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

3
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18
19 **Abstract**

20
21 Muddy floods, i.e. runoff from cultivated areas carrying large quantities of soil, are frequent and
22 widespread in the European loess belt. They are mainly generated in dry zero-order valleys and are
23 nowadays considered as the most likely process transferring material eroded from cultivated hillslopes
24 during the Holocene to the flood plain. The huge costs of muddy flood damages justify the urgent
25 installation of control measures. In the framework of the 'Soil Erosion Decree' of the Belgian Flemish
26 region, a 12 ha-grassed waterway and three earthen dams have been installed between 2002-2004 in
27 the thalweg of a 300-ha cultivated dry valley in the Belgian loess belt. The measures served their
28 purpose by preventing any muddy flood in the downstream village, despite the occurrence of several
29 extreme rainfall events (with a maximum return period of 150 years). The catchment has been
30 intensively monitored from 2005-2007 and 39 runoff events were recorded in that period. Peak
31 discharge (per ha) was reduced by 69% between the upstream and the downstream extremities of the
32 grassed waterway (GWW). Furthermore, runoff was buffered for 5-12 hours behind the dams, and the
33 lag time at the outlet of the catchment was thereby increased by 75%. Reinfiltration was also observed
34 within the waterway, runoff coefficients decreasing by a mean of 50% between both extremities of the
35 GWW. Sediment discharge was also reduced by 93% between the GWW's inflow and the outlet.
36 Before the installation of the control measures, specific sediment yield (SSY) of the catchment reached
37 3.5 t ha⁻¹ yr⁻¹ and an ephemeral gully was observed nearly each year in the catchment. Since the
38 control measures have been installed, no (ephemeral) gully has developed and the SSY of the
39 catchment dropped to a mean of 0.5 t ha⁻¹ yr⁻¹. Hence, sediment transfer from the cultivated dry valley
40 to the alluvial plain should dramatically decrease. Total cost of the control measures that are built for a
41 20 year-period is very low (126 € ha⁻¹) compared to the mean damage cost associated with muddy

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

44

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

47

48

49 **1. Introduction**

50

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

58 About 90% of muddy floods observed in the Belgian loess belt are generated on
59 cultivated hillslopes (10-30 ha) and in dry zero-order valleys (30-300 ha; Evrard et al.,
60 2007a). Numerous studies carried out in cultivated catchments of the European loess belt
61 showed that most sediments produced during the Holocene have been stored in the dry valley
62 bottom near the catchment outlet and have not been delivered to downstream rivers (e.g. Bork
63 et al., 1998; Lang et al., 2003; Rommens et al., 2005; de Moor and Verstraeten, in press).
64 Rommens et al. (2006) also estimated the Holocene alluvial sediment storage in a small (52
65 km^2) river catchment of the Belgian loess belt. They showed that sediment supply towards the
66 alluvial plain has increased dramatically since Medieval times compared to the rest of the
67 Holocene period and occurred at a mean rate of $1.3 \text{ t ha}^{-1} \text{ yr}^{-1}$. Since 50% of sediment eroded
68 from hillslopes was stored in colluvial deposits, mainly located in dry zero-order valley
69 bottoms, muddy floods caused by severe erosion on agricultural land are the mostly likely
70 process transporting sediments from the dry valleys to the alluvial plains. During heavy
71 rainfall in late spring and summer, ephemeral gullies form in these dry valleys. These shallow
72 ($\sim 0.1 \text{ m}$) but wide ($\sim 3 \text{ m}$) gullies act as an important conveyor of sediment and may
73 aggravate the off-site damage produced by muddy floods (Nachtergaele and Poesen, 2002;
74 Verstraeten et al., 2006).

75 The huge costs associated to this damage, which appears to have occurred more
76 frequently during the last decade, justifies the urgent installation of mitigation measures
77 (Evrard et al., 2007a). Two types of measures can be carried out to control muddy floods. On

78 the one hand, alternative farming practices implemented at the field scale, such as sowing of
79 cover crops during the intercropping period, reduced tillage or double sowing in zones of
80 concentrated flow, limit runoff generation and erosion production (Gyssels et al., 2002; Leys
81 et al., in press). However, the implementation of these practices directly depends on the
82 farmer's willingness. Except for sowing of cover crops (e.g. in Belgium; Bielders et al.,
83 2003), the adoption of such practices remains rather limited in Europe (Holland, 2004). It will
84 probably still take several years or even decades before reduced tillage and double sowing are
85 applied generally. On the other hand, 'curative' measures aim to reinfiltrate or buffer runoff
86 once it is formed, as well as to trap sediments and pollutants. Typically, grass buffer strips,
87 grassed waterways (GWW) and detention ponds (retaining runoff for a certain time behind a
88 small dam) serve this purpose (Fiener and Auerswald, 2005). Such curative measures are most
89 effective when they are implemented in the framework of integrated catchment management.
90 Hence, a local water board should be responsible for deciding in consultation with farmers
91 where to install these measures within the catchment and for ensuring their maintenance.

92 From 2001 onwards, municipalities in the Belgian Flemish region are eligible for
93 subsidies to draw up an erosion mitigation scheme (Verstraeten et al., 2003). Several small-
94 scale measures such as dams and GWW are being installed in the field but there is a need to
95 evaluate their efficiency before generalising their installation in problem areas. Furthermore,
96 since muddy floods are generated on large surfaces (10-300 ha; Evrard et al., 2007a), the
97 effect of control measures should be investigated at similar scales. However, previous
98 research has focused on the effect of grass buffer strips and has mostly been carried out on
99 experimental plots (typically 500 m², see e.g. Van Dijk et al., 1996; Patty et al., 1997; Le
100 Bissonnais et al., 2004). With respect to the effect of GWW in the European context, it has
101 only been assessed at the micro-catchment scale (max. 8 ha; Fiener and Auerswald, 2005;
102 Fiener et al., 2005). Large quantities of concentrated runoff leading to muddy floods cannot
103 be generated on such small surfaces and a specific study is hence needed at the scale of the
104 larger catchments, which are the source areas of muddy floods.

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

108

109 2. Materials and methods

110

111 2.1. General context

112

113 The Belgian loess belt (~ 9000 km²) is a plateau with a mean altitude of 115 m gently
114 sloping to the North (Fig. 1a). Annual mean temperature varies between 9-10°C, while annual
115 precipitation ranges from 700-900 mm (Hufty, 2001). Soils are mainly loess-derived Haplic
116 Luvisols (World Reference Base, 1998). Arable land covers 65% of the total surface
117 (Statistics Belgium, 2006). During the last three decades, the area covered by summer crops
118 (sugar beet – *Beta vulgaris L.*, maize – *Zea Mays L.*, potatoes – *Solanum tuberosum L.* and
119 chicory – *Cichorium intybus L.*) increased at the expense of winter cereals (Evrard et al.,
120 2007a). The summer crops provide little cover to the soil during the thunderstorms that occur
121 in late spring or early summer, which leads to the formation of a soil surface crust with a very
122 low infiltration rate. High quantities of runoff are then generated on these crusted soils during
123 intense precipitation (Evrard et al., in press).

124 The region of Sint-Truiden has been repeatedly affected by muddy floods, and the
125 local water agency (Melsterbeek Water Board) decided to tackle the problem (Fig. 1a). In the
126 framework of the ‘Erosion Decree’ adopted by the Flemish government in 2001, they drew
127 up an erosion mitigation scheme at the catchment scale (200 km²). Between 2002-2005, 120
128 grass strips and GWW have been installed, covering a surface of ~ 25 ha (0.13% of total
129 area). Furthermore, 35 earthen dams have been built.

130

131 2.2. Study area

132

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

136 A 300 ha-catchment draining into Velm, locally known as ‘Heulen Gracht’, was
137 selected for detailed monitoring (Fig. 2). Cropland covers 79% of the catchment surface.
138 Orchards (17%) and roads (3%) are the other main types of land use. A typical topsoil sample
139 in this catchment contains 80% silt, 10% clay and 10% sand and the mean slope reaches
140 1.3%.

141 An earthen dam was built close to the catchment outlet in April 2002 to prevent
142 muddy floods (dam # 3 in Fig. 2). A GWW was also sown in the thalweg in 2003, covering
143 12 ha (4% of total catchment surface; Fig. 2). Grass species consist of a mix of *Lolium*

144 *multiflorum* Lam., *Lolium perenne* L., *Festuca rubra* L. subsp. *Rubra* and *Dactylis glomerata*
145 L. Two additional dams were built across the GWW in August 2004 (dams # 1 and 2 in Fig.
146 2).

147

148 2.3. Impact of control measures on runoff

149

150 Rainfall is measured at 0.1 mm resolution using two tipping bucket rain gauges
151 located at the catchment outlet and just upstream of the GWW (Fig. 2). The catchment was
152 equipped with a discharge measurement station in April 2006. It consists of a San Dimas
153 flume connected with a flowmeter (Sitrans Probe LU, Peterborough, Ontario, Canada).
154 Finally, a water level logger (Global Water-WL 15, Gold River, California, USA) was
155 installed in May 2005 behind each of the three earthen dams built across the GWW. A
156 topographic survey was carried out in Spring 2005 to determine the volume-depth curves of
157 the detention ponds (Table 1). Water temporarily stored in the detention ponds drains through
158 a pipe at the bottom of the dam. Water levels are converted to outflow discharges using Eq. 1
159 (Ilaco, 1985) :

$$160 \quad Q = A \times (2gh)^{0.5} \quad (1)$$

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

163

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

171

172 2.4. Impact of control measures on erosion

173

174 The rills and gullies that were formed during the monitoring period have been mapped,
175 their length, depth and width measured. The cross-sectional area of erosion features has been
176 computed for 67 transects within the catchment. The mass of eroded soil is determined using
177 the mean value of bulk density measured for cropland in loess soils of central Belgium (1.43 g

178 cm⁻³; Goidts and van Wesemael, 2007). Sediment thickness in the detention pond located
179 behind dam # 3 (Fig. 2) was measured with an estimated precision of 5 mm with a meter on a
180 5m-grid after each important rainfall event (with ≥ 10 mm of cumulative rainfall). Data are
181 interpolated to estimate sediment volume and mass. The calculated erosion rates are compared
182 to the output of an empirical relationship between catchment area (A, ha) and specific
183 sediment yield (SSY, t ha⁻¹ yr⁻¹) obtained for 26 cultivated catchments of the Belgian loess
184 belt over a period of 2-46 years during the 20th century (Eq. 2; Verstraeten and Poesen, 2001).

$$185 \quad SSY = 26A^{-0.35} \quad (2)$$

186

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

197

198 *2.5. Impact of control measures on muddy floods*

199

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

206

207 **3. Results**

208

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

211

212 3.1. Impact of control measures on runoff

213

214 The San Dimas flume recorded 39 runoff events in 2006 and 2007 (Table 2). Runoff
215 coefficients of the catchment upstream of the GWW calculated based on the San Dimas flume
216 discharge varied between 0.07% and 22.7%, with a mean of 7.4% (Table 2). Usually, runoff
217 coefficients were higher in spring and summer (8.3%) than in autumn and winter (3.8%). The
218 highest coefficients were measured in August 2006, which was a very wet month, as well as
219 during the extreme event of June 11 2007. The heaviest and most intense storms have led to
220 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
221 11 2007; Table 2).

222 Some 53 rainfall-runoff events have been measured behind the dams (Table 2). Before
223 the installation of dams 2 and 3 in August 2004 (Fig. 2), runoff events with a discharge \geq
224 $0.03 \text{ m}^3 \text{ s}^{-1}$ have been observed at dam 3 during low-intensity precipitation (e.g. in February,
225 2003; Table 2). After the installation of the two additional dams, notable runoff has been
226 measured behind the dam at the outlet (dam 3; Fig. 2) during only 13 events. These events
227 correspond to: (i) prolonged periods of rain in winter ($\geq 30 \text{ mm}$ in 48 hours) or (ii) to heavy
228 thunderstorms between May and August ($\geq 20 \text{ mm}$ in a few hours). All runoff parameters are
229 significantly different between both extremities of the GWW at the 95% confidence interval
230 (Table 3).

231 An important and significant decrease of the peak discharge per unit area (mean of
232 69%) was observed between the San Dimas flume (just upslope of the GWW) and the
233 catchment outlet. Loss of runoff, probably due to infiltration in the GWW and behind the
234 dams, has also been observed. Runoff coefficients decreased by a mean of 40% between both
235 extremities of the GWW (Table 3). The reduction was higher during low-intensity rainfall
236 (mean of 43% for events with an $I_{\max} < 40 \text{ mm h}^{-1}$) than during intense thunderstorms (mean
237 of 20% for events with an $I_{\max} > 40 \text{ mm h}^{-1}$; Table 2).

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

243 Peak flow left the San Dimas flume and reached the outlet of the first dam in a mean
244 of 2 hours 25 minutes (mean propagation velocity of the peak discharge of 0.04 m s^{-1}). Peak
245 outflow from the first dam reached the outlet of the second pond in a mean of 32 minutes

246 (mean propagation velocity of 0.09 m s^{-1}). Some 64 minutes were then needed for peak runoff
247 to reach the outlet of the third dam (mean propagation velocity of 0.14 m s^{-1}). The
248 propagation of the peak discharge was hence slowed down in the GWW, but the decrease was
249 not linear between the dams (Table 2).

250

251 *3.2. Impact of control measures on specific sediment yield*

252

253

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

257 Six major erosion events have been documented between April-September 2002
258 (Table 4). The first erosion event occurred in May 2002. The summer crops were already
259 sown at that time, and tillage erased erosion features remaining from the winter period. Total
260 volume of the rills and gullies reached $\sim 1500 \text{ m}^3$ in September 2002, corresponding to a soil
261 loss due to rill and gully erosion of 2175 T . Rill and gully cross-section was very variable (0.2
262 -2.5 m^2), both between and within fields. Erosion rate reached a mean value of 7.25 t ha^{-1} at
263 the catchment scale in 2002, without taking sheet erosion into account.

264 Measurements of sediment concentrations in the flume as well as in the outflow of the
265 dams are available for 13 events recorded in 2006 and 2007 (Table 5). Much of the sediment
266 was trapped behind the first dam. Sediment concentration in the first dam's outflow is
267 decreased by a mean of 86% compared to the concentration measured in the San Dimas
268 flume. It further decreased by 16% due to trapping behind the second dam. In contrast, an
269 increase of sediment concentration (+ 38%) was generally measured at the catchment outlet
270 compared to the second dam outflow. This is due to the inflow of runoff loaded with
271 sediments, flowing from row crop fields located along this part of the GWW. However,
272 sediment concentrations at the outlet were reduced by a mean of 88% (0.9 g l^{-1}) compared to
273 the ones measured in the flume (mean of 5.4 g l^{-1}). Sediment discharge was reduced by a
274 mean of 93%, decreasing from 3.2 kg s^{-1} in the flume to 0.2 kg s^{-1} at the outlet. However, this
275 difference was not statistically significant at 95% confidence interval (Table 3). This is
276 probably due to the rather low number of events for which sediment data are available, as well
277 as to the important seasonal variation of runoff and sediment production on cropland in the
278 Belgian loess belt. Rainfall simulations have shown that sediment production is much lower
279 on crusted soils in August (3 g l^{-1}) than on fragmentary soils (40 g l^{-1}) at the end of spring
280 (Evrard et al., in press). During the extreme event of June 11 2007, 84 t of sediments were

281 trapped behind the three successive dams. It represents 72% of soil loss measured in the San
282 Dimas flume. No more rills have been observed in the thalweg since the sowing of the GWW
283 and the construction of the dams despite the occurrence of several extreme events.

284

285 *3.3. Impact of control measures on muddy floods*

286

287 Soil erosion and flooding are ancient problems in the area. Flooding of the nearby
288 Gingelom village was already very frequent during the 18th century (Aumann and
289 Vandenghoer, 1989). Intense soil erosion was explicitly mentioned in the 1960s for the nearby
290 Gingelom village (Fig. 1b; T'Jonck, 1967). However, the off-site consequences have become
291 more frequent during the last two decades (Evrard et al., 2007a). Fire brigade interventions
292 due to muddy floods in the Velm village dramatically increased since 1980 (Table 4). All
293 muddy floods were triggered by heavy thunderstorms (between 14-70 mm of rainfall, with a
294 mean of 35.5 mm) and occurred between May and August (Table 4). Six heavy storms (20-70
295 mm precipitation) occurred in 2002, each leading to the flooding of the village. The three
296 events in August 2002 were rather extreme, having a return period between 20- and > 200
297 years (after Delbeke, 2001).

298 Since the installation of the GWW and the two additional earthen dams in 2004, no
299 muddy flood has been recorded in Velm village, despite the occurrence of several extreme
300 events (Table 2). The measures have particularly served their purpose during the extreme
301 event of June 11 2007 (having a return period of 150 years, according to Delbeke, 2001),
302 buffering runoff during 17 hours and preventing any flood in Velm village (Fig. 4). Peak
303 discharge per unit area decreased by 79% and the lag time dramatically increased (from 10
304 minutes in the flume to 5 hours 30 minutes at the outlet).

305

306 **4. Discussion**

307

308

309 *4.1. Effectiveness of the grassed waterway and earthen dams*

310

311 The propagation of the peak discharge was drastically slowed down within the section
312 with the GWW and the earthen dams. However, there was no important reinfiltration in
313 GWW for moderate and extreme storms. This is due to a high soil compaction (bulk density
314 of 1.59 g cm⁻³ in the GWW compared to a mean of 1.43 g cm⁻³ for cropland in the Belgian
315 loess belt according to Goidts and van Wesemael, 2007). This confirms the results of rainfall

316 simulations carried out in the Belgian loess belt showing that grass strips and GWW have a
317 higher runoff coefficient (62-73%) than most cultivated soils (13-58%; Evrard et al., in press).

318 Sediment trapping is very high and occurs mainly behind the first dam, except during
319 extreme events. These observations confirm the main results of a former modelling exercise
320 (Evrard et al., 2007b). The model simulated that the GWW led to a 50% decrease of peak
321 discharge, which is consistent with field observations. Our findings also agree with the results
322 of a similar study analysing the impact of a GWW on runoff and erosion in a micro-catchment
323 (8 ha) in southern Germany (Fiener and Auerswald, 2005; Fiener et al., 2005). The German
324 ponds were very efficient in trapping sediments (between 50-80% of sediments were trapped)
325 and reducing peak runoff rates. However, two main differences with our study can be
326 outlined, besides the different catchment sizes. In Germany, no event having a return period
327 of > 5 years occurred during the 9-year experiment, while we observed that the dams
328 particularly served their purpose during extreme events. Furthermore, an intensive soil and
329 water conservation scheme was implemented in the German catchments draining to the ponds,
330 limiting sediment and runoff inputs (Auerswald et al., 2000). Our study shows that even
331 without widespread implementation of alternative farming practices, the measures are
332 effective in controlling muddy floods. They offer, therefore, a solution that can be
333 implemented in the short term to protect the most endangered villages against muddy floods.

334

335 *4.2. Evaluation of erosion rates and sediment delivery*

336

337 Based on field measurements in 2002, rill and gully erosion rates reached 7.25 t ha^{-1}
338 for that specific year. This figure does not take sheet erosion into account. Often, interrill
339 erosion has been estimated as a fraction of total soil loss. This fraction ranges between 10-
340 20% of the total soil loss in the Belgian loess belt (Govers and Poesen, 1988; Takken et al.,
341 1999; Steegen et al., 2000). Total erosion was hence underestimated in our study and should
342 be close to 8.3 t ha^{-1} . This figure is consistent with the range of annual erosion rates measured
343 in central Belgium ($6.5\text{-}12.3 \text{ t ha}^{-1} \text{ yr}^{-1}$; Verstraeten et al., 2006).

344 Nachtergaele and Poesen (1999) calculated a mean ephemeral gully erosion rate of
345 $2.33 \text{ t ha}^{-1} \text{ yr}^{-1}$ (over a six months period during which summer ephemeral gullies remain
346 active). The ephemeral gully in the thalweg of the Heulen Gracht Catchment was observed on
347 all aerial photographs available for the study area (between 1947-1996), always appearing at
348 the same location (Fig. 1b). Hence, no increase of gully erosion throughout the study period

349 was found. The highest erosion rate was even observed in 1947 ($3.43 \text{ t ha}^{-1} \text{ yr}^{-1}$), which shows
350 that erosion is not a recent phenomenon in the study area.

351 Steegen (2001) showed that summer extreme events have a particularly important
352 effect on long-term landscape evolution. For instance, a summer rainfall with a 10 year-return
353 period that occurred in a 250 ha-catchment in the Belgian loess belt exported several times the
354 mean long-term erosion rate ($7 \text{ t ha}^{-1} \text{ yr}^{-1}$ for the extreme event, after Steegen et al., 2000; vs.
355 $2.6 \text{ t ha}^{-1} \text{ yr}^{-1}$ for the long-term mean, after Vandaele, 1997).

356 During the extreme event of June 2007, the three ponds trapped sediments (84 t in
357 total). Since the control measures prevent the formation of rills and gullies in the catchment,
358 erosion rates are dramatically reduced. Only interrill erosion is still observed at a mean rate of
359 $0.5 \text{ t ha}^{-1} \text{ yr}^{-1}$, thereby drastically decreasing sediment delivery to the alluvial plain.

360

361 *4.3. Cost-efficiency of control measures*

362

363 Immediately after thunderstorms, people need assistance from the fire brigade and
364 municipal services to pump water from cellars and clean up the roads. Fire brigade
365 interventions after the thunderstorms of August 2002 in the Melsterbeek Catchment (Fig. 1a)
366 cost $\sim \text{€ } 25,000$ (i.e. 125 € km^{-2}). Muddy floods also led to numerous cases of damage to
367 private property. According to 1601 records submitted by Belgian households to the Disaster
368 Fund, mean damage amount was $\text{€ } 4,436$ (SD= $3,406 \text{ €}$; Evrard et al., 2007a). The villages of
369 Velm and Gingelom were particularly affected by the thunderstorms of May and August 2002
370 (Table 4). Households from these two villages submitted 268 records to the Belgian Disaster
371 Fund. They received $\text{€ } 636,967$ (mean of $\text{€ } 2,377$ per record).

372 Overall, muddy floods lead to a damage cost of $54 \text{ € ha}^{-1} \text{ yr}^{-1}$ in the region of Velm.
373 Total cost of the control measures installed in the area reached 126 € ha^{-1} . The measures are
374 built for a 20 year-period according to the Soil Erosion Decree. Farmers receive additional
375 subsidies each year for the maintenance of grass strips ($21 \text{ € ha}^{-1} \text{ yr}^{-1}$). Compared to the
376 damage cost of muddy floods ($54 \text{ € ha}^{-1} \text{ yr}^{-1}$), the investments would be cost-efficient in ~ 3
377 years if the measures are effective and no muddy flood occurs. Our results prove that the
378 measures serve their purpose. In Velm village, total investment ($\text{€ } 351,528$) represents the
379 damage cost to private properties caused by the single August 2002 flood.

380 The Flemish authorities calculated that the construction of all the control measures
381 proposed in the municipal erosion mitigation schemes that were approved by their
382 administration would cost between $7.7\text{-}9.6$ million € yr^{-1} during the period 2006-2025, which

383 is not disproportionate compared with the total damage cost associated with muddy floods in
384 the Flemish municipalities of the Belgian loess belt (between 8-86 million € yr⁻¹; Evrard et al.,
385 2007a).

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388 **5. Conclusions**

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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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411 **Acknowledgements**

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534 **Figure captions**

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

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

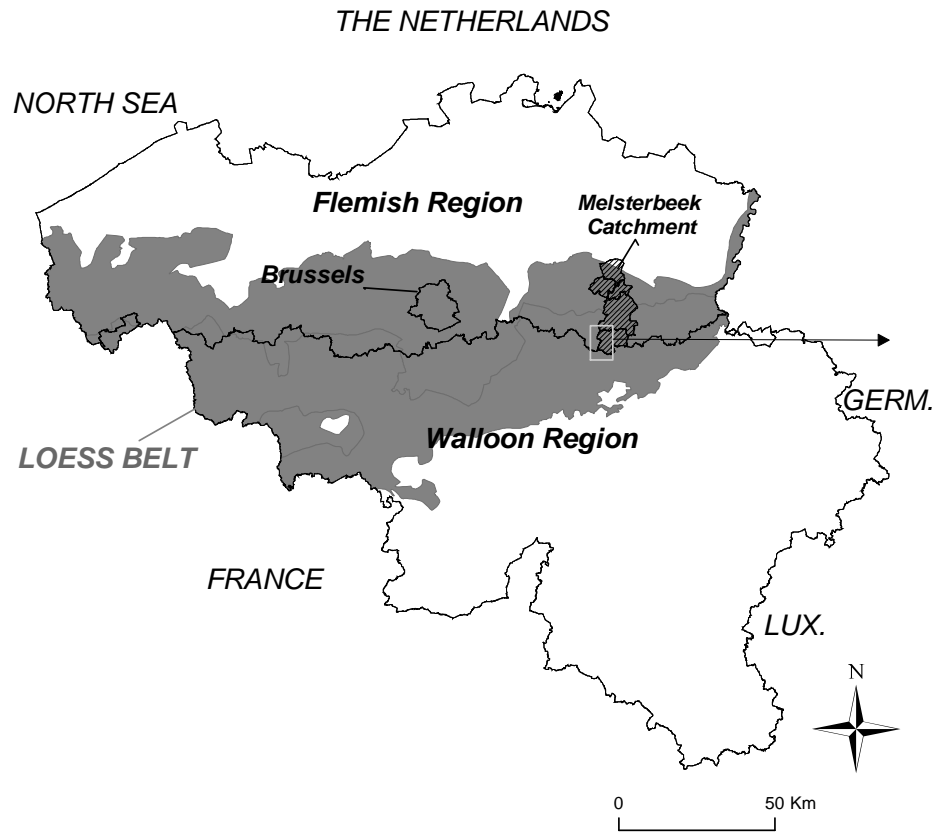
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544 Fig. 3. Monthly distribution of observed rainfall events during the period 2003-2007 with >
545 15 mm of cumulative precipitation, and number of recorded runoff events.

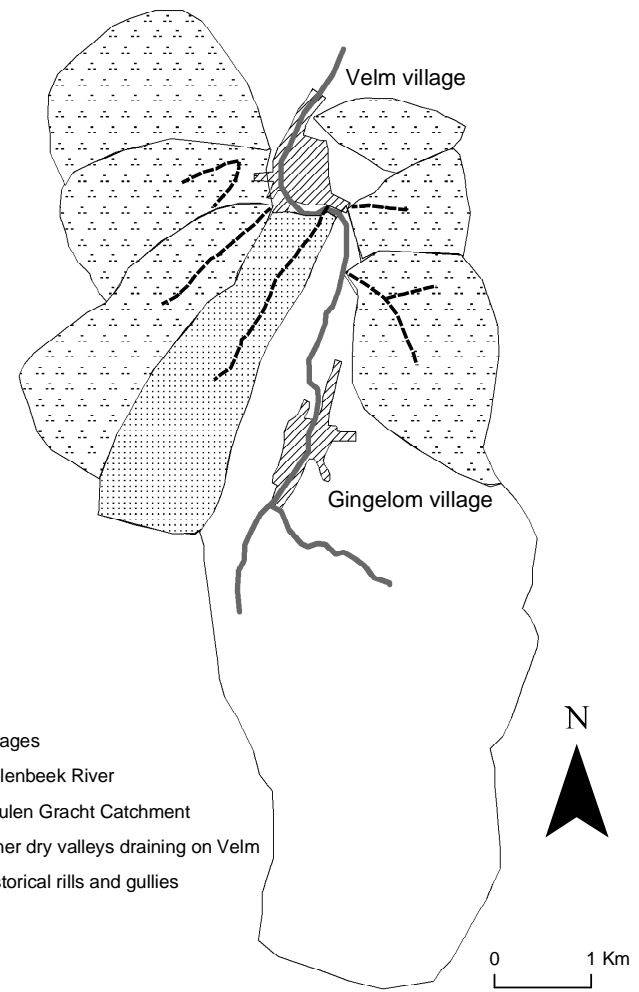
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548 Fig. 4. Rainfall, inflow and outflow hydrographs measured during the thunderstorm of June
549 11 2007.



(a)



(b)

Fig. 1

Figure 2

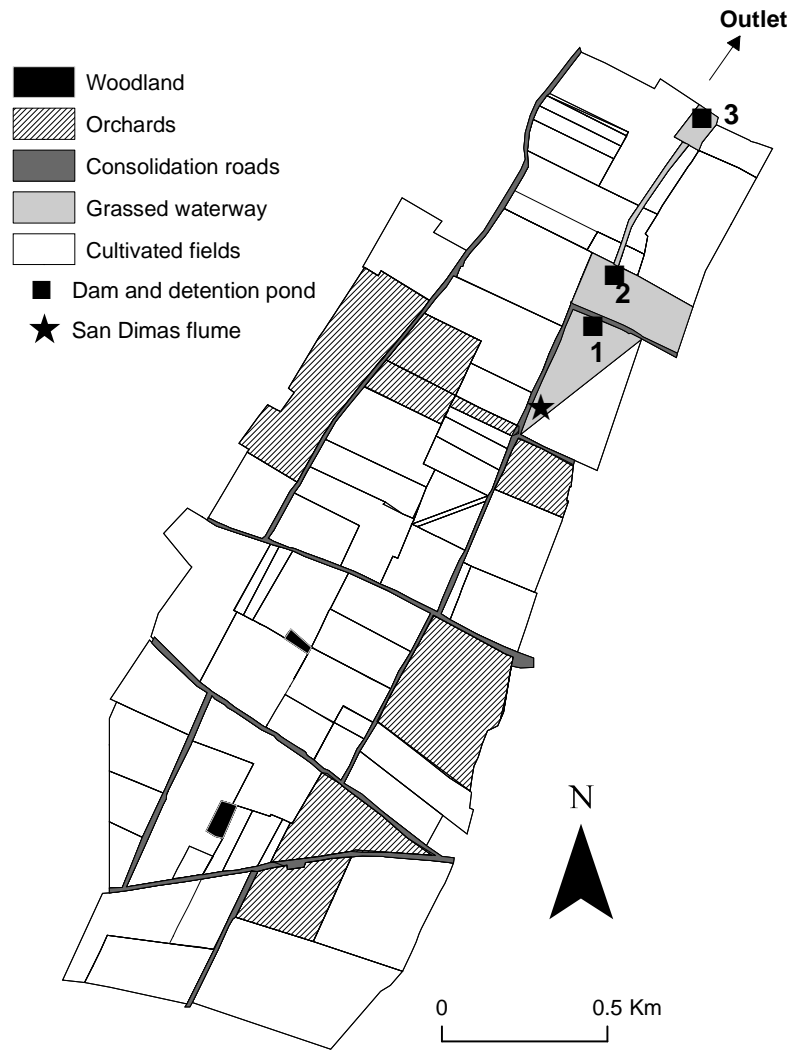


Fig. 2

Figure 3

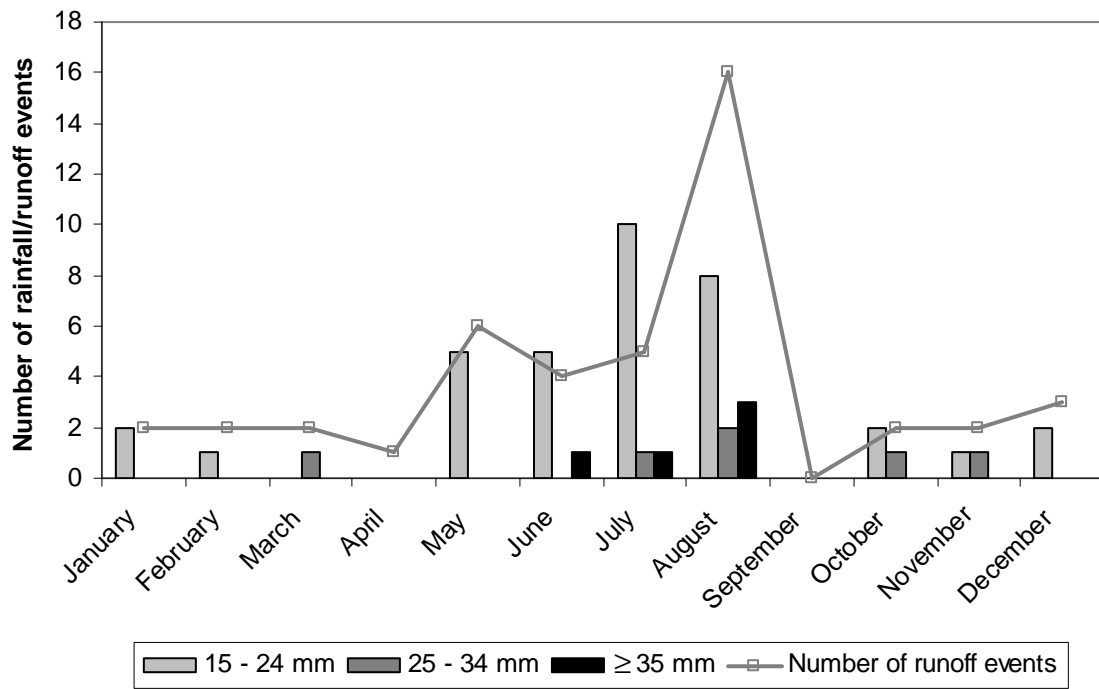


Fig. 3

Figure 4

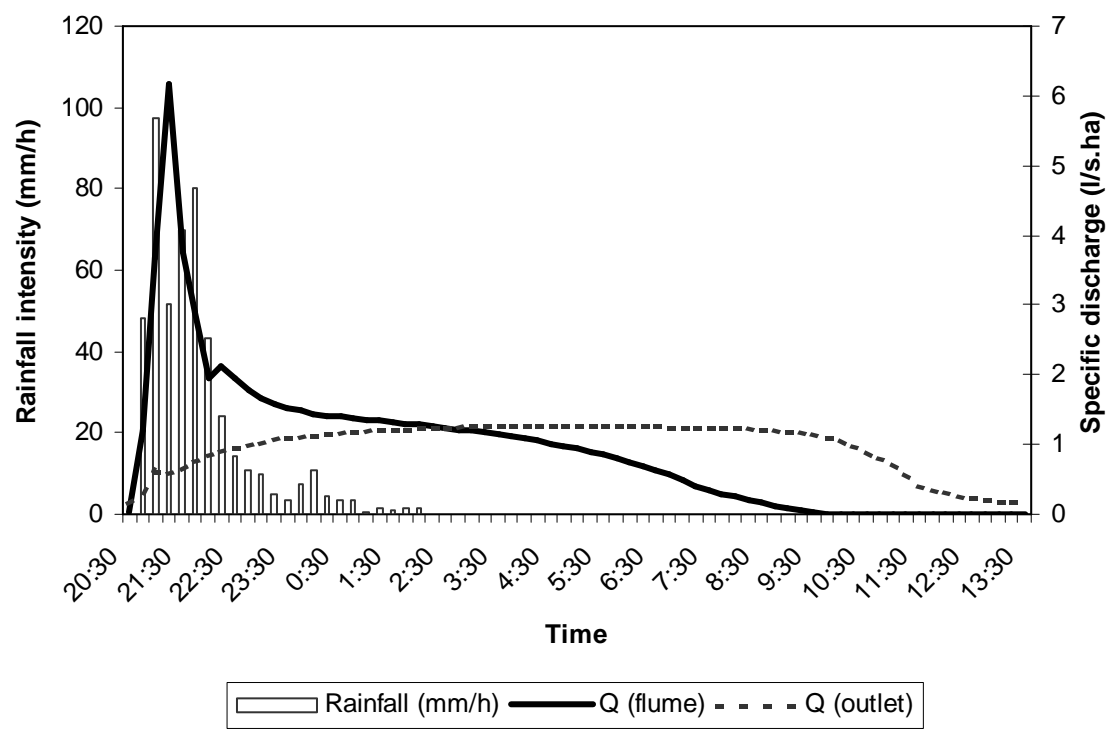


Fig. 4

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

Date (d/m/y)	Rainfall data			Flume		Pond # 1		Pond # 2		Pond # 3 ^a			
	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

^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 3Table 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
<i>t</i> stat	2.4		2.5		- 2.8		- 8.1		1.9	
P ($T \leq t$)	< 0.01		< 0.05		< 0.01		< 0.0001		0.064 (NS)	

NS = not significant.

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.

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	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