landbouwgronden te

bepalen : (1) de bodembedekking door het gewas of gewasresten; (2) de vorming van een verslempingskorst en (3) de ruwheid van het oppervlak. De evolutie van deze karakteristieken werd opgevolgd op 65 percelen tijdens het jaar 2005. Het afvoerpotentieel van de 17 meeste waargenomen combinaties van de hiervoor vermelde bodemkarakteristieken werd bepaald op het terrein aan de hand van regensimulaties (0.5 m²). Hierbij werd een hevige bui gesimuleerd die representatief is voor de buien die aanleiding geven tot modderoverlast in Midden-België. Geen oppervlakkig afstromend water wordt waargenomen in het geval van onbedekte bodems zonder verslempingskorst (geploegd of niet), noch in het geval van bodems bedekt met gewassen en die een onderbroken korst en een middelmatige ruwheid (1-2 cm) vertonen. Tijdens de andere experimenten schommelden de gemiddelde afvoercoëfficiënten (d.i. verhouding tussen hoeveelheid afstromend water en neerslag) tussen 13% (tarwe in juli) en 58% (suikerbieten en maïs in mei en juni). Grasbufferstroken en grasgangen vertonen een hogere gemiddelde afvoercoëfficiënt (62 en 73% respectievelijk) dan akkerpercelen (13-58%). Bovendien kan worden aangetoond dat metingen op microplots (d.i. 0.5 m²) kunnen gebruikt worden om het afvoerpotentieel op perceelsniveau in te schatten. Een classificatie van het afvoerrisico, gebaseerd op de monitoring van de bodemkarakteristieken, werd toegepast voor de belangrijkste akkerbouwgewassen in Midden-België. Februari en de periode tussen mei en september zijn het meest kritisch voor afvoerproductie op perceelsniveau. Toch blijkt uit de monitoring van het 16 ha groot-stroomgebiedje te Walhain dat de hoogste afvoervolumes en piekafvoeren worden waargenomen tussen mei en augustus, hoofdzakelijk tijdens hevige buien. Dit verklaart waarom 85% van de evenementen met modderoverlast in de Belgische Leemstreek, optreden tijdens deze periode.

Betrouwbaarheid van expert erosie/afvoer modellen: toepassing van 'STREAM' in verschillende gebieden

Tijdens de laatste jaren werd de Europese Leemstreek geconfronteerd met een significante toename van milieuproblemen gerelateerd aan bodemerosie in agrarische gebieden. De vraag naar concrete maatregelen is dan ook zeer groot. Ruimtelijke erosie/afvoer modellen die toepasbaar zijn op stroomgebiedsniveau, kunnen ons helpen om de impact van verschillende bestrijdingsmaatregelen en/of bestrijdingsscenario's in te schatten. Modellen gebaseerd op expertkennis, leveren goede resultaten maar gebruiken hoofdzakelijk beslissingsregels die alleen in lokale omstandigheden geldig zijn. Het STREAM model, oorspronkelijk ontworpen voor

condities in Normandië (Frankrijk) werd toegepast (i) op twee stroomgebieden van de Belgische leemstreek met gelijkaardige bodem-, klimaat- en bodemgebruikskennmerken als Normandië en (ii) op een stroomgebied in het zuiden van Frankrijk dat verschillende bodem-, klimaat- en bodemgebruikskarakteristieken vertoont. Zonder aanpassing van de oorspronkelijke beslissingsregels zijn de resultaten van het STREAM model voor de twee Belgische stroomgebieden weinig bevredigend. Indien de beslissingsregels worden aangepast, zijn de modelvoorspellingen m.b.t. erosie en afvoer wel beter. Wat het Franse stroomgebied betreft worden de regels onmiddellijk aangepast aangezien de hierboven vermelde verschillen met Normandië. Niettemin zijn de resultaten niet zo bevredigend als voor België. Dit kan verklaard worden door het feit dat STREAM geen rekening houdt met afstroming te wijten aan verzadiging van de bodemtoplaag (zgn. *saturation excess flow*). STREAM is dus een betrouwbaar ruimtelijk erosie/afvoer model in gebieden waar de afstroming ontstaat door *hortonian overland flow*. Niettemin is een voorafgaande aanpassing van de beslissingsregels van het model nodig, op basis van lokale gegevens (plot, veld, stroomgebied), noodzakelijk.

Doeltreffendheid van een grasgang in de bestrijding tegen modderoverlast: Case-study

Het dorp Velm (deelgemeente van Sint-Truiden in de provincie Limburg) wordt zeer frequent geconfronteerd met modderoverlast. Door het dorp stroomt een, deels ingebuisde, waterloop. De inbuizing werd gedimensioneerd op basis van het oevervol debiet van deze waterloop. Met de waterafvoer afkomstig uit zeven hoger gelegen droge valleien werd er daarentegen geen rekening gehouden. Deze case-study wordt uitgevoerd in een van deze valleien (Heulen Gracht, 300 ha). Het '*Meshed Hydrological Model*' (MHM) wordt gebruikt om de effecten van een aantal scenario's op de afvoerproductie in te schatten. Deze scenario's kunnen als volgt worden samengevat: (i) aanleg van erosiebestrijdingsmaatregelen, (ii) seizoenale variabiliteit van gewasbedekking en (iii) wijzigingen in perceelspatroon en wegennet door de ruilverkaveling. De ruimtelijke spreiding van de teelt en bedekkingsgraad werd in 2003 regelmatig in kaart gebracht. De 'wintertoestand' vertoont een vrij hoog afvoerpotentieel en is dus gekozen als '*worst-case scenario*'. Erosiebestrijdingsmaatregelen, (zoals een grasgang van 12 ha en een aarden dam aan de uitlaat van het stroomgebied), aangelegd na de overstroming van Velm tijdens een extreme bui in augustus 2002, verlagen het overstromingsrisico te Velm. Het MHM model voorspelt een afname van de piekafvoer en het afvoervolume uit de Heulen Gracht met meer dan 40%. In het *worst-case*

scenario zou het totale afvoervolume achter de dam kunnen gebufferd worden. De ruilverkaveling uitgevoerd in de jaren 1970 geeft aanleiding tot een toename van de piekafvoer en het afvoervolume met 33% en 19% respectievelijk. De nieuwe ruilverkavelingsweg in de thalweg speelt hierbij een belangrijke rol. Om de aanvoer van water en modder uit de Heulen Gracht tot een minimum te beperken, zijn er twee extra dammen aangelegd in de thalweg van het stroomgebied van de Heulen Gracht.

Het effect van een grasgang en aarden dammen systematisch gemeten

Modderoverlast treedt meestal stroomafwaarts van droge valleien op. Tegenwoordig worden modderstromen beschouwd als één van de belangrijkste aanvoerprocessen van sediment van agrarische gebieden naar de vallei. De enorme schade veroorzaakt door modderoverlast rechtvaardigt de dringende aanleg van bestrijdingsmaatregelen. In het kader van het erosiebesluit van het Vlaams Gewest werden tussen 2002 en 2004 in de thalweg van een droge vallei (300 ha) een grasgang van 12 ha en drie aarden dammen aangelegd. Deze maatregelen hebben verhinderd dat het dorp Velm nog geconfronteerd werd met modderoverlast, ondanks het optreden van verscheidene extreme buien met een herhalingsstijd tot 150 jaar. Tijdens een intensieve monitoring in het stroomgebied tussen 2005 en 2007, werden 39 afvoerevenementen geregistreerd. Het afvoerdebiet (per ha) stroomafwaarts van de grasgang is 69% lager dan het afvoerdebiet stroomopwaarts van de grasgang. Bovendien wordt de afvoer ongeveer 5 tot 12 uur lang gebufferd achter de dammen, wat leidt tot een toename van de '*lag time*' met 75%. Bovendien leiden de maatregelen tot een belangrijke reductie van de afvoercoëfficiënt (50%) en het sedimentdebiet (93%). Vóór de installatie van de maatregelen bedroeg de specifieke sedimentexport (SSE) van het stroomgebied van de Heulen Gracht $3.5 \text{ t ha}^{-1} \text{ jaar}^{-1}$ en vormde zich elk jaar een aanzienlijk tijdelijk ravijn in de thalweg van het stroomgebied. Sinds de aanleg van de maatregelen werd geen tijdelijk ravijn meer waargenomen en de SSE van het stroomgebied werd sterk gereduceerd en bereikt nu $0.5 \text{ t ha}^{-1} \text{ jaar}^{-1}$. Het sedimenttransport vanuit de droge vallei naar de riviervallei is hierbij aanzienlijk afgenomen. De totale kost van de ingrepen, aangelegd voor een periode van 20 jaar, is laag (126 € ha^{-1}) in vergelijking met de gemiddelde omvang van de schade veroorzaakt door modderoverlast in het studiegebied ($54 \text{ € ha}^{-1} \text{ jaar}^{-1}$). Gelijkaardige ingrepen kunnen ook in andere, vaak geteisterde, dorpen van de Belgische Leemstreek worden aangelegd.

Ontwerp van bestrijdingsmaatregelen in agrarische stroomgebieden

Eenvoudige methodes zijn nodig om bestrijdingsmaatregelen (o.a. grasgangen, aarden damconstructies) te ontwerpen. Om het afvoervolume voor een gegeven scenario in twee agrarische stroomgebieden (Heulen Gracht, 300 ha; Gelinden, 200 ha) in te schatten, werd gebruik gemaakt van het (aangepaste) STREAM model. Dit scenario bestaat uit een hevige bui (50 mm neerslag in één uur) in de maand juni en een heterogeen gewaspatroon (afwisseling van wintertarwe en zomergewassen). Het model voorspelt een belangrijke afname van het afvoervolume (80%) indien op 1/3 van de totale oppervlakte van het akkerareaal in het stroomgebied niet-kerende bodembewerking wordt toegepast. Vervolgens wordt hierop een methodologie voor het dimensioneren van de grasgangen ontworpen, zodat deze het waterafvoer met een niet erosieve snelheid (zonder vorming van tijdelijk ravijn) kunnen afvoeren. De aanleg van kleinschalige dammen is nodig om de geconcentreerde waterafvoer in de grasgangen tijdelijk te bufferen. Niettemin moeten we beseffen dat de uitgevoerde maatregelen slechts een oplossing bieden voor een gegeven veiligheidsniveau.

Besluit

Deze thesis brengt belangrijke inzichten in de ruimtelijke en tijdelijke variabiliteit van modderoverlast in de Belgische Leemstreek. De condities die aanleiding geven tot modderoverlast worden verfijnd en de doeltreffendheid van piloot bestrijdingsmaatregelen wordt aangetoond.

Bijgevolg kunnen enkele beleidsaanbevelingen worden geformuleerd. Modderoverlast is sterk afhankelijk van eventueel toekomstige wijzigingen in bodembedekking en bodemgebruik. De beste oplossing om modderoverlast te vermijden is het beperken van erosie en afstroming op de akkerpercelen zelf (brongerichte aanpak). Dit zou o.a. kunnen bereikt worden door het creëren van een bijkomende stimulans voor de toepassing van niet-kerende bodembewerking. Daarnaast moet de aanleg van nieuwe gebouwen in risicozones worden vermeden. Gelet op de voorspelde toename van de frequentie van hevige buien in de toekomst (o.i.v. klimaatsverandering), zijn bijkomende symptoomgerichte maatregelen noodzakelijk aangelegd om de meeste geteisterde dorpen afdoend te beschermen. Grasbufferstroken zorgen voor een bescherming tijdens neerslagevenementen met een lage of middelmatige intensiteit ($< 23 \text{ mm uur}^{-1}$). Grasgangen en aarden dammen moeten aangelegd worden om de vorming van

tijdelijke ravijnen te vermijden, een belangrijke hoeveelheid van de geërodeerde sedimenten op te vangen en het afstromend water tijdelijk te bufferen. Deze ingrepen moeten ontworpen worden op basis van neerslagevenementen met een hoge terugkeerperiode. Alle maatregelen zouden beheerd moeten worden door het waterschap (100-1000 km²).

In de toekomst zouden dynamische afvoer/erosie modellen op stroomgebiedsniveau (100-300 ha) ontwikkeld moeten worden. Bovendien zou de impact van de bestrijdingsmaatregelen op de afvoer- en sedimenttransport (en verbonden substanties) ingeschat worden op de schaal van deelbekkens (100-1000 km²).

Appendix: Agri-Environmental Measures in the Belgian loess belt

Farmers have to fulfil minimum environmental standards in order to receive their EU single payments. If the farmers want to go beyond those standards, they have the possibility to implement Agri-Environmental Measures (AEMs) during a five-year minimum period. They are hence paid by society for the environmental service they deliver. Agri-environmental schemes are flexible and implemented differently according to the state or region in Europe (European Commission, Directorate-General for Agriculture, 2005). Such flexibility enables the regions or states to meet certain local environmental needs.

In Wallonia, two AEMs contribute to runoff and erosion mitigation even if they were not designed to achieve this specific objective: (i) installation of Grass Buffer Strips (GBS) and (ii) sowing of cover crops during the intercropping period. Farmers' participation rate to these measures increased from 1998 to 2006 in the Walloon loess belt and reached 17% in 2006 (Fig. 7.5).

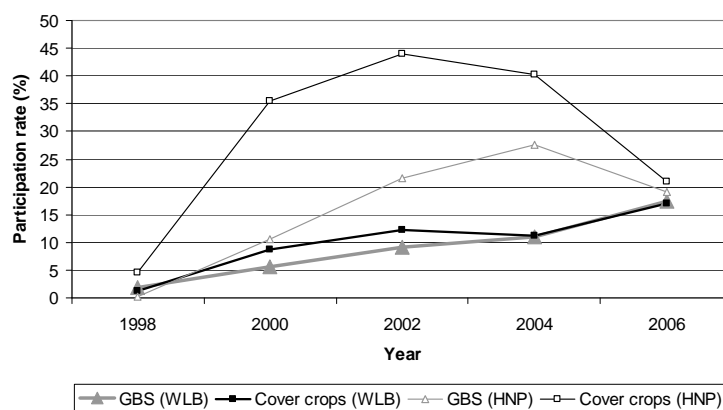


Figure 7.5: Evolution (1998-2006) of farmers' participation to two AEMs (GBS-Grass Buffer Strips; cover crops during the intercropping period) in the Walloon loess belt (WLB) and the 233 km²-Hillsland Natural Park (HNP), Belgium. Data available from MRW-DGA and GIREA-UCL (2006).

In the 233 km²-‘Hillsland natural park’⁴, agricultural advisers convinced farmers to install GBS where muddy floods have routinely damaged roads or houses. Consequently, in 2002, farmers’ participation rate to AEMs was much higher in the area covered by the park (27% for GBS; 40% for sowing a cover crop during the intercropping period) compared to the mean rates for the Walloon loess belt (12% for GBS and cover crops). The extension officers stopped their advice at the end of 2002 and the farmers’ participation rate in the area covered by the park subsequently decreased until it reached the mean participation level for the Walloon loess belt (Fig. 7.5). In Flanders, similar AEMs (management of field edges; sowing of cover crops) have been available to farmers since 1999. The increase in the area with cover crops occurred later than in Wallonia (Fig. 7.6). Cover crops have not been subsidised by the Flemish government since 2007,

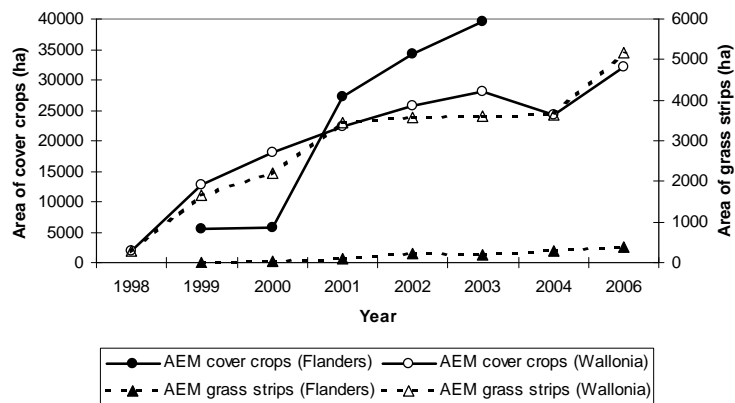


Figure 7.6: Evolution of AEM adoption between 1998 and 2006 in Belgium (Flemish data from the VLM; Walloon data from MRW-DGA and GIREA-UCL).

since it is considered that it should be part of standard good environmental practices. In contrast, the area of cover crops keeps increasing in Wallonia, after a slight decrease in 2004 due to important changes to the Walloon agri-environmental scheme. Since January 2005, a new AEM enables the Walloon farmers to install GBS with the specific objective of erosion mitigation for which they need an agreement designed by an expert. This new rule leads to an extra subsidy (€1250 ha⁻¹ instead of €900 ha⁻¹ for standard GBS). In Flanders, a package of five AEMs aiming at erosion control (dam and detention pond; direct drilling; grass buffer strips; grassed waterway; minimum tillage) has existed since

⁴In French: ‘Parc Naturel du Pays des Collines’. This park regroups the municipalities of Ath, Ellezelles, Flobecq, Frasnes-les-Anvaing and Mont-de-l’Enclus.

2005. Overall, AEMs for erosion mitigation are more widespread in Wallonia than in Flanders (Fig. 7.7). Several explanatory factors can be put forward. First, in Wallonia, extension officers visit the fields where erosion problems are observed and propose to the farmers the most suitable solution. Second, 'word of mouth' about AEMs is probably more efficient among the Walloon farmers, their number being smaller and their capacities to invest larger, because of the much greater farm size.

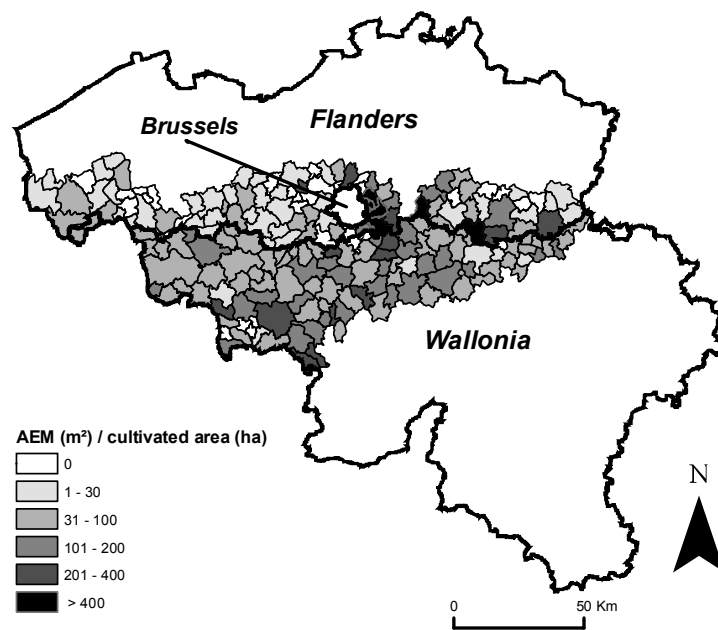


Figure 7.7: Area covered by specific AEMs for erosion mitigation by the end of 2006 in the municipalities of central Belgium (m^2 AEM per ha of cropland). Flemish data from the VLM; Walloon data from MRW-DGA and GIREA-UCL.

Bibliography

- ADALI Convention, 2002. Adaptation des Aménagements hydrauliques à la Lutte contre les Inondations.(In French)- Technical report.
- Andrieux, P., 2006. Etats de surface et infiltrabilité des sols en milieu méditerranéen cultivé. (In French). In: Proceedings of the 14th Conference of International Soil Conservation Organization. Marrakech, Morocco, May 14-19.
- Armand, R., Bockstaller, C., Auzet, A., 2007. Soil surface characteristics variability in conservation tillage context and identification of relevant processes for modelling. In: Proceedings of the COST 634 conference on 'Soil and hillslope management using scenario analysis and runoff-erosion models: a critical evaluation of current techniques'. Florence, Italy, May 7-9.
- Auerswald, K., 1991. Onsite und Offsite-Schäden durch Bodenerosion. (In German). Berichte über Landwirtschaft 205, 75–82.
- Auerswald, K., Albrecht, H., Kainz, M., Pfadenhauer, J., 2000. Principles of sustainable land-use systems developed and evaluated by the Munich Research Alliance on Agro-Ecosystems (FAM). Petermanns Geographische Mitteilungen 144 (2), 16–25.
- Aumann, F., Vandenghoer, C., 1989. Baron Surlet de Chokier, regent van België: Mens en Mythe (1769-1839). (In Dutch). Gemeentebestuur, Gingelom.
- Auzet, A., 1987. L'érosion des sols par l'eau dans les régions de grande culture: aspects agronomiques. (In French) - Technical report .
- Auzet, A., Boiffin, J., Ludwig, B., 1995. Concentrated flow erosion in cultivated catchments: influence of soil surface state. Earth Surface Processes & Landforms 20, 759–767.
- Auzet, A., Le Bissonnais, Y., Souchère, V., 2006. France. In: Boardman, J., Poesen, J. (Eds.), Soil erosion in Europe. Wiley, Chichester, pp. 369–383.

- Banse, D., 1935. *Histoires des rues de Fécamp*. (In French). Fécamp, Banse.
- Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Poesen, J., 2000. Characteristic of sediment deposits formed by intense rainfall events in small catchments in the Belgian loam belt. *Geomorphology* 32, 69–82.
- Beven, K., 2001a. Calibration, validation and equifinality in hydrological modelling: A continuing discussion. In: Anderson, M., Bates, P. (Eds.), *Model validation: Perspectives in Hydrological Science*. John Wiley, Chichester, pp. 43–55.
- Beven, K., 2001b. *Rainfall - Runoff modelling. The primer*. Wiley, Chichester.
- Beven, K., Kirkby, M., 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Science - Bulletin des Sciences Hydrologiques* 24, 43–69.
- Beven, K., Wood, E., 1983. Catchment geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology* 65, 139–158.
- Bielders, C., Ramelot, C., Persoons, E., 2003. Farmer perception of runoff and erosion and extent of flooding in the silt-loam belt of the Belgian Walloon Region. *Environmental Science & Policy* 6, 85–93.
- Boardman, J., 1995. Damage to property by run off from agricultural land, South Downs, southern England, 1976-1993. *The Geographical Journal* 161 (2), 177–191.
- Boardman, J., Evans, R., Ford, J., 2003. Muddy floods on the South Downs, southern England: problem and responses. *Environmental Science & Policy* 6, 69–83.
- Boardman, J., Favis-Mortlock, D., 1999. Frequency-magnitude distributions for soil erosion, runoff and rainfall - a comparative analysis. *Zeitschrift für Geomorphologie* 115, 51–70.
- Boardman, J., Ligneau, L., De Roo, A., Vandaele, K., 1994. Flooding of property by runoff from agricultural land in northwestern Europe. *Geomorphology* 10, 183–196.
- Boardman, J., Poesen, J., 2006. Soil erosion in Europe: Major processes, causes and consequences. In: Boardman, J., Poesen, J. (Eds.), *Soil erosion in Europe*. Wiley, Chichester, pp. 479–487.

- Boardman, J., Verstraeten, G., Bielders, C., 2006. Muddy floods. In: Boardman, J., Poesen, J. (Eds.), *Soil erosion in Europe*. Wiley, Chichester, pp. 743–755.
- Bollinne, A., Laurant, A., Boon, W., 1979. L'érosivité des précipitations à Florennes. Révision de la carte des isohyètes et de la carte d'érosivité de la Belgique. (In French). *Bulletin de la Société Géographique de Liège* 15, 77–99.
- Bork, H., Bork, H., Dalchow, C., Faust, B., Piorr, H., Schatz, T., 1998. *Landschaftsentwicklung in Mitteleuropa*. (In German). Klett-Perthes, Gotha.
- Bowyer-Bower, T., Burt, T., 1989. Rainfall simulators for investigating soil response to rainfall. *Soil Technology* 2, 1–16.
- Bresson, L., Boiffin, J., 1990. Morphological characterisation of soil crust development stages on an experimental field. *Geoderma* 47, 301–325.
- Caquot, A., 1941. Écoulement des eaux pluviales. *Compte rendu de l'Académie des Sciences de Paris* du 20 octobre 1941.
- Cerdan, O., 2001. Analyse et modélisation du transfert de particules solides à l'échelle de petits bassins versants cultivés. (In French). Ph.D. thesis, Université d'Orléans.
- Cerdan, O., Couturier, A., Le Bissonnais, Y., Lecomte, V., Souchère, V., 2002a. Incorporating soil surface crusting processes in an expert-based runoff model : Sealing and Transfer by Runoff and Erosion related to Agricultural Management. *Catena* 46, 189–205.
- Cerdan, O., Le Bissonnais, Y., Couturier, A., Bourennane, H., Souchère, V., 2002b. Rill erosion on cultivated hillslopes during two extreme rainfall events in Normandy, France. *Soil & Tillage Research* 67, 99–108.
- Cerdan, O., Le Bissonnais, Y., Govers, G., Lecomte, V., Van Oost, K., Couturier, A., King, C., Dubreuil, N., 2004. Scale effect on runoff from experimental plots to catchments in agricultural areas in Normandy. *Journal of Hydrology* 299, 4–14.
- Cerdan, O., Le Bissonnais, Y., Souchère, V., Martin, P., Lecomte, V., 2002c. Sediment concentration in interrill flow : Interactions between soil surface conditions, vegetation and rainfall. *Earth Surface Processes & Landforms* 27, 193–205.

- Cerdan, O., Le Bissonnais, Y., Souchère, V., Martin, P., Saby, N., 2002d. Modelling interrill erosion in small cultivated catchments. *Hydrological Processes* 16 (16), 3215–3226.
- Chahinian, N., Moussa, R., Andrieux, P., Voltz, M., 2006a. Accounting for temporal variation in soil hydrological properties when simulating surface runoff on tilled plots. *Journal of Hydrology* 326 (1-4), 135–152.
- Chahinian, N., Voltz, M., Moussa, R., Trotoux, G., 2006b. Assessing the impact of the hydraulic properties of a crusted soil on overland flow modelling at the field scale. *Hydrological Processes* 20 (8), 1701–1722.
- Chapelle-Barry, C., 2008. Dans le sillon du non-labour. (In French). *Agreste Primeur* 207.
- Chaplot, V., Le Bissonnais, Y., 2000. Field measurement of interrill erosion under different slopes and plot sizes. *Earth Surface Processes & Landforms* 25, 145–153.
- Chaubey, I., Edwards, D., Daniel, T., Moore, P., Nichols, D., 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. *Transactions of the ASAE* 37, 845–850.
- Chow, T., Rees, H., Daigle, J., 1999. Effectiveness of terraces/grassed waterway systems for soil and water conservation : A field evaluation. *Journal of Soil & Water Conservation* 3, 577–583.
- Chow, V., Maidment, D., Mays, L., 1988. *Applied Hydrology*. McGraw-Hill, New York.
- Cochet, A., 1842. Les inondations; pèlerinages à Fécamp, Yport, Vaucotte et Étretat, après les inondations du 24/9/1842. (In French). Périaux, Rouen.
- Crobeddu, E., Bennis, S., Rhouziane, S., 2007. Improved rational hydrograph method. *Journal of Hydrology* 3, 63–72.
- Delbeke, L., 2001. Extreme neerslag in Vlaanderen. (In Dutch) - Technical report. Ministerie van de Vlaamse Gemeenschap, Afdeling Water, Brussels.
- de Moor, J., Verstraeten, G., 2008. Alluvial and colluvial sediment storage in the Geul River catchment (The Netherlands) - combining field and modelling data to construct a Late Holocene sediment budget. *Geomorphology* 95 (3-4), 487–503.

- Denis, J., 1992. Géographie de la Belgique. (In French). Crédit Communal de Belgique, Brussels.
- De Roo, A., Wesseling, C., Ritsema, C., 1996. LISEM : a single-event physically based hydrological and soil erosion model for drainage basins. I. Theory, input and output. *Hydrological processes* 10, 1107–1117.
- Deschênes, M., Bélanger, L., Giroux, J., 2003. Use of farmland riparian strips by declining and crop damaging birds. *Agriculture Ecosystems & Environment* 95, 567–577.
- Dosskey, M., 2001. Towards quantifying water pollution abatement in response to installing buffers on cropland. *Environmental Management* 28 (5), 577–598.
- Dunne, T., Zhang, W., Aubry, B., 1991. Effects of rainfall, vegetation and microtopography on infiltration and runoff. *Water Resources Research* 27, 2271–2285.
- El Idrissi, A., 1996. Effet de l'humidité initiale du sol sur le processus de ruissellement à l'échelle de la parcelle et du bassin versant. (In French). Ph.D. thesis, Université catholique de Louvain.
- El Idrissi, A., Persoons, E., 1997. MHM : le Modèle Hydrologique Maillé. (In French). In: FAO (Ed.), *International Workshop on Remote Sensing and Water Resources*. Montpellier (France).
- European Commission, Directorate-General for Agriculture, 2005. Agri-environment measures. Overview on general principles, types of measures and application. European Commission, Brussels.
URL http://ec.europa.eu/agriculture/publi/reports/agrienv/rep_en.pdf
- European Environment Agency, 2000. Down to Earth: Soil degradation and sustainable development in Europe. Vol. 16. Environmental Issue Series, Copenhagen.
- Favis-Mortlock, D., 1998. Evaluation of field-scale erosion models on the UK South Downs. In: Boardman, J., Favis-Mortlock, D. (Eds.), *Modelling Soil Erosion by Water*. Springer-Verlag, Berlin Heidelberg, pp. 43–53.
- Favis-Mortlock, D., Boardman, J., MacMillan, V., 2001. The limits of erosion modelling: why we should proceed with care. In: Harmon, R., Doe, W. (Eds.), *Landscape erosion and evolution modelling*. Kluwer Academic, New York, pp. 477–516.

- Fiener, P., 2003. Concepts and effects of a multi-purpose grassed waterway. Long-term measuring and mathematical modelling of runoff reduction and sediment trapping. Ph.D. thesis, Technische Universität München.
- Fiener, P., Auerswald, K., 2003a. Concepts and effects of a multi-purpose grassed waterway. *Soil Use & Management* 19, 65–72.
- Fiener, P., Auerswald, K., 2003b. Effectiveness of grassed waterways in reducing runoff and sediment delivery from agricultural watersheds. *Journal of Environmental Quality* 32, 927–936.
- Fiener, P., Auerswald, K., 2005a. Measurement and modelling of concentrated runoff in grassed waterways. *Journal of Hydrology* 301, 198–215.
- Fiener, P., Auerswald, K., 2005b. Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil & Tillage Research* 87 (1), 48–58.
- Fiener, P., Auerswald, K., Weigand, S., 2005. Managing erosion and water quality in agricultural watersheds by small detention ponds. *Agriculture Ecosystems & Environment* 110 (3-4), 132–142.
- Fohrer, N., Berkenhagen, J., Hecker, J., Rudolph, A., 1999. Changing soil and surface conditions during rainfall: Single rainstorm/subsequent rainstorms. *Catena* 37 (3-4), 355–375.
- Gamper, C., Thöni, M., Weck-Hannemann, H., 2006. A conceptual approach to the use of Cost Benefit and Multi Criteria Analysis in natural hazard management. *Natural Hazards & Earth System Sciences* 6, 293–302.
- Goidts, E., van Wesemael, B., 2007. Regional assessment of soil organic carbon changes under agriculture in southern Belgium (1955-2005). *Geoderma* 141, 341–354.
- Gómez, J., Nearing, M., Giráldez, J., Alberts, E., 2001. Analysis of sources of variability of runoff volume in a 40 plot experiment using a numerical model. *Journal of Hydrology* 248, 183–197.
- Govers, G., Poesen, J., 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. *Geomorphology* 1, 343–354.
- Gyssels, G., Poesen, J., Liu, G., 2006. Effects of cereal roots on detachment rates of single- and double-drilled topsoils during concentrated flow. *European Journal of Soil Science* 57 (3), 381–391.

- Gyssels, G., Poesen, J., Nachtergaele, J., Govers, G., 2002. The impact of sowing density of small grains on rill and ephemeral gully erosion in concentrated flow zones. *Soil & Tillage Research* 64 (3-4), 189–201.
- Hang, P., 2002. Conception et développement du modèle OGIVE et application à des micro-bassins versants belges. (In French). Ph.D. thesis, Université catholique de Louvain.
- Hanley, N., Shogren, J., White, B., 2001. *Introduction to Environmental Economics*. Oxford University Press, Oxford.
- Henin, S., Gobillot, T., 1950. L'érosion en France. (In French). *Bulletin Technique d'Information du Ministère de l'Agriculture* 6, 431–433.
- Holland, J., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agriculture Ecosystems & Environment* 103 (1), 1–25.
- Hong, Y., Yeh, N., Chen, J., 2006. The simplified methods of evaluating detention storage volume for small catchment. *Ecological Engineering* 26, 355–364.
- Hooke, J., Mant, J., 2000. Geomorphological impacts of a flood event on ephemeral channels in SE Spain. *Geomorphology* 34, 163–180.
- Hubert, P., 2005. La prédétermination des crues. (In French). *Comptes-Rendus Géoscience* 337, 219–227.
- Hufty, A., 2001. *Introduction à la climatologie*. (In French). De Boeck Université, Brussels.
- Ilaco, 1985. *Agricultural compendium for rural development*. Elsevier, Amsterdam.
- Imeson, A., Kirkby, M., 1996. Scaling up processes and models from the field plot to the watershed and regional areas. *Journal of Soil & Water Conservation* 51 (5), 391–396.
- Instruction Technique, 1977. *Instruction technique relative aux réseaux d'assainissement des agglomérations*. (In French) - Technical report. Ministère de l'Équipement et de l'Aménagement du Territoire, instruction interministérielle no. IT 77 284 INT, Paris, France.
- IPCC, 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental

- Panel on Climate Change. Cambridge University Press, Cambridge (UK) and New-York (USA).
- Jetten, V., Favis-Mortlock, D., 2006. Modelling soil erosion in Europe. In: Boardman, J., Poesen, J. (Eds.), *Soil erosion in Europe*. Wiley, Chichester, pp. 695–716.
- Joannon, A., Papy, F., Martin, P., Souchère, V., 2005. Planning work constraints within farms to reduce runoff at catchment level. *Agriculture Ecosystems & Environment* 111, 13–20.
- Joannon, A., Souchère, V., Martin, P., Papy, F., 2006. Reducing runoff by managing crop rotation at the catchment level, considering agronomic constraints at farm level. *Land Degradation & Development* 17, 467–478.
- Jobin, B., Bélanger, L., Boutin, C., Maisonneuve, C., 2004. Conservation value of agricultural riparian strips in the Boyer River watershed, Québec, Canada. *Agriculture Ecosystems & Environment* 103, 413–423.
- Joel, A., Messing, I., Seguel, O., Casanova, M., 2002. Measurement of surface water runoff from plots of two different sizes. *Hydrological Processes* 16, 1467–1478.
- Jonkman, S., Bočkarjova, M., Kok, M., Bernardini, P., in press. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecological Economics*.
- King, C., Lecomte, V., Le Bissonnais, Y., Baghdadi, N., Souchère, V., Cerdan, O., 2005. Remote-sensing data as an alternative input for the 'STREAM' runoff model. *Catena* 62, 125–135.
- Kirpich, T., 1940. Time of concentration of small agricultural watersheds. *Journal of Civil Engineering* 10 (6), 362.
- Kuichling, G., 1889. The relation between the rainfall and the discharge of sewers in populous districts. *ASCE Transactions* 120, 1–56.
- Kwaad, F., 1991. Summer and winter regimes of runoff generation and soil erosion on cultivated soils (The Netherlands). *Earth Surface Processes & Landforms* 16, 653–662.
- Lamandé, M., Hallaire, V., Curmi, P., Pérès, G., Cluzeau, D., 2003. Changes of pore morphology, infiltration and earthworm community in a loamy soil under different agricultural managements. *Catena* 54, 637–649.

- Lang, A., Bork, H., Mäkel, R., Preston, N., Wunderlich, J., Dikau, R., 2003. Changes in sediment flux and storage within a fluvial system: some examples from the Rhine catchment. *Hydrological Processes* 17, 3321–3334.
- Larue, J., 2001. La morphogenèse accélérée menace-t-elle les régions rurales de l'ouest du bassin parisien? (In French). *Géographie Physique et Quaternaire* 55 (3), 243–255.
- Laurant, A., Bollinne, A., 1976. L'érosivité des pluies à Uccle (Belgique). (In French) . *Bulletin des Recherches Agronomiques de Gembloux* 11 (1-2), 149–168.
- Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science* 47, 425–437.
- Le Bissonnais, Y., Benkhadra, H., Chaplot, V., Fox, D., King, D., Daroussin, J., 1998. Crusting, runoff and sheet erosion on silty loamy soils at various scales and upscaling from m² to small catchments. *Soil & Tillage Research* 46 (1-2), 69–80.
- Le Bissonnais, Y., Blavet, D., De Noni, G., Laurent, J., Asseline, J., Chenu, C., 2007. Erodibility of Mediterranean vineyard soils: relevant aggregate stability methods and significant soil variables. *European Journal of Soil Science* 58 (1), 188–195.
- Le Bissonnais, Y., Cerdan, O., Lecomte, V., Benkhadra, H., Souchère, V., Martin, P., 2005. Variability of soil surface characteristics influencing runoff and interrill erosion. *Catena* 62, 111–124.
- Le Bissonnais, Y., Lecomte, V., Cerdan, O., 2004. Grass strip effects on runoff and soil loss. *Agronomie* 24, 129–136.
- Lefèvre, P., 1958. Quelques phénomènes d'érosion en Picardie. (In French). *Annales d'Agronomie* 6, 91–129.
- Legout, C., Leguédois, S., Le Bissonnais, Y., 2005. Aggregate breakdown dynamics under rainfall compared with aggregate stability measurements. *European Journal of Soil Science* 56 (2), 225–238.
- Léonard, J., Andrieux, P., 1998. Infiltration characteristics of soils in Mediterranean vineyards in Southern France. *Catena* 32, 209–223.

- Leys, A., Govers, G., Gillijns, K., Poesen, J., 2007. Conservation tillage on loamy soils: explaining the variability in interrill runoff and erosion reduction. *European Journal of Soil Science* 58, 1425–1436.
- Liégeois, M., 2005. Des aléas et des hommes. Elaboration d'une méthode de diagnostic de la vulnérabilité à l'aléa érosion. (In French). PhD thesis, E.N.S.-L.S.H. Lyon.
- Linsley, R., Franzini, J., Freyberg, D., Tchobanoglous, G., 1992. *Water Resources Engineering*, 4th Edition. Mac Graw-Hill.
- Lloyd-Davies, D., 1906. The elimination of stormwater from Sewerage Systems. *Proceedings of the Institution of Civil Engineers* 164, 41–67.
- Léonard, J., Ancelin, O., Ludwig, B., Richard, G., 2006. Analysis of the dynamics of soil infiltrability of agricultural soils from continuous rainfall-runoff measurements on small plots. *Journal of Hydrology* 326 (1-4), 122–134.
- Louchart, X., Voltz, M., Andrieux, P., Moussa, R., 2001. Herbicide transport to surface waters at field and watershed scales in a Mediterranean vineyard area. *Journal of Environmental Quality* 30, 982–991.
- Martin, P., 1999. Reducing flood risk from sediment-laden agricultural runoff using intercrop management techniques in Northern France. *Soil & Tillage Research* 52 (3-4), 233–245.
- Mersie, W., Seybold, C., Mc Namee, C., M.A., L., 2003. Abating endosulfan from runoff using vegetative filter strips: the importance of plant species and flow rate. *Agriculture Ecosystems & Environment* 97, 215–223.
- Ministère de l'Agriculture, 1958. L'agriculture belge. Structure et situation. (In French) - Technical report. Brussels.
- Ministère de l'Équipement et des Transports - Direction des Routes de Liège, 2002. Bilan de fonctionnement hydraulique et écologique des bassins d'orage de l'autoroute E40. (In French) - Technical report.
- Mitchell, T., Carter, T., Jones, P., Hulme, M., New, M., 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1991-2000) and 16 scenarios (2001-2100). Tyndall Centre Working Paper No. 55. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

- Moore, I., Burch, G., Mackenzie, D., 1988. Topographic effects on the distribution of surface soil water and the location of ephemeral gullies. *Transactions of the ASAE* 31 (4), 1098–1107.
- Morgan, R., 1995. *Soil erosion and conservation*, 2nd Edition. Longman, Harlow.
- Morgan, R., 2005. *Soil erosion and conservation*, 3rd Edition. Blackwell Publishing, Oxford.
- Moussa, R., Voltz, M., Andrieux, P., 2002. Effects of the spatial organization of agricultural management on the hydrological behaviour of a farmed catchment during flood events. *Hydrological Processes* 16 (2), 393–412.
- Mulvaney, T., 1851. On the use of self-registering rain and flood gauges in making observation of the relation of rainfall and flood discharges in a given catchment. *Proceedings of Civil Engineers of Ireland* 4, 18–31.
- Musy, A., Higy, C., 2004. *Hydrologie. Une science de la nature*. (In French). Presses Polytechniques et Universitaires Romandes, Lausanne.
- Nachtergaele, J., Poesen, J., 1999. Assessment of soil losses by ephemeral gully erosion using high-altitude (stereo) aerial photographs. *Earth Surface Processes & Landforms* 24, 693–706.
- Nachtergaele, J., Poesen, J., 2002. Spatial and temporal variations in resistance of loess-derived soils to ephemeral gully erosion. *European Journal of Soil Science* 53, 449–463.
- Nash, I., Sutcliffe, J., 1970. River flow forecasting through conceptual models. Part I: a discussion of principles. *Journal of Hydrology* 10, 282–290.
- Nearing, M., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M., Nunes, J., Renschler, C., 2005. Modelling response of soil erosion and runoff to changes in precipitation and cover. *Catena* 61 (2-3), 131–154.
- Ntaguzwa, D., 1999. *La relation pluie-débit et l'incertitude en modélisation hydrologique. Application aux bassins versants du complexe des barrages de l'Eau d'Heure (Belgique)*. (In French). Ph.D. thesis, Université catholique de Louvain.
- Onstad, C., 1984. Depressional storage on tilled soil surfaces. *Transactions of the ASAE* 27, 729–732.

- Pan, C., Shangguan, Z., 2006. Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions. *Journal of Hydrology* 331 (1-2), 178–185.
- Papy, F., Douyer, C., 1991. Influence des états de surface du territoire agricole sur le déclenchement des inondations catastrophiques. (In French). *Agronomie* 11, 201–215.
- Patton, P., Schumm, S., 1975. Gully erosion, Northwestern Colorado: a threshold phenomenon. *Geology* 3, 88–90.
- Patty, L., Réal, B., Gril, J., 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds of water. *Pesticide Science* 49, 243–251.
- Peduzzi, P., Concato, J., Kemper, E., Holford, T., Feinstein, A., 1996. A simulation study of the number of events per variable in logictic regression analysis. *Journal of Clinical Epidemiology* 49 (12), 1373–1379.
- Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. *Catena* 50, 91–133.
- Poiret, M., 1999. Crop trends and environmental impacts. European Commission. Directorate-General for Agriculture, Brussels.
- Prosser, I., Dietrich, W., Stevenson, J., 1995. Flow resistance and sediment transport by concentrated overland flow in a grassland valley. *Geomorphology* 13, 71–86.
- Randriamaherisoa, A., 1993. Modèle Hydrologique Maillé et Système d'Information Géographique. L'impact de la déforestation sur le régime hydrologique de la Lokoho (Madagascar)-(In French). Ph.D. thesis, Université catholique de Louvain.
- Renard, K., Foster, G., Weesies, G., McCool, D., Yoder, D., 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Vol. 703. USDA, Washington D.C.
- Ritson, C., Harvey, D. E., 1997. *The Common Agricultural Policy*. Cab International, Wallingford.

- Rodhe, A., Seibert, J., 1999. Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators. *Agricultural & Forest Meteorology* 98-99, 325–340.
- Römkens, M., Prasad, S., 2006. Rain infiltration into swelling/schrinking/cracking soils. *Agricultural Water Management* 86 (1-2), 196–205.
- Rommens, T., Verstraeten, G., Bogman, P., Peeters, I., Poesen, J., Govers, G., Van Rompaey, A., Lang, A., 2006. Holocene alluvial sediment storage in a small river catchment in the loess area of central Belgium. *Geomorphology* 77, 187–201.
- Rommens, T., Verstraeten, G., Poesen, J., Govers, G., Van Rompaey, A., Peeters, I., Lang, A., 2005. Soil erosion and sediment deposition in the Belgian loess belt during the Holocene: establishing a sediment budget for a small agricultural catchment. *The Holocene* 15 (7), 1032–1043.
- Schmitt, T., Dosskey, M., Hoagland, K., 1999. Filter strip performance and processes for different vegetation, widths and contaminants. *Journal of Environmental Quality* 32, 927–936.
- Schouten, C., Rang, M., Huigen, P., 1985. Erosie en wateroverlast in Zuid-Limburg. (In Dutch). *Landschap* 2, 118–132.
- Schröder, R., Auerswald, K., 2000. Modellierung des Jahresgangs der Verschlammungsinduzierten Abflussbildung in kleinen, landwirtschaftlich genutzten Einzugsgebieten. (In German). *Zeitschrift für Kulturtechnik und Landentwicklung* 41, 167–172.
- Schuler, J., Kächele, H., Müller, K., Helming, K., Zander, P., 2006. Economic frame for soil conservation policies. In: Boardman, J., Poesen, J. (Eds.), *Soil erosion in Europe*. Wiley, Chichester, pp. 791–803.
- Selby, M., 1993. *Hillslope materials and processes*, 2nd Edition. Oxford University Press, Oxford.
- Shaw, E., 1995. *Hydrology in Practice*, 3rd Edition. Chapman & Hall, London.
- Silburn, D., Freebairn, D., Rattray, D., 2007. Tillage and the environment in sub-tropical Australia - Tradeoffs and challenges. *Soil & Tillage Research* 97 (2), 306–317.

- Soil Conservation Service, 1972. National Engineering Handbook, section 4. U.S. Department of Agriculture, Washington D.C.
- Souchère, V., Cerdan, O., Ludwig, B., Le Bissonnais, Y., Couturier, A., Papy, F., 2003. Modelling ephemeral gully erosion in small cultivated catchments. *Catena* 50, 489–505.
- Souchère, V., King, D., Daroussin, J., Papy, F., Capillon, A., 1998. Effects of tillage on runoff direction: consequences on runoff contributing area within agricultural catchments. *Journal of Hydrology* 206, 256–267.
- Souchère, V., Cerdan, O., Dubreuil, N., Le Bissonnais, Y., King, C., 2005. Modelling the impact of agri-environmental scenarios on runoff in a cultivated catchment (Normandy, France). *Catena* 61, 229–240.
- Souchère, V., King, C., Dubreuil, N., Lecomte-Morel, V., Le Bissonnais, Y., Chalot, M., 2003. Grassland and crop trends: role of the European Union Common Agricultural Policy and consequences for runoff and soil erosion. *Environmental Science & Policy* 6, 7–16.
- Spaeter, S., Cochard, F., Rozan, A., 2006. Prevention and compensation of muddy floods: some economic insights. Vol. 2006-29. Bureau d'Economie Théorique et Appliquée, Strasbourg, France.
- Stammers, R., Boardman, J., 1984. Soil erosion and flooding on downland areas. *Surveyor* 164, 8–11.
- Statistics Belgium, 2006.
URL <http://www.statbel.fgov.be/>
- Steege, A., 2001. Sediment deposition in and export from small agricultural catchments. Ph.D. thesis, K.U. Leuven.
- Steege, A., Govers, G., 2001. Correction factors for estimating suspended sediment export from loess catchments. *Earth Surface Processes & Landforms* 26 (4), 441–449.
- Steege, A., Govers, G., Nachtergaele, J., Takken, I., Beuselinck, L., Poesen, J., 2000. Sediment export by water from an agricultural catchment in the Loam Belt of central Belgium. *Geomorphology* 33, 25–36.
- Takken, I., Beuselinck, L., Nachtergaele, J., Govers, G., Poesen, J., Degraer, G., 1999. Spatial evaluation of a physically based distributed erosion model (LISEM). *Catena* 37, 431–447.

- Takken, I., Govers, G., Jetten, V., Nachtergaele, J., Steegen, A., Poesen, J., 2001. Effects of tillage on runoff and erosion patterns. *Soil & Tillage Research* 61 (1-2), 55–60.
- Temple, D., 1991. Changes in vegetal flow retardance during long-duration flows. *Transactions of the American Society of Agricultural Engineers* 25, 1300–1303.
- T'Jonck, G., 1967. La lutte contre l'érosion. Un cas à Gingelom. L'amélioration de la structure agraire: problèmes techniques particuliers. (In French). *Société Nationale Terrienne*, 9–15.
- Tomer, M., James, D., Isenhardt, T., 2003. Optimizing the placement of riparian practices in a watershed using terrain analysis. *Journal of Soil & Water Conservation* 58 (4), 198–206.
- Uri, N., Atwood, J., Sanabria, J., 1998. The environmental benefits and costs of conservation tillage. *Science of the Total Environment* 216, 13–32.
- USDA-SCS, 1973. A method for estimating volume and rate of runoff in small watersheds - Technical report. No. 149.
- Valentin, C., Bresson, L., 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. *Geoderma* (55), 225–245.
- Vandaele, K., 1997. Temporele en ruimtelijke dynamiek van bodemerosieprocessen in landelijke stroomgebieden (Midden België). Een terreinstudie. (In Dutch). PhD thesis, K.U. Leuven.
- Vandaele, K., Poesen, J., 1995. Spatial and temporal patterns of soil erosion rates in an agricultural catchment, central Belgium. *Catena* 25, 213–226.
- Vandaele, K., Poesen, J., Govers, G., van Wesemael, B., 1996. Geomorphic threshold conditions for ephemeral gully incision. *Geomorphology* 16, 161–173.
- Van Dijk, P., Auzet, A., Lemmel, M., 2005. Rapid assessment of field erosion and sediment transport pathways in cultivated catchments after heavy rainfall events. *Earth Surface Processes & Landforms* (30), 169–182.
- Van Dijk, P., Kwaad, F., 1996. Runoff generation and soil erosion in small agricultural catchments with loess-derived soils. *Hydrological Processes* (10), 1049–1059.

- Van Dijk, P., Kwaad, F., Klapwijk, M., 1996a. Retention of water and sediment by grass strips. *Hydrological Processes* (10), 1069–1080.
- Van Dijk, P., Van der Zijp, M., Kwaad, F., 1996b. Soil erodibility parameters under various cropping systems of maize. *Hydrological Processes* (10), 1061–1061.
- Van Oost, K., 2003. Spatially distributed modelling of surface runoff. PhD thesis, K.U. Leuven.
- Van Oost, K., Govers, G., Cerdan, O., Thauré, D., Van Rompaey, A., Steegen, A., Nachtergaele, J., Takken, I., Poesen, J., 2005. Spatially distributed data for erosion model calibration and validation: The Ganspoel and Kinderveld datasets. *Catena* 61, 105–121.
- Van Orshoven, J., Maes, J., Vereecken, H., Feyen, J., Didal, R., 1988. A structured database of Belgian soil profile data. *Pédologie* 38, 191–206.
- Vanwalleghem, T., Bork, H., Poesen, J., Schmidtchen, G., Dotterweich, M., Nachtergaele, J., Bork, H., Deckers, J., Brüsch, B., Bungeneers, J., De Bie, M., 2005. Rapid development and infilling of a buried gully under cropland, central Belgium. *Catena* 63 (2-3), 221–243.
- Varnes, D., 1984. Landslide hazard zonation: a review of principles and practice. Commission on landslides of the IAEG UNESCO. *Natural Hazards* 3, 61.
- Verstraeten, G., 2000. Modderoverlast, sedimentatie in wachtbekkens en begroting van de sedimentexport naar waterlopen in Midden-België. (In Dutch). PhD thesis, K.U. Leuven.
- Verstraeten, G., Poesen, J., 1999. The nature of small-scale flooding, muddy floods and retention pond sedimentation in central Belgium. *Geomorphology* 29, 275–292.
- Verstraeten, G., Poesen, J., 2001. Factors controlling sediment yield from small intensively cultivated catchments in a temperate humid climate. *Geomorphology* 40, 123–144.
- Verstraeten, G., Poesen, J., Goossens, D., Gillijns, K., Bielders, C., Gabriels, D., Ruyschaert, G., Van Den Eeckhaut, M., Vanwalleghem, T., Govers, G., 2006. Belgium. In: Boardman, J., Poesen, J. (Eds.), *Soil erosion in Europe*. Wiley, Chichester, pp. 385–411.

- Verstraeten, G., Poesen, J., Govers, G., Gillijns, K., Van Rompaey, A., Van Oost, K., 2003. Integrating science, policy and farmers to reduce soil loss and sediment delivery in Flanders, Belgium. *Environmental Science & Policy* 6, 95–103.
- Verstraeten, G., Van Oost, K., Van Rompaey, A., Poesen, J., Govers, G., 2001. Integraal land-en waterbeheer in landelijke gebieden met het oog op het beperken van bodemverlies en modderoverlast (proefproject gemeente Gingelom). (In Dutch). K.U. Leuven, Laboratory for Experimental Geomorphology.
- Veyret, Y., 2007. Dictionnaire de l'Environnement. (In French). Armand Colin, Paris.
- Vianello, M., Vischetti, C., Scarponi, L., Zanin, G., 2005. Herbicide losses in runoff events from a field with a low slope: Role of a vegetative filter strip. *Chemosphere* 61, 717–725.
- Wells, D., Krakiwsky, E., 1971. The Method of Least Squares. UNB, Lecture Notes No. 18, May 1971.
- World Reference Base, 1998. World Reference Base for Soil Resources. FAO, World Resources report n°84, Rome, Italy.
- Wrigley, N., 1985. Categorical data analysis for geographers and environmental scientists. Longman, London.

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