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A grassed waterway and earthen dams to control muddy floods from a cultivated catchment of the Belgian loess belt

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Abstract

Muddy floods, i.e. runoff from cultivated areas carrying large quantities of soil, are frequent and widespread in the European loess belt. They are mainly generated in dry zero-order valleys and are nowadays considered as the most likely process 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 2002-2004 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 from 2005-2007 and 39 runoff events were recorded in that 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 5-12 hours behind the dams, and the lag time at the outlet of the catchment was thereby increased by 75%. Reinfiltration was also observed within the waterway, runoff coefficients decreasing by a mean of 50% between both extremities of the GWW. Sediment discharge was also reduced by 93% between the GWW's inflow and the outlet. Before the installation of the control measures, specific sediment yield (SSY) of the catchment reached 3.5 t ha^{-1} yr^{-1} and an ephemeral gully was observed 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 t ha^{-1} yr^{-1}. 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 (126 € ha^{-1}) compared to the mean damage cost associated with muddy

floods in the study area (54 € ha^{-1} yr^{-1}). Similar measures should therefore be installed to protect other flooded villages of the Belgian loess belt and comparable environments.

Keywords : muddy floods; grassed waterway; earthen dams; runoff control; sediment delivery; cost-efficiency.

1. Introduction

Muddy floods consist of water flowing from agricultural fields carrying large quantities of soil as suspended sediment or bedload (Boardman et al., 2006). They are therefore considered as a fluvial process rather than a mass movement one. Even though they are frequent and widespread in the European loess belt, they are mainly reported from central Belgium (Verstraeten and Poesen, 1999; Evrard et al., 2007a), northern France (Souchère et al., 2003) and southern England (Boardman et al., 2003). Muddy floods cause numerous off-site impacts, such as flooding of property, sedimentation and eutrophication in watercourses.

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; Evrard et al., 2007a). 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, in press). Rommens et al. (2006) also estimated the Holocene alluvial sediment storage in a small (52 km²) river catchment 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 the mostly likely process transporting sediments from the dry valleys to the alluvial plains. During heavy rainfall in late spring and summer, ephemeral gullies form in these dry valleys. These shallow (~ 0.1 m) but wide (~ 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 to this damage, which appears to have occured more frequently during the last decade, justifies the urgent installation of mitigation measures (Evrard et al., 2007a). 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., in press). However, the implementation of these practices directly depends on the farmer's willingness. Except for sowing of cover crops (e.g. in Belgium; Bielders et al., 2003), the adoption of such practices remains rather limited in Europe (Holland, 2004). It will probably still take several years or even decades before reduced tillage and double sowing are applied generally. 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, grass buffer strips, grassed waterways (GWW) and detention ponds (retaining runoff for a certain time behind a small dam) serve this purpose (Fiener and Auerswald, 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 efficiency before generalising their installation in problem areas. Furthermore, since muddy floods are generated on large surfaces (10-300 ha; Evrard et al., 2007a), 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 m^2, see e.g. Van Dijk et al., 1996; 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 micro-catchment scale (max. 8 ha; Fiener and Auerswald, 2005; 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 paper 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. The cost-efficiency of the control measures is also discussed.

2. Materials and methods

2.1. General context

The Belgian loess belt (~ 9000 km²) is a plateau with a mean altitude of 115 m gently sloping to the North (Fig. 1a). Annual mean temperature varies between 9-10°C, while annual precipitation ranges from 700-900 mm (Hufty, 2001). Soils are mainly loess-derived Haplic Luvisols (World Reference Base, 1998). Arable land covers 65% of the total surface (Statistics Belgium, 2006). During the last three decades, the area covered by summer crops (sugar beet – *Beta vulgaris L.*, maize – *Zea Mays L.*, potatoes – *Solanum tuberosum L.* and chicory – *Cichorium intybus L.*) increased at the expense of winter cereals (Evrard et al., 2007a). The summer crops provide little cover to the soil during the thunderstorms that occur in late spring or early summer, which leads to the formation of a soil surface crust with a very low infiltration rate. High quantities of runoff are then generated on these crusted soils during intense precipitation (Evrard et al., in press).

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. 1a). In the framework of the ‘Erosion Decree’ adopted by the Flemish government in 2001, they drew up an erosion mitigation scheme at the catchment scale (200 km²). Between 2002-2005, 120 grass strips and GWW have been installed, covering a surface of ~ 25 ha (0.13% of total area). Furthermore, 35 earthen dams have been built.

2.2. Study area

Velm has the local reputation of a ‘devastated village’, since it was flooded several times during the last two decades. Runoff loaded with sediments is generated in cultivated dry zero-order valleys covering a total area of 930 ha that drain to the village (Fig. 1b).

A 300 ha-catchment draining into Velm, locally known as ‘Heulen Gracht’, was selected for detailed monitoring (Fig. 2). Cropland covers 79% of the catchment surface. Orchards (17%) and roads (3%) are the other main types of land use. A typical topsoil sample in this catchment contains 80% silt, 10% clay and 10% sand and the mean slope reaches 1.3%.

An earthen dam was built close to the catchment outlet in April 2002 to prevent muddy floods (dam # 3 in Fig. 2). A GWW was also sown in the thalweg in 2003, covering 12 ha (4% of total catchment surface; Fig. 2). Grass species consist of a mix of *Lolium* *multiflorum Lam.*, *Lolium perenne L.*, *Festuca rubra L. subsp. Rubra* and *Dactylis glomerata L.* Two additional dams were built across the GWW in August 2004 (dams # 1 and 2 in Fig. 2).

2.3. 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. 2). 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, Ontario, Canada). Finally, a water level logger (Global Water-WL 15, Gold River, California, USA) was installed in May 2005 behind each of the three earthen dams built across the GWW. A topographic survey was carried out in Spring 2005 to determine the volume-depth curves of the detention ponds (Table 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. 1 (Ilaco, 1985) :

$$Q = A \times (2gh)^{0.5} \qquad (1)$$

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

The impact of the control measures on runoff is estimated by comparing peak discharges per unit area ($l\ s^{-1}\ ha^{-1}$), 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, North Carolina, USA) to detect any significant differences between both extremities of the GWW at 95% confidence intervals.

2.4. Impact of control measures on erosion

The rills and gullies that were formed during the monitoring period have been mapped, 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. 2) was measured with an estimated precision of 5 mm with a meter on a 5m-grid after each important rainfall event (with ≥ 10 mm of 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, t ha^{-1} yr^{-1}) obtained for 26 cultivated catchments of the Belgian loess belt over a period of 2-46 years during the 20th century (Eq. 2; Verstraeten and Poesen, 2001).

$$SSY = 26A^{-0.35} \qquad (2)$$

A suspended sediment sampler (ISCO-6712, Lincoln, Nebraska, USA) was 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.

2.5. 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 Gorsem (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.

3. Results

Between 2002-2007, 77% of events with ≥ 15 mm precipitation occurred between May and September. Similarly, 70% of runoff events occurred during this period (Fig. 3).

3.1. Impact of control measures on runoff

The San Dimas flume recorded 39 runoff events in 2006 and 2007 (Table 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 2). 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 $m^3 s^{-1}$ on June 14 2006 and 1.47 $m^3 s^{-1}$ on June 11 2007; Table 2).

Some 53 rainfall-runoff events have been measured behind the dams (Table 2). Before the installation of dams 2 and 3 in August 2004 (Fig. 2), runoff events with a discharge ≥ 0.03 $m^3 s^{-1}$ have been observed at dam 3 during low-intensity precipitation (e.g. in February, 2003; Table 2). After the installation of the two additional dams, notable runoff has been measured behind the dam at the outlet (dam 3; Fig. 2) during only 13 events. These events correspond to: (i) prolonged periods of rain in winter (≥ 30 mm in 48 hours) or (ii) to heavy thunderstorms between May and August (≥ 20 mm in a few hours). All runoff parameters are significantly different between both extremities of the GWW at the 95% confidence interval (Table 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. Runoff coefficients decreased by a mean of 40% between both extremities of the GWW (Table 3). The reduction was higher during low-intensity rainfall (mean of 43% for events with an $I_{\max} < 40$ mm h^{-1}) than during intense thunderstorms (mean of 20% for events with an $I_{\max} > 40$ mm h^{-1}; Table 2).

Runoff was buffered during 5-12 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 2).

3.2. Impact of control measures on specific sediment yield

According to Eq. (2), the specific sediment yield for a catchment of the size of the Heulen Gracht should be 3.5 t ha^{-1} yr^{-1}. The gullies observed since the 1940s and draining to Velm are mapped in Fig. 1b.

Six major erosion events have been documented between April-September 2002 (Table 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 ~ 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 -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.

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 5). Much of the sediment was trapped behind the first dam. Sediment concentration in the first dam's outflow is 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 concentrations at the outlet were reduced by a mean of 88% (0.9 g l^{-1}) compared to the ones measured in the flume (mean of 5.4 g l^{-1}). Sediment discharge was reduced by a mean of 93%, 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 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. Rainfall simulations have shown that sediment production is much lower on crusted soils in August (3 g l^{-1}) than on fragmentary soils (40 g l^{-1}) at the end of spring (Evrard et al., in press). During the extreme event of June 11 2007, 84 t of sediments were trapped behind the three successive dams. It represents 72% of soil loss measured in the San Dimas flume. No more rills 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.

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 (Fig. 1b; T'Jonck, 1967). However, the off-site consequences have become more frequent during the last two decades (Evrard et al., 2007a). Fire brigade interventions due to muddy floods in the Velm village dramatically increased since 1980 (Table 4). All muddy floods were triggered by heavy thunderstorms (between 14-70 mm of rainfall, with a mean of 35.5 mm) and occurred between May and August (Table 4). Six heavy storms (20-70 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 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. 4). 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).

4. Discussion

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 reinfiltration 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%; Evrard et al., in press).

Sediment trapping is very high and occurs mainly behind the first dam, except during extreme events. These observations confirm the main results of a former modelling exercise (Evrard et al., 2007b). The model simulated that the GWW led to a 50% decrease of peak discharge, which is consistent with 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, 2005; Fiener et al., 2005). The German ponds were very efficient in trapping sediments (between 50-80% 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.

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 10-20% 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 (between 1947-1996), always appearing at the same location (Fig. 1b). 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}), which shows that erosion is not a recent phenomenon in the study area.

Steegen (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 Steegen 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 rills and 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}, thereby drastically decreasing sediment delivery to the alluvial plain.

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 (Fig. 1a) cost ~ € 25,000 (i.e. 125 € km^{-2}). Muddy floods also led to numerous cases of damage to private property. According to 1601 records submitted by Belgian households to the Disaster Fund, mean damage amount was € 4,436 (SD= 3,406 €; Evrard et al., 2007a). The villages of Velm and Gingelom were particularly affected by the thunderstorms of May and August 2002 (Table 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 in ~ 3 years 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 7.7-9.6 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 8-86 million € yr^{-1}; Evrard et al., 2007a).

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 maximum 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 5-12 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 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}, 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 and comparable environments. These measures could be combined with alternative farming practices, such as reduced tillage. However, there is a need to study the impact of these practices on runoff and erosion at the catchment scale.

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References

Aumann, F., Vandenghoer, C., 1989. Baron Surlet de Chokier, regent van België: Mens en Mythe (1769-1839). (In Dutch). Gemeentebestuur Gingelom.

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.

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

Bork, H.-R., Bork, H., Dalchow, C., Faust, B., Piorr, H.-P., Schatz, T., 1998. Landschaftsentwicklung in Mitteleuropa. (In German). Klett-Perthes, Gotha.

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., Verstraeten, G., Bielders, C., 2006. Muddy floods. In: Boardman, J., Poesen, J. Soil Erosion in Europe. Wiley, Chichester, pp. 743-755.

Delbeke, L., 2001. Extreme neerslag in Vlaanderen. (In Dutch). Technical report. Aminal, Afdeling Water. Ministerie van de Vlaamse Gemeenschap.

de Moor, J.J.W., Verstraeten, G., in press. 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.

Evrard, O., Bielders, C.L., Vandaele, K., van Wesemael, B., 2007a. Spatial and temporal variation of muddy floods in central Belgium, off-site impacts and potential control measures. Catena 70, 443-454.

Evrard, O., Persoons, E., Vandaele, K., van Wesemael, B., 2007b. Effectiveness of erosion mitigation measures to prevent muddy floods: A case study in the Belgian loam belt. Agriculture Ecosystems & Environment 118, 149-158.

Evrard, O., Vandaele, K., Bielders, C.L., van Wesemael, B., in press. Seasonal evolution of runoff generation on agricultural land in the Belgian loess belt and implications for muddy flood triggering. Earth Surface Processes & Landforms.

Fiener, P., Auerswald, K., 2005. 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.

Goidts, E., van Wesemael, B., 2007. Regional assessment of soil organic carbon changes under agriculture in Southern Belgium (1955-2005). Geoderma 141, 341-354.

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., 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.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture, Ecosystems & Environment 103 (1), 1-25.

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

Ilaco, 1985. Agricultural compendium for rural development. Elsevier, Amsterdam.

Lang, A., Bork, H.-R., 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.

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

Leys, A., Govers, G., Gillijns, K., Poesen, J., in press. Conservation tillage on loamy soils: explaining the variability in interrill runoff and erosion reduction. European Journal of Soil Science.

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.

Patty, L., Réal, B., Gril, J.J., 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds of water. Pesticide Science 49, 243-251.

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.

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.

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

Statistics Belgium, 2006. URL: http://www.statbel.fgov.be

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

Steegen A., 2001. Sediment deposition in and export from small agricultural catchments. Unpublished PhD thesis, Faculty of Sciences, Geography, K.U. Leuven.

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.

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.

Vandaele, K., 1997. Temporele en ruimtelijke dynamiek van bodemerosieprocessen in landelijke stroomgebieden (Midden-België): een terreinstudie. (In Dutch). Unpublished PhD thesis, Faculty of Sciences, Geography, K.U. Leuven.

Van Dijk, P.M., Kwaad, F.J.P.M., Klapwijk, M., 1996. Retention of water and sediment by grass strips. Hydrological Processes 10, 1069-1080.

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., 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., Poesen, J., Goossens, D., Gillijns, K., Bielders, C., Gabriels, D., Ruysschaert, G., Van Den Eeckhaut, M., Vanwalleghem, T., Govers, G., 2006. Belgium. In : Boardman, J., Poesen, J. Soil Erosion in Europe. Wiley, Chichester, pp. 385-411.

World Reference Base, 1998. World Reference Base for Soil Resources. FAO, World Resources Report n°84, Rome, Italy.

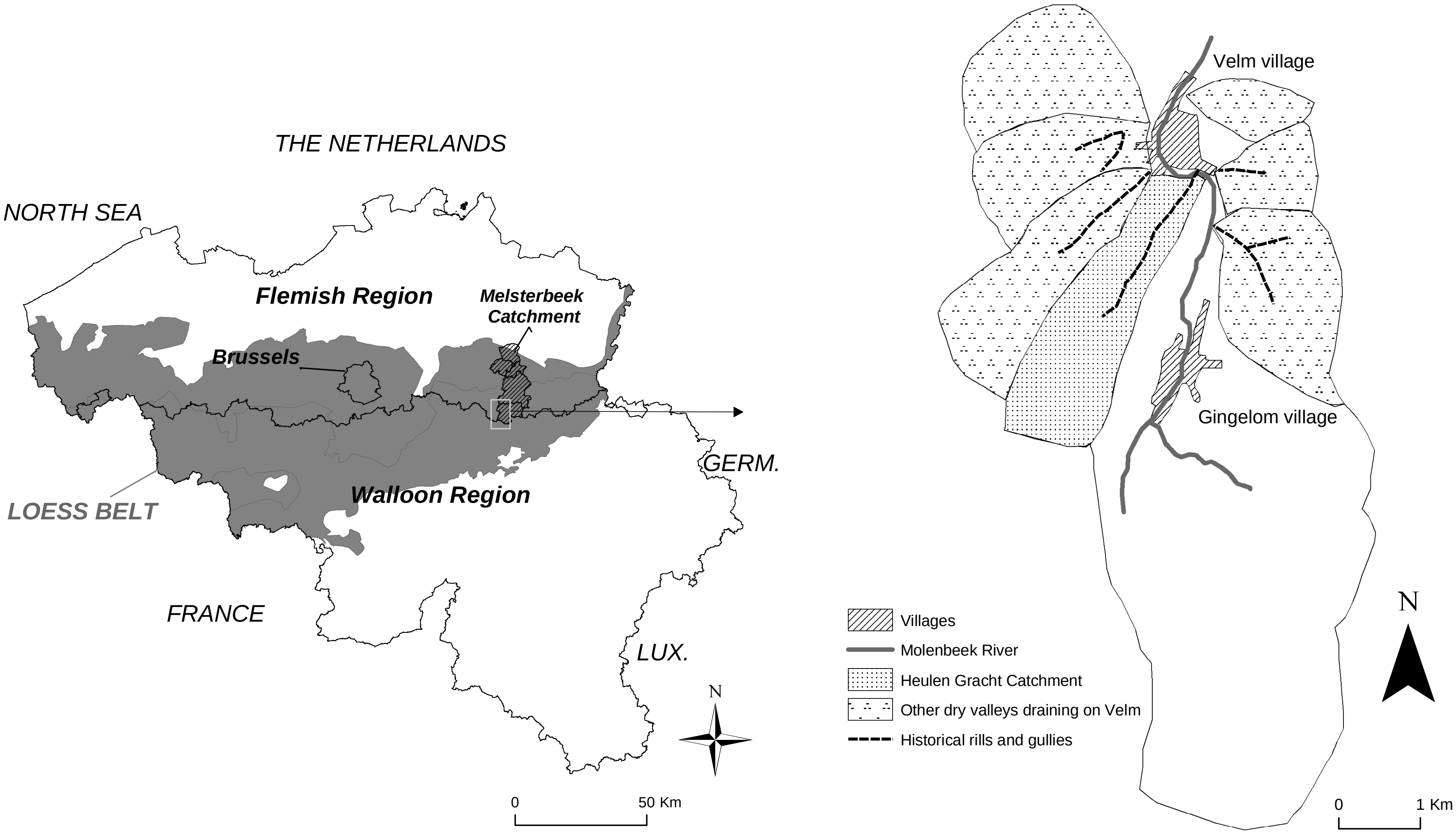
Figure captions

Fig. 1. (a) Location of Melsterbeek Catchment and Velm village in the Belgian loess belt. (b) Network of dry valleys draining to Velm village. Dotted lines represent historical gullies and rills observed in the area.

Fig. 2. Land use and location of muddy flood control measures within the Heulen Gracht Catchment.

Fig. 3. Monthly distribution of observed rainfall events during the period 2003-2007 with > 15 mm of cumulative precipitation, and number of recorded runoff events.

Fig. 4. Rainfall, inflow and outflow hydrographs measured during the thunderstorm of June 11 2007.


THE NETHERLANDS
NORTH SEA
Flemish Region
Melsterbeek Catchment
Brussels
LOESS BELT
Walloon Region
GERM.
FRANCE
LUX.
N
0
50 Km
Velm village
Gingelom village
Villages
Molenbeek River
Heulen Gracht Catchment
Other dry valleys draining on Velm
Historical rills and gullies
N
0
1 Km

(a) (b)

Fig. 1

Figure 2

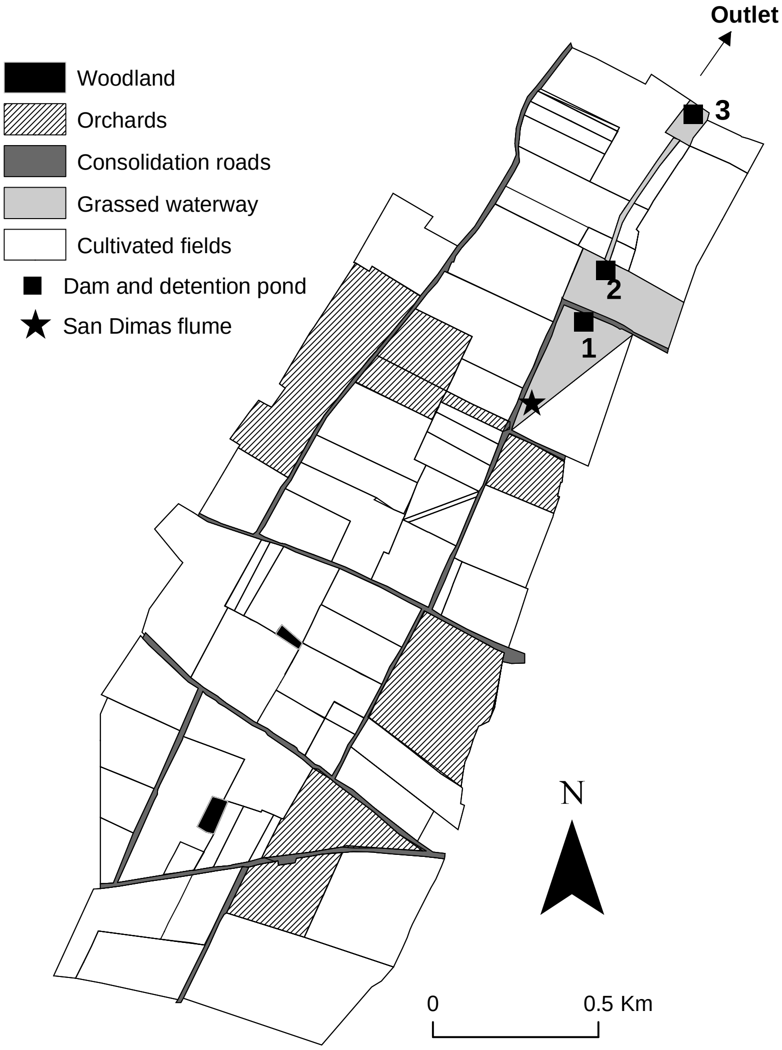


Fig. 2

Figure 3

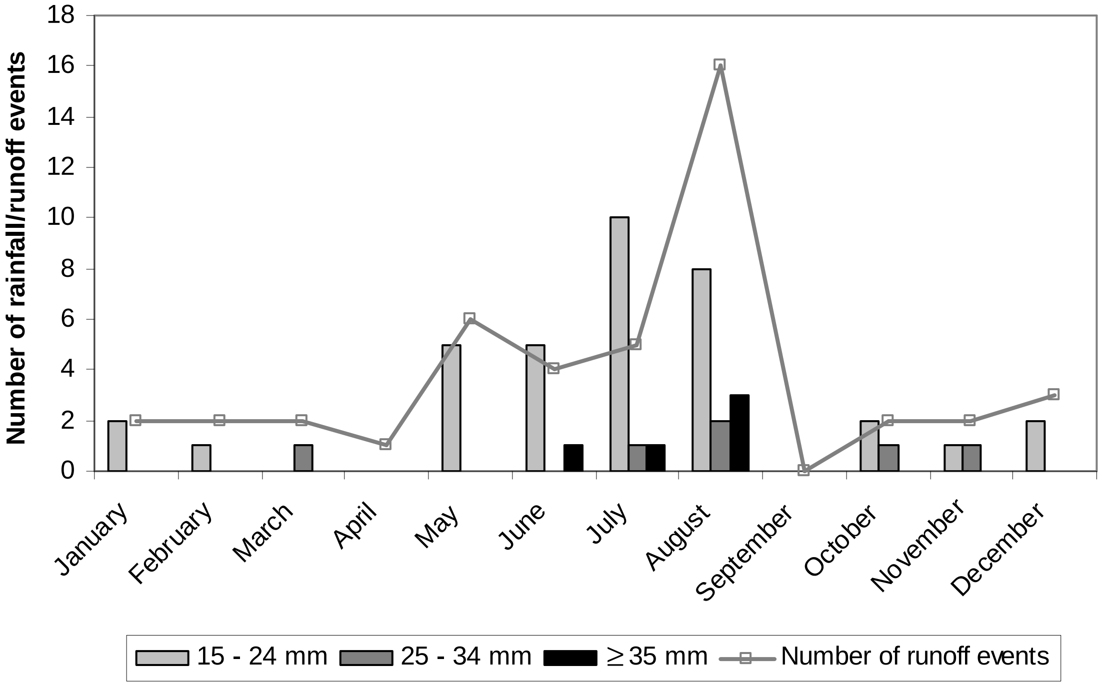


Fig. 3

Figure 4

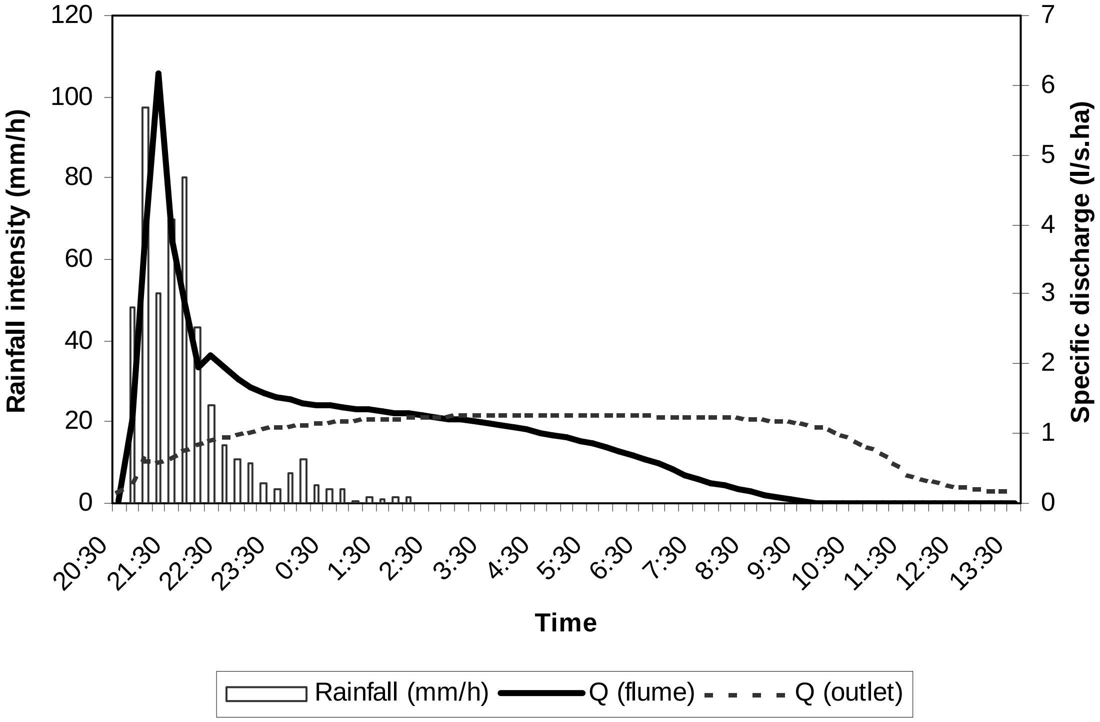


Fig. 4

Table 1. Characteristics of the detention ponds of the Heulen Gracht Catchment. Location of the ponds is given in Fig. 2

Pond	Max. dam Height (m)	Width of overflow (m)	Max. storage volume (m^3)	Diameter orifice plates (m)	Volume / catch. area (mm)
1	2.1	10.5	3500	0.2/0.25	1.46
2	2.2	12.6	6200	0.2/0.2	2.38
3	0.95	3.0	2000	0.25/0.25	0.67

Table 2

Table 2. Results of runoff measurements in the San Dimas flume and the detention ponds of the Heulen Gracht Catchment

	Rainfall data				Flume		Pond # 1		Pond # 2		Pond # 3 [a]		
Date (d/m/y)	A (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								0.05		
13/08/2004	11.2	23	< 2								0.05		
14/08/2004	20.6	14	< 2								0.26		
01/07/2005	17.4	0.8	2				0.08	7.25	0.23	16.5	< 0.03		
14/08/2005	36.6	20.5	5				NA		NA		0.07		
23/10/2005	25.6	12	<2				0.04	7.5	0		< 0.03		
25/10/2005	14.8	10	< 2				0.05	6.75	0		< 0.03		
31/03/2006	26	21	< 2				0.08	10.7	0.08	12.33	0.09	2	
01/04/2006	7	14	< 2				0.06	6.33	0.06	7	< 0.03		
05/05/2006	10.8	3	< 2	38	0.008	0.07	0		0		< 0.03		
18/05/2006	6	1	< 2	34	0.03	2	0		0		< 0.03		1.6
21/05/2006	18	3	< 2	38	0.25	4.4	0.10	9.33	0.10	10.4	0.08	4	5.3
26/05/2006	11.1	10	< 2	8	0.04	3.4	0.07	11	0.07	11	< 0.03		NA
29/05/2006	14.6	7	< 2	18	0.14	6.7	0.10	12	0.10	14.4	0.08	7	4.5
14/06/2006	24.7	1	10	94	0.44	5.2	0.28	10.4	0.26	11.4	0.24	9.84	5.9
03/08/2006	12.9	4	< 2	30	0.09	10.2	0		0		< 0.03		8.1
04/08/2006	17.6	5	< 2	36	0.11	9.6	0		0		< 0.03		7.6
05/08/2006	8.2	2	< 2	30	0.29	8.9	0.05	7.25	0.05	6.3	< 0.03		7.1

14/08/2006	22.5	6	2	29	0.16	8.9	0.08	11.1	0.08	11.75	0.09	1.66	1.7
15/08/2006	10	3	< 0	23	0.09	14	0.06	10	0.06	12.7	< 0.03		11.2
16/08/2006	10.3	1.5	< 2	32	0.33	20.9	0.09	10.4	0.09	12.5	0.07	3.9	4.5
19/08/2006	7.9	0.33	< 2	43	0.12	2.5	0.08	13.25	0.07	14.66	< 0.03		2
21/08/2006	23.4	4	2	37	0.37	9	0.17	14.33	0.13	15	0.11	8.75	3.9
17/11/2006	14.8	7	< 2	17	NA	NA	0.07	10.5	0.07	8	< 0.03		NA
19/11/2006	8.4	5.5	< 2	7	NA	NA	0.05	17	0.05	21.9	< 0.03		NA
07/12/2006	7	2.5	< 2	6	0.11	4.6	0.05	14.5	0.05	18.5	< 0.03		3.7
08/12/2006	12	3	< 2	10	0.03	2.1	0.07	13.5	0.07	16.5	< 0.03		1.6
12/12/2006	6.2	5	< 2	6	0.03	6.1	0.06	NA	0.06	NA	0.04	NA	4.9
18/01/2007	16	17.5	< 2	7	0.03	2.6	0.07	21.4	0.07	18.4	< 0.03		2.1
19/01/2007	13	6	< 2	11	0.12	4.1	0.10	17	0.10	18.4	0.08	4.5	3.3
26/02/2007	15.7	14.5	< 2	17	0.14	3.6	0.09	15.5	0.09	18.5	0.07	3.5	2.4
28/02/2007	10.2	7	< 2	12	0.09	4.5	0.06	9.5	0.06	11	< 0.03		3.5
07/03/2007	10.6	22	< 2	7	0.06	2.5	0.03	8	0.03	8.4	< 0.03		2.0
25/05/2007	13.5	2	< 2	74	0.19	3.3	0.04	4.5	0.04	3.25	< 0.03		2.7
11/06/2007	43	1	150	110	1.47	22.7	0.44	14	0.39	15.15	0.37	16.25	16.4
18/06/2007	5	0.33	< 2	19	0.10	19.6	0.04	NA	0.07	19	0.05	3	4.5
25/06/2007	10.8	10	< 2	41	0.05	0.8	0.03	NA	0.04	7.7	< 0.03		0.6
20/07/2007	14.5	6	< 2	30	0.06	1.2	0.07	NA	0.03	7	< 0.03		0.9
28/07/2007	15.9	9.5	< 2	16	0.14	4.8	0.07	14	0.03	13	0.05	1.5	0.8
02/08/2007	19.4	4	2	20	0.31	9.5	0.16	17	0.13	16.5	0.10	8	3.9
09/08/2007	50	14	50	12	0.34	15.1	0.28	34	0.27	33	0.26	28.5	9.5
21/08/2007	20.8	17	< 2	34	0.24	6.9	0.11	19.5	0.11	20	0.09	8	2.6

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[a] Data for the period 2002-2004 are available from ‘crest stage recorder’ measurements. Such a recorder consists of a plastic tube with a length of water-sensitive tape which changes colour on contact with water.

A : 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.

NA : Not available.

Table 3

Table 3. Summary of *t*-test results to detect significant differences in the flume (upstream of GWW) and at the outlet. SD = standard deviation.

Parameter	Peak discharge per ha		Runoff coefficient		Flow duration		Lag time		Sediment discharge	
	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
t stat	2.4		2.5		- 2.8		- 8.1		1.9	
P (T≤ *t*)	< 0.01		< 0.05		< 0.01		< 0.0001		0.064 (NS)	

NS = not significant.

Table 4

Table 4. Muddy flood events requiring fire brigade interventions in Velm village between 1977-2002 and associated rainfall depth. Return periods after Delbeke (2001).

Date	Daily rainfall (mm)	Duration (hours)	Return period
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	NA		
08/05/2000	NA		
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

Table 5

Table 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.

	San Dimas Flume			Dam 1	Dam 2	Dam 3
Date (d/m/y)	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	NA
29/05/2006	20	10	10	0.2	0.1	NA
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	NA	NA
07/03/2007	2	1.1	2	0.9	0.3	NA
25/05/2007	2	2.1	2	0.7	NA	NA
11/06/2007	117	5	24	1.6	1.9	2.2
18/06/2007	10	4.4	4	0.3	0.2	NA
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