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Flash floods and muddy floods in Wallonia: recent temporal trends, spatial distribution and reconstruction of the hydrosedimentological fluxes using flood marks and sediment deposits

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Flash floods and muddy floods in Wallonia: recent temporal trends, spatial distribution and reconstruction of the hydrosedimentological fluxes using flood marks and sediment deposits

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Introduction

1 Among the variety of natural hazards, flash floods are one of the deadliest and most devastating in terms of economic losses (Johnson, 2000; Gaume *et al.*, 2009; Llasat *et al.*, 2014). The definition of a flash flood is quite ambiguous in the literature. However, it is always associated with high flow velocity, strong rainfall intensity and often steep slopes but also, more implicitly with relatively small watersheds (Hirschboeck, 1988; Douvinet & Delahaye, 2010) ranging from a few square kilometres to a couple of hundreds square

kilometres (Scarwell & Laganier, 2004). Muddy floods are caused by runoff carrying large quantities of soil from bare or relatively bare agricultural fields (Boardman & Vandaele, 2010) and generally occur in valleys without permanent watercourses (Evrard *et al.*, 2007). The disambiguation between these two phenomena in testimonies may be difficult due to the incompleteness of the data sources. This paper will address both flash floods and muddy floods as they are reported in the newspapers. In their European analysis of flash floods, Gaume *et al.* (2009) considered a maximum catchment area of 500 km^2 and a rainfall event inferior to 24 h. Most flash flood events are attributed to precipitation generated in stationary Mesoscale Convective Systems (Anquetin *et al.*, 2010). The risk to be affected by such a flood is a combination of property vulnerability and flash-flood hazard (Verstraeten & Poesen, 1999). The concepts of urbanization and population density therefore also come into play. Numerous papers including the synthetic analysis of Gaume *et al.* (2009) report case studies all over the world. In the European context, most studies were conducted in the Mediterranean mountainous region (Poesen & Hooke, 1997), due to the hydroclimatic particularities, urbanization and intense rainfall events (Vinet, 2008, 2010) and in the loess areas such as the Belgium loess belt, the South Downs in the UK, the Pays de Caux in northern France and the Limburg in the Netherlands (Bielders *et al.*, 2003).

2 Despite strongly different contexts, most studies show that some human factors often make the situation worse, such as the urbanization of hazardous zones of concentrated runoff downstream large areas of monocultures, the undersized design of the drainage system as it was seen in Nîmes (France) (Fabre, 1989) or the location of campgrounds in areas with high risk and a lack of maintenance of dams, as in Biescas in the upper basin of Gállego river in Spanish Pyrenees (Benito *et al.*, 1998; Gutiérrez *et al.*, 1998). In the area of Nîmes, Davy (1990) used historical data and mentioned three comparable events of high intensity (in 1557, 1599 and 1868) and several others with a slightly lower intensity. She concluded that these events occur with a return period of about 50 years. Others examples were studied in Mediterranean mountainous region (Cosandey, 1993; Ruin *et al.*, 2008) and showed radical geomorphological changes in rivers affected by flash floods as the Guil river (Tricart, 1961; Arnaud-Fassetta *et al.*, 2005) and the Bez river (Lahousse & Salvador, 1998). Regarding the size of the catchment, we can note that the devastating flood event of Ouvèze on September 22, 1992 is still considered by Piegay & Bravard (1997) as a flash flood despite a peak flow reaching nearly 1,000 $m^3.s^{-1}$ and a catchment area of about 600 km^2. In the United States, Davis (1998) used a cut-off threshold of 100 square miles (corresponding to about 260 km^2). In humid temperate climate, many flash flood cases were also described in England (Harvey, 1986), in the Paris Basin (Dacharry, 1988; Douvinet & Delahaye, 2010; Douvinet *et al.*, 2013) and in the Ardennes (Pissart, 1961); some of these events were pluri-centennial floods (Petit, 1995). Several studies were conducted in Belgium, most of them refer to muddy flood events rather than flash flood events. Evrard *et al.* (2007) compiled a database of 367 locations affected by muddy floods in 204 municipalities in the loess belt, completing the surveys of farmers carried out earlier by Verstraeten & Poesen (1999) and Bielders *et al.* (2003). These compilation studies give precise information on recent muddy flood events. However, the limited historical memory of the survey respondents does not allow a clear analysis of long-term trends Bielders *et al.* (2003).

3 It is clear from the literature that the greatest part of flash floods with major geomorphologic impacts often occurs in small ungauged catchments (Collier, 2007;

Anquetin *et al.*, 2010; Ruiz-Villanueva *et al.*, 2010; Hapuarachchi *et al.*, 2011; Alfieri *et al.*, 2012). The watershed may be equipped with a gauging station. However, this equipment may be destroyed by the extreme water velocity or the estimated peak flow is very uncertain due to the extrapolation of the rating curve. Obtaining flow rates estimate through indirect evidences is necessary in order to characterize these events in terms of bed load transport and soil erosion through suspended load.

4 This paper will show how these estimates were accomplished after a major flash flood event in the area of Liège (Belgium) on May 29, 2008 and the uncertainties that are associated with these indirect reconstructions. We had the opportunity to perform field surveys after this event that caused heavy damage and affected several streams with forested and partially urbanized watersheds. We have not focused our initial observations on urban areas because the experience gained during the flood mapping of the urban region of Liège (Van Campenhout *et al.*, 2007) and in Wallonia (Peeters *et al.*, 2006) ensured us that a wide variety of information would be available in urban area: pictures, movies, surveys of the residents and information from the municipal and intervention services (firemen, civil defence, ...). Our observations focused on the forested parts of the watershed where flood marks and ephemeral information about the flash flood was available. A particular methodology was used to reconstruct the flow rate, estimate the vertical and lateral erosion, attempt to quantify the bed load and suspended load transport in these ungauged catchments.

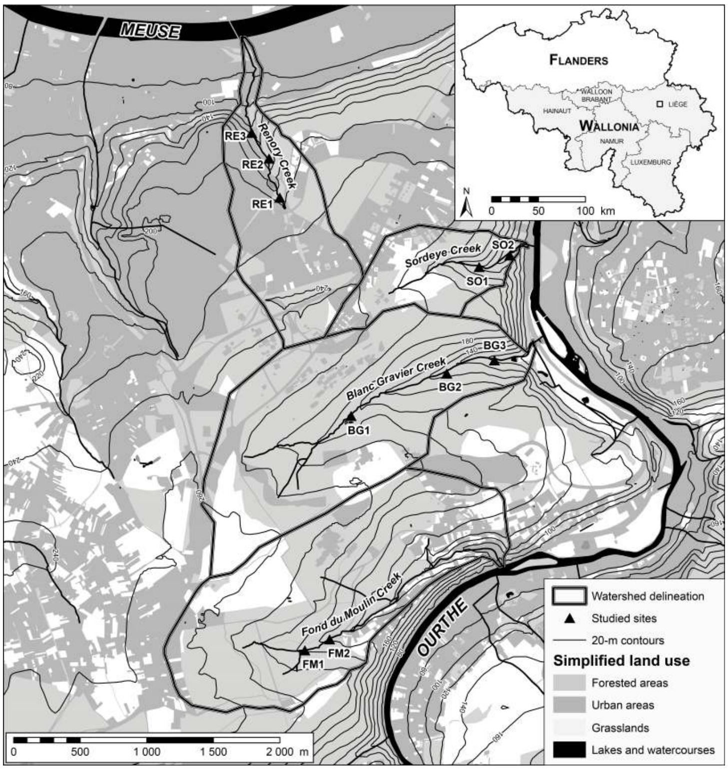
Hydrosedimentological characteristics of the May 29, 2008 major flash flood event in Liège

Location of the flash flood

5 On May 29, 2008 in the early morning, a storm cell oscillated along the Belgian-German border and generated intense rainfall on the southern part of the Liège urban area, corresponding to the interfluve between the Ourthe valley and the Meuse valley (Figure **1**). The rain gauge located on the Sart Tilman plateau has recorded 92.5 mm between 6 am and 9:30 am (Deliège *et al.*, 2009), with a maximum hourly intensity reaching 76.7 $mm.h^{-1}$ which corresponds to a return period much greater than 200 years (Mohymont & Demarée, 2006). Considering the Ruthy's curve that envelopes the most extreme rainfall events recorded in Belgium between 1889 and 1960 (Ruthy, 1961), the rainstorm observed at Liège is even more extreme. Rivers of this region with high slopes suffered from flash floods devastating both forested and urban areas. Newspapers reported that the damage was estimated by insurance companies at € 33 million for 9,000 people affected by this event in the province of Liège. Unfortunately, we have not had access to the insurance databases to pinpoint the precise location and the characteristics of the damage. These costs are signicantly high for a single flood event in Belgium. Evrard *et al.* (2007) showed that extreme events in the loess belt generate yearly a societal cost between 16 and € 172 million. Topographic surveys were performed quickly during the days following the event in order to reconstitute the hydrological conditions and to assess geomorphological and sedimentological impacts of this flash flood on peri-urban steep watersheds. Four creeks were affected by the May 29, 2008 flash flood in varying magnitude. Two of them are almost exclusively forested (Sordeye Creek and Blanc Gravier Creek), the other watersheds are partially urbanized (Renory Creek, urbanized in its lower part and the

Fond du Moulin Creek where the lower two-thirds are highly urbanized). The area of these catchments ranges from 0.65 to 2.53 km² and the average slope of the thalweg from 6.6 to 13.2% (Table **1**). The geological substrate consists in Devonian rocks: schists, quartzites and micaceous sandstone (Emsian and Praguian: 400 Ma) and sandy Carboniferous shales (299-325 Ma). On the plateau, these rocks are overlain by Cenozoic sands (Oligocene, 28-33.7 Ma), quaternary wind deposits, gravel terraces of the Meuse and the Ourthe and slope deposits. According to the flood areas mapped in 2004 on the basis of residents survey (Peeters *et al.*, 2006), no significant overflow was identified in the urban areas of these watersheds in the last 20-25 years corresponding to the period of analysis.

Figure 1. Watersheds affected by the May 29, 2008 flash flood with the land use map as background.



SOURCES: NGI TOPOGRAPHIC MAPS, 2003; PUBLIC SERVICE OF WALLONIA, 2008

Table 1. Watershed characteristics.

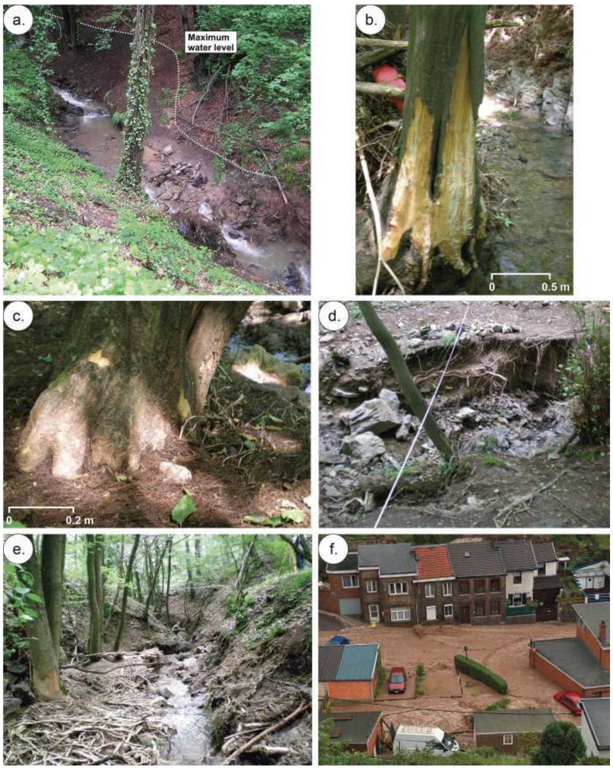
Catchment	Spring elevation (m)	Outlet elevation (m)	Mean slope (%)	Area (km²)	Maximum length (m)
Fond du Moulin	238	75	11.9	2.53	1370
Blanc Gravier	240	78	6.6	2.51	2455
Renory	200	60	9.7	1.18	1437

Sordeye	225	75	13.2	0.65	1138

Methodology used for estimating peak flow rate, bed incision, suspended load and bed load transport

6 Three or four 50 to 100-m long sections in the forested part of each stream were accurately surveyed in the weeks following the event while the flood marks were visible. These sections are representative of the geomorphological variety of these watercourses. Figure **2a** shows the boundary corresponding to the maximum flood water level. The presence of dead leaves, swept away by the water flow, provided an excellent topographic indicator equivalent to high water marks, with an accuracy reaching a few centimetres. The following parameters were measured at ten locations: the water level on the right bank and the left bank (to identify asymmetry), the width of the channel at the peak flow and the slope of the water surface.

Figure 2. a. Position of the maximum water level determined with flood marks; b. Bark and trunk abrasion caused by the bed load transport and floating logs (site RE2); c. Trunk injuries caused by shocks with floating logs, about 1 m above the thalweg (site RE2); d. 1-m deep incision in the colluviums (site RE2); e. Bare roots at site BG1; f. Flash flood in the urbanized part of the Fond du Moulin Creek.

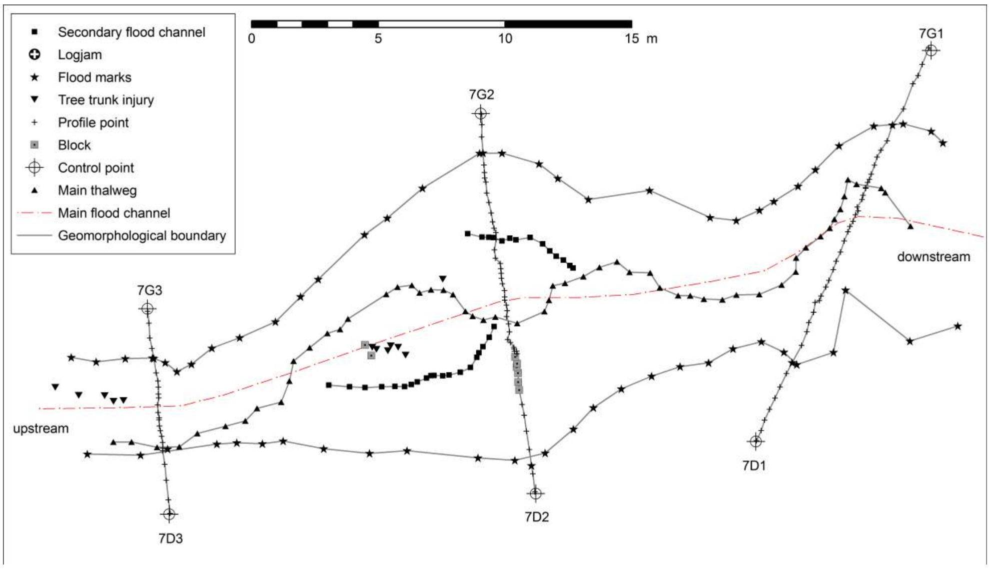


SOURCES: RESIDENT'S PHOTOGRAPH, MAY 29, 2008 10:11

7 Figure **3** shows a sample of topographic survey of each geomorphological element, the effect of the flash flood on the riparian vegetation and the location of transverse profiles. These ones were positioned to highlight areas with deep incision, asymmetries of the water surface between the left and the right banks in meandering reaches. The effects of

such an intense flood on the riparian vegetation are important: some tree trunks were ripped off by the water flow then transported by flotation and finally impacted other trees on the banks (Figure **2c**). These trunk injuries are located high up on the trees and allow confirming the maximum water level measured with other flood marks. Scars represent the most commonly used dendrogeomorphic evidence of past flood activity (Ballesteros Cánovas *et al.*, 2011). However, an uncertainty has to be taken into account, depending on the diameter of the trunks and their position at the moment of impact.

Figure 3. Example of topographic survey on site RE2 (Renory Creek).



8 The watersheds of these steep creeks have a significant amount of colluviums on their slopes. The bed load of these streams is composed of gravel and pluri-decimetric blocks. The flash flood transported the bed load and the colluvium load coming from the incision of the slopes and the alluvial plains. The particle size analysis will be detailed below. The mobilization and the mixing of blocks during the flood leave irreparable damages at the bottom of the trees (Figure **2b**). The bark has been abraded; the trunk shows many traces of impacts and allows quantifying the thickness of the mobilized pebbles layer.

9 The longitudinal slope of the water surface at the flood peak, the maximum depth and the asymmetry between the banks have been observed and measured from topographic survey of each reach. Unfortunately, we were not able to trace the chronology of the bed load incision. It is probable that the inception of the incision started with the sudden rise in the water level and reached the maximum at the flood peak, when the unit stream power reaches its peak. The estimated water depths are then probably slightly overestimated when they are measured in incised reaches.

10 Significant incision phenomena were observed on the four studied streams in their forested part. In absence of pre-flood topographic data, the incision depth was reconstructed by an estimation of the shape and the assumed elevation of the thalweg before the devastating flood. We observed locally incision deeper than 1 m in the Renory Creek with a width reaching about 3 m (Figure **2d**), corresponding to a local incision of 3 cubic metres per linear metre. We cannot, however, extrapolate these punctual observations to the entire length of the creek because this incision varies greatly from one reach to another, depending on the substratum. In areas where the major bed is

covered with trees, the incision phenomenon has led to another result. The sediment around the tree roots has been removed by the water flow. Then, their bark was deeply abraded by the mobilization of bed load during the event (Figure **2e**).

11 The Fond du Moulin watercourse includes in its lower part a significant urbanization, essentially located along the river. Most houses are located on the lower part of the slopes and a few of them directly overlap the creek, leading to significant damages. At many places, the road has bypassed the usual course of the river. The photographs taken by the local residents near the flood peak have helped to identify the hydrological characteristics of the flash flood and estimate the flow rate (Figure **2f**).

12 The Blanc Gravier and Sordeye watersheds have their outlet in the Ourthe valley where a major road has been flooded. A fluvial fan was developed in the Ourthe river bed while a 10- to 15-cm thick sediment layer was observed in the downstream part of the Blanc Gravier Creek, due to the accumulation zone created by the flat surface of the road.

Topographic and hydrological data

13 The hydrological characteristics of the flood in each watershed were compiled in Table **2**. For each cross section, the area, the perimeter, the width and the hydraulic radius were measured thanks to flood marks. It is necessary to note that these values correspond to the maximum level reached during the flood. In the absence of gauging station in these catchments with a surface area of less than 3 km^2, it was not possible to estimate the evolution of the flow rate during the event without the help of a hydraulic modelling using rainfall data. The Manning coefficient was estimated at 0.06 for all sectors, in accordance with the values proposed in the literature for forested substrates with obstructions (Bravard & Petit, 2000).

14 Using the values of hydraulic radius R, the local slope S (in $m.m^{-1}$) and the Manning's n value, the maximum flow velocity V_{max} was calculated (Equation **1**).

15 ***Equation 1***

$$V_{max} = \frac{R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}}{n}$$

16 Then the maximum flow rate Q_{max} (in $m^3.s^{-1}$) and the maximum unit stream power ω_{max} (in $W.m^{-2}$) were estimated from the wet section A (Equation **2**) and the width w of the river during the flood (Equation **3**). These values are summarized in Table **2**.

17 ***Equation 2***

$$Q_{max} = V_{max} \cdot A$$

18 ***Equation 3***

$$\omega_{max} = \frac{\rho \cdot g \cdot Q_{max} \cdot S}{w}$$

Table 2. Summary of the characteristics of transverse profiles, velocities, flow rates and unit stream powers observed during the flood (average and standard deviation values for each studied reach).

Location, ID and number of cross-sections at each reach		W Width (m)	S Local slope ($m.m^{-1}$)	v_{max} Max. velocity ($m.s^{-1}$)	Q_{max} Max. flow rate ($m^3.s^{-1}$)	ω_{max} Max. unit stream power ($W.m^{-2}$)	Max. depth (m)	Area (km^2)
Blanc Gravier (BG1) (n=3)	Average	5.7	0.095	4.3	25.7	4,795	1.50	1.32
	Std. dev	1.5	0.040	0.7	4.9	668		
Blanc Gravier (BG2) (n=3)	Average	6.3	0.080	4.5	34.8	4,655	2.46	2.08
	Std. dev	0.8	0.008	0.1	7.6	631		
Blanc Gravier (BG3) (n=4)	Average	10.6	0.067	2.4	15.3	710	2.50	2.35
	Std. dev	4.0	0.023	1.1	20.0	704		
Sordeye (SO1) (n=2)	Average	3.8	0.123	3.7	9.8	2,650	1.38	0.61
	Std. dev	1.3	0.016	0.6	5.1	351		
Sordeye (SO2) (n=3)	Average	5.1	0.161	3.5	9.7	2,919	1.58	0.73
	Std. dev	1.6	0.056	0.2	6.8	1,761		
Renory (RE1) (n=3)	Average	5.5	0.144	3.5	8.3	2,642	2.15	0.37
	Std. dev	0.8	0.014	0.9	4.5	1,771		
Renory (RE2) (n=3)	Average	8.7	0.104	3.5	22.8	3,502	2.32	0.84
	Std. dev	4.6	0.061	1.5	22.2	1,698		
Renory (RE3) (n=3)	Average	5.2	0.100	3.3	12.6	2,838	1.59	0.95
	Std. dev	1.2	0.063	0.9	2.6	827		
Fond du Moulin (FM1) (n=3)	Average	6.5	0.060	1.7	3.3	315	1.64	0.57
	Std. dev	1.2	0.000	0.3	1.3	151		
Fond du Moulin (FM2) (n=5)	Average	4.3	0.073	2.7	6.4	987	2.07	1.00
	Std. dev	1.7	0.045	0.8	2.7	341		

19 The lack of gauging station in these watersheds makes the validation of the flow rate estimations difficult. However, extreme flow rate estimations in the Blanc Gravier Creek

were computed when the university campus was built on the Sart Tilman Plateau. This peak value was calculated with the Soil Conservation Service Method at the outlet of the Blanc Gravier and reached 25 $m^3.s^{-1}$ (Spronck *et al.*, 1965). This value is in accordance with the average value obtained with the flood marks in the three studied reaches (24.3 $m^3.s^{-1}$). The flat topography observed at the outlet reach introduces a high variability of the estimates and forced us to take into account a mean value through the entire watershed. The Myer value corresponding to this estimation reaches 15.3. The largest values measured in Belgium reached 18 in streams located on the slopes of the High Fens, 40 km to the east-south-east of Liège (Collard *et al.*, 2012).

20 Many other methods exist in the literature to estimate the extreme peak flow in ungauged catchments. We mention in particular the method of envelope curves developed by Francou & Rodier (1967). From a dataset of extreme floods observed in the last two centuries in 1,400 watersheds in the entire world, with areas comprised between 10^{-2} and 10^6 km^2, these authors have established the following law (Equation **4**):

21 ***Equation 4***

$$\frac{Q}{Q_0} = \left(\frac{A}{A_0}\right)^{1 - \frac{k}{10}}$$

22

23 where Q is the peak flow rate (in $m^3.s^{-1}$), A the area of the watershed (in km^2), $Q_0 = 10^6$ and $A_0 = 10^8$.

24 The k parameter is a regionalized parameter: it varies in France from 5.5 in Mediterranean area to 3.5 in the northern oceanic zone. As this law is linked with the maximum observed floods, these flow estimates are not associated with a return period. However, the authors indicate that the majority of the points used to calibrate the k parameter correspond to a return period of about 100 years (Lang & Lavabre, 2007).

25 The use of this equation, with the k parameter equals to 3.945, adjusted to the estimated average flow rate on the Blanc Gravier Creek (24.3 $m^3.s^{-1}$), gives the results presented in Table **3**. The maximum flow rate estimated with flood marks, the unit discharge (discharge divided by the watershed area) and the maximum flow rate estimated by the WOLF model, developed by the HECE team (Hydraulics in environmental and civil engineering, University of Liège) are also presented in this table (Deliège *et al.*, 2009). The WOLF model uses explicit resolution of hydraulic differential equations at high spatial and temporal resolutions. This physically-based and spatially distributed model is able to represent the runoff in the whole drainage network and simulate the effect of different scenarios (land use modifications, impact of retention basins). It is useful to note that the modelling team took into account outlets located downstream relative to the studied sections in forested area. The modelled flow rates show high values as they correspond to larger watersheds. The adapted k parameter fits with the geographical situation of the studied watersheds, namely basins in an oceanic climate but including steep slopes, characteristic of Mediterranean watersheds. There is a good correlation between the flow rates calculated from the flood marks and the Francou & Rodier estimation for the Renory and Sordeye watercourses. We note a significant difference for the Fond du Moulin Creek which is probably due to the presence of a small diameter pipe in the

central part of the watershed; it led to the creation of a temporary lake in the forested area and has limited the flow rate at the outlet.

Table 3. Flow rates comparison rates between observations, HECE modelling results and Francou & Rodier (1967) model.

Catchments	Watershed area (km^2)	Outlet flow rate from flood marks ($m^3.s^{-1}$)	Outlet unit flow rate ($m^3.s^{-1}.km^{-2}$)	Max. flow rate according to Francou & Rodier (1967) ($m^3.s^{-1}$)	Modelled watershed area (km^2)	Modelled max. flow rate (HECE) ($m^3.s^{-1}$)	Modelled max. unit flow rate (HECE) ($m^3.s^{-1}.km^{-2}$)
Blanc Gravier Creek	2.40	24.3	10.1	-	2.80	28.0*	10.0
Renory Creek	1.06	14.6	13.8	14.8	1.32	14.2**	10.8
Sordeye Creek	0.64	9.8	15.3	10.9	-	-	-
Fond du Moulin Creek (at the forested outlet)	0.98	5.2	5.3	14.1	2.90	42.5***	14.7

* FLOW RATE CALCULATED AT THE CONFLUENCE OF THE BLANC GRAVIER CREEK AND THE OURTHE RIVER (2.80 KM^2) ** FLOW RATE MODELLED AT THE FORESTED OUTLET OF THE RENORY WATERSHED (1.32 KM^2), TAKING INTO ACCOUNT THE MALFUNCTION OF ONE OF THE TWO STORM BASINS UPSTREAM; *** FLOW RATE CALCULATED AT THE CONFLUENCE OF THE FOND DU MOULIN CREEK AND THE OURTHE RIVER (2.90 KM^2)

26 The unit flood discharge presented in Table **3** was compared to literature data using the flash flood compilation produced by Gaume *et al.* (2009). Values obtained in the area of Liège range from 5.3 to 15.3 $m^3.s^{-1}.km^{-2}$. They are lower than the envelope line presented by Gaume *et al.* (2009). We also note that the publications addressing this range of small watersheds (lower than 2.5 km^2) are relatively rare in the literature.

Block deposits size analysis and estimation of peak flow using unit stream power law

27 As it was highlighted above, the flash flood caused large incisions in the alluvial and slopes deposits. Blocks and gravels were mobilized over long distances. Even small tributaries of the main watercourses showed massive bed load mobilization. Figure **4** shows an important block deposit on the road along the Fond du Moulin Creek, coming

from a little tributary on the left bank of the creek. The enlargement of the flow on the road decreased the competence and induced the accumulation of blocks, despite the low roughness of the road surface.

Figure 4. Pluri-decimetric block deposits from a small tributary of the Fond du Moulin watercourse.

Source: Bernard Chandelon, http://blueperrot.blogspot.com/, May 29, 2008 12:41

28 Pluri-decimetric blocks were mobilized and created accumulation in low slope reaches (Figure 5). Their mobilization is attested not only by the before and after photos but also by their imbrication, stacked together in the flow direction and covering roots and fresh vegetation. Size analysis surveys were carried out on several block deposits. The streams have mobilized a wide range of element sizes; granulometric indices show a bad classification of these deposits.

Figure 5. Evolution of the alluvial plain of the Blanc Gravier Creek from two photos taken at the same location before and after the flood.

SOURCE: L. SCHMITZ

29 The biggest mobilized blocks were measured on each site. These measurements allow estimating the unit stream power and the maximum peak discharge through an indirect

calculation method. Indeed, the size of the mobilized elements during a flood can be linked with the unit stream power needed to move them. There are few relationships developed for rivers transporting elements with a b-axis greater than 500 mm. We can mention the one developed by Costa (1983) in Colorado rivers and the relationship of Williams (1983). More recently, the same type of law has been proposed in Mediterranean watersheds (Jacob, 2003; Gob, 2005; Gob *et al.*, 2003, 2005; Jacob *et al.*, 2006). Riggs (1976) also proposed a simplified slope-area method for estimating flood discharge, without specifying the associated return period. All these relationships have the following form:

30 ***Equation 5***

$$\omega_0 = a \cdot D_i^b$$

31 where ω_0 is the critical unit stream power of the bed load mobilization (W.m^{-2}), D_i the size of the element (mm) and *a* and *b* two parameters of the equation **5**. The unit stream powers that are estimated here represent the minimum power that can mobilize the block taken into account in the equation.

32 These laws are developed on the basis of the mobilization of individual elements (D_i). It was arbitrarily chosen to use as D_i value the b-axis of the biggest block found on each site. Indeed, the coarse elements allow assessing the maximum competence of the mobilizing floods. Several tests were conducted with these data. The best fits were obtained with the equation proposed by Jacob (2003, see Equation **6**), who computed the parameters on a river located in the Cévennes region. The Chassezac River, studied by Jacob (2003) is a step-pool river. In this type of river bed, the roughness caused by the bed morphology is significant. In this case, the unit stream power needed to mobilize the bed load is higher than the power required in pool-riffle rivers.

33 ***Equation 6***

$$\omega = 0.025 \cdot D_i^{1.647}$$

34 Petit *et al.* (2005a) showed that the characteristics of the rivers had a great influence on the mobilization threshold. In medium-sized watercourses, the unit stream power required to mobilize bed load elements has to be higher due to the loss of energy caused by the resistance of the minor bed morphology. Results obtained with the Jacob (2003) equation are presented in Table **4**. These values are high compared to those calculated in a series of Ardennian rivers for which the maximum unit stream power ranged from 100 and 200 W.m^{-2} (Petit *et al.*, 2005a, 2005b).

Table 4. Calculation of unit stream power and theoretical flow rate with the law identified by Jacob (2003).

Watercourse	*Site*	*Mean slope (m.m^{-1})*	*Mean width (m)*	*b-axis (mm)*	*Unit stream power (W.m^{-2})*	*Flow rate (m^3.s^{-1})*
Blanc-Gravier Creek	BG3	0.068	10.6	660	1,101	17.6
	BG1	0.095	5.7	670	1,128	6.9
Sordeye Creek	SO2	0.161	5.1	500	697	2.2

	SO1	0.123	3.7	460	607	1.9
Renory Creek	RE3	0.100	5.2	550	815	4.3
	RE2	0.104	8.7	590	915	7.8
	RE1	0.144	4.0	490	674	1.9
Fond du Moulin Creek	FM2	0.054	4.3	540	791	6.4
	FM1	0.060	6.5	410	503	5.5

35 Values obtained with Jacob's fit, between 550 and 1,100 $W.m^{-2}$, are much higher than those obtained with the Costa's equation. Such values of unit stream powers are extremely rare in the Ardennian rivers, even for a 100-year flood. These values confirm the exceptional character of this flash flood.

36 Tests made with Riggs' equation show an underestimation of about 20-30%. From these calculations, we can highlight the lower estimated flow rate values using particle size method with respect to the analysis of the water level thanks to the flood marks. Two hypotheses may explain these differences: first, approximations resulting from the absence of direct observations of the phenomenon and the use of theoretical equations developed for streams of different contexts; second, the lack of mobilizable elements above a b-axis of about 700 mm in the slope deposits, leading to an underestimation of the competence of the flash flood.

37 As a comparison, the major flash flood that affected the Chefna River, a small tributary of the Amblève River, has transported quartzite blocks up to 950 mm on August 26, 1969. Some blocks over 1.25 m of b-axis were tilted during the flash flood which caused many geomorphologic changes (Tenret, 1969). The estimation of the peak flow discharge in this 7.84-km^2 watershed reaches about 40 $m^3.s^{-1}$ and a unit stream power of around 2,000 $W.m^{-2}$.

Order of magnitude of the watershed erosion caused by the flash flood

38 The flash flood caused massive watershed erosion in terms of suspended load and fine sediment, coming essentially from bank erosion and bed incision. The forest cover has limited the runoff in the headwaters. In the downstream part of the Blanc Gravier Creek, a pond was cleaned of sediment in 2006. After the May 29, 2008 event, the almost complete filling of the lake by fine particles allowed us to estimate an accumulation of about 300 m^3, i.e. about 480 tons considering a bulk density of 1.6. In addition, we estimated the thickness of sediment accumulated in the decantation zone on the road located downstream the pond. It reached 10 to 15 cm of thickness on an area of about 3,000 m^2, leading to a mass of fine sediment of about 600 tons. Considering these observations, the suspended load transport was estimated at a minimum value of 440 $t.km^{-2}$ for this unique event. In Ardennian rivers the mean watershed soil erosion ranges in average from 20 to 50 $t.km^{-2}.year^{-1}$ (Van Campenhout *et al.*, 2013).

39 Regarding the bed load transport, the volume of the main accumulation of blocks and pebbles located in the downstream part of the Blanc Gravier Creek has been measured with a total station. It reaches 74 m^3, which corresponds to 122 tons considering the porosity of this angular assembly. Taking into account the area of the associated watershed, the unit solid discharge was estimated at 51 $t.km^{-2}$ for the bed load. Estimations of bed load discharge for Ardennian rivers give average values ranging from 0.36 $t.km^{-2}.yr^{-1}$ (Ourthe River in Famenne, 1,285 km^2) to 2.21 $t.km^{-2}.yr^{-1}$ (Wamme River, 139 km^2) for a complete year (Petit *et al.*, 1996), including all the hydrologic events. Single flood events may generate higher bed load transport rates; Houbrechts *et al.* (2012) observed a mobilization of 2.07 $t.km^{-2}$ for a 11.2-year recurrence flood in the Aisne basin and up to 4 $t.km^{-2}$ for a decennial flood on Eastern Ourthe River (Petit *et al.*, 1996; Houbrechts *et al.*, 2006). The value measured after the Sart Tilman flash flood, around 50 $t.km^{-2}$, for a single coarse elements accumulation (corresponding to the most important block deposit observed in the Blanc Gravier watershed) clearly shows the uniqueness of this torrential event and its implications on the bed load transport.

Spatial and temporal distribution of recorded events in Wallonia

Methodology of database compilation

40 The second topic of this paper addresses the spatial and temporal distribution of flash floods and muddy floods in Wallonia. It is mainly based on several works that used press information to create the most comprehensive database of extreme events. Compiling historical information about the location, the frequency and the characteristics of these events is not an easy task. On the Walloon territory, about one hundred of them have been recorded for the period 1906-2000 by Lejeune (2001). Gérard (2013) extended the flash flood and muddy flood analysis in Wallonia to the first decade of the 21th century, including a reanalysis of old newspaper archives[1] and web archives[2]. A wide variety of keywords has been used to find information about flash floods in these databases. Indeed, the journalistic language is often approximate compared to the scientific definition of these natural events. The disambiguation between intense local runoff, muddy floods and flash floods cannot easily be done from press archives. In addition, the distinction between a flash flood and a typical river overflow can be complex, especially when exceptional rainfalls affect large areas, leading to flash floods in the small watersheds and flooding major beds of large rivers. Note that these newspaper archive researches were performed in French language only. Daily newspapers in the German-speaking part of the country (East Belgium) have not been analysed. This bias can be another cause of incompleteness of the database. It is quite difficult to estimate its effect because this part of the country corresponds to a low population density, which strengthens the possibility of not transcribing all the events in local or regional newspapers.

41 The completeness of the database is difficult to achieve due to several bias that can be observed in the information sources, especially when we try to get historical data. In the frame of this analysis, data were collected using newspaper and web-based sources, books and papers related with the territory of Wallonia, since the beginning of the 20th century. The use of newspaper data leads to an incompleteness of the database. The facts that are related in the newspapers usually do not take into account events that did not cause

damage to urban areas. A major flash flood occurring in a forested area may not be reported. On the other hand, a minor event generating many damages in a city will be reported by the majority of the newspapers, including testimonies of the residents and numerous photographs of the affected area that enable defining with good accuracy the characteristics of the event (precise location, origin of the muddy water flow, delineation of the flooded area and estimation of the water level at the peak of the event). These characteristics are often unknown when flash floods occur in forested area or in the least densely populated rural areas. These biases lead to an incompleteness of the database; they have to be kept in mind when analysing the spatial distribution of the events that will be presented later.

42 Lejeune (2001) also studied the return period of extreme rainfall events and the spatial distribution of flash floods using newspaper articles for the period 1906-2001 and two other studies in link with floods in the lower Ourthe and Lesse watersheds. Several study cases were conducted to obtain more information regarding the characteristics of the most important events recorded in the press. Its database contains 70 flash floods that occurred between 1906 and 2001, affecting 253 communities.

Results

43 It is generally believed that flash floods and muddy floods only occur in loamy regions where thick erodible soils are available on moderate to steep slopes. The database describing the spatial repartition from 1906 to 2013 also shows events in areas where slopes are lower and soil is not constituted of loess. Figure **6** presents the spatial distribution of the flash floods recorded from 1906 to 2013 through the press archives. At this scale, each point represents one or several flash flood events occurring at the same location. Press papers do not always allow a perfect location of the damages. The municipalities of Hesbaye and Brabant Plateau covered with loess show the highest density of flash floods in Wallonia, especially in the valleys of the Gette, the Geer, the Mehaigne and the Senne. The Gette watershed shows a higher density of events than the Geer watershed, probably due to the larger agricultural plots in the Gette basin and the urbanization of several preferential runoff axes. Gérard (2013) studied the spatial extent and the density of flash flood at the scale of agro-geographic homogeneous areas (Génicot, 1987) and at the municipality scale. In addition to the well-known location of flash flood events in the northern part of Wallonia, he has highlighted a high density of events in the slopes of the tributaries of the Sambre and Meuse rivers in the Condroz region, where the population density exceeds 100 inhabitants.km^{-2} (Figure **7**, showing the population density by municipality in 2012 with a classification highlighting the low-density areas that are subjected to the database incompleteness bias). The boundary between the Ardennes massif and the Fagne, linked to steeper slopes than observed in the loamy region, and the southern part of the Lorraine region also show many events, despite the absence of loess layer on the geological substratum and a lower population density (below 50 inhabitants.km^{-2}). Any type of soil is susceptible to be affected by major flash flood and very steep slopes are not a necessary condition to generate extreme events. This spatial analysis suggests that the rainfall intensity and the total amount of precipitations are the main triggering factors, before the physical characteristics of the affected watersheds. A rainfall data analysis showed that there is a huge correlation between the flash flood occurrence and the threshold of 40 mm.day^{-1} (Gérard, 2013). This value is consistent with the observations of Evrard *et al.* (2007), showing that muddy

floods are generated in small and medium catchments with 99% probability after 43 mm rainfall, with a seasonal differentiation. The 40-mm threshold is relatively low and corresponds to a return period of about 9 months in the most southern part of Wallonia, a little less than one year in the High Fens (in the most eastern part of Wallonia), two years in Namur (at the confluence of the Sambre River and the Meuse River) and three years in the western part of the Scheldt basin (Mohymont & Demarée, 2006). The extreme spatial variability of rainstorms behind these flood events often requires the use of radar data to assess the intensity and the variability of the phenomenon at a local scale (Douvinet & Delahaye, 2010).

Figure 6. Spatial distribution of flash floods and muddy floods in the Walloon Region for the period 1906-2013 from press archives.

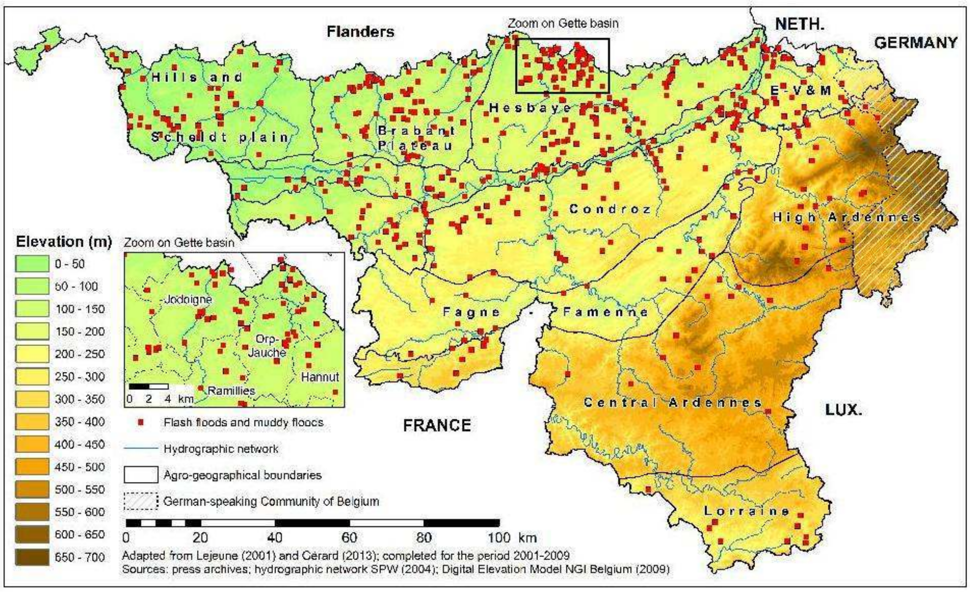
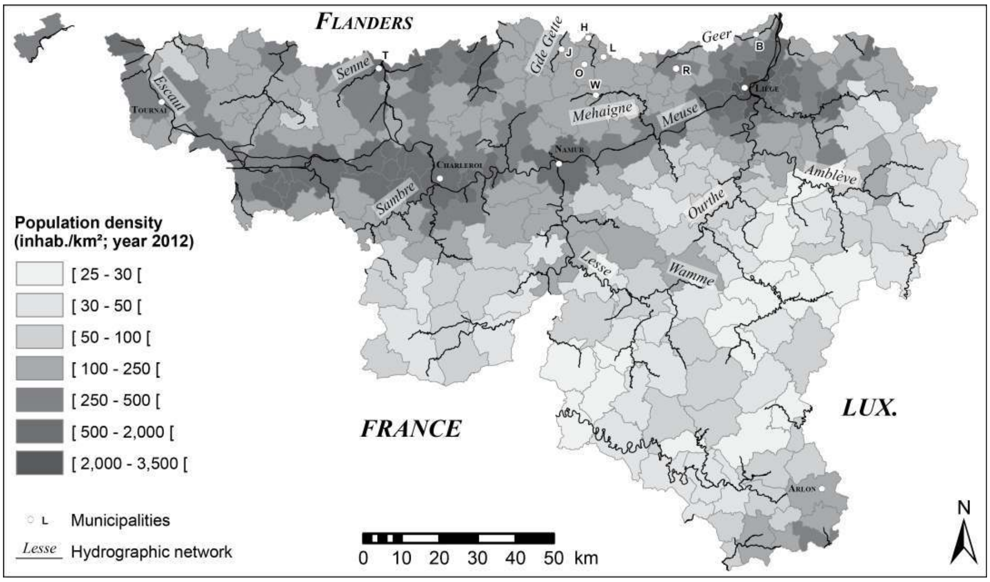


Figure 7. Population density in each municipality of Wallonia.



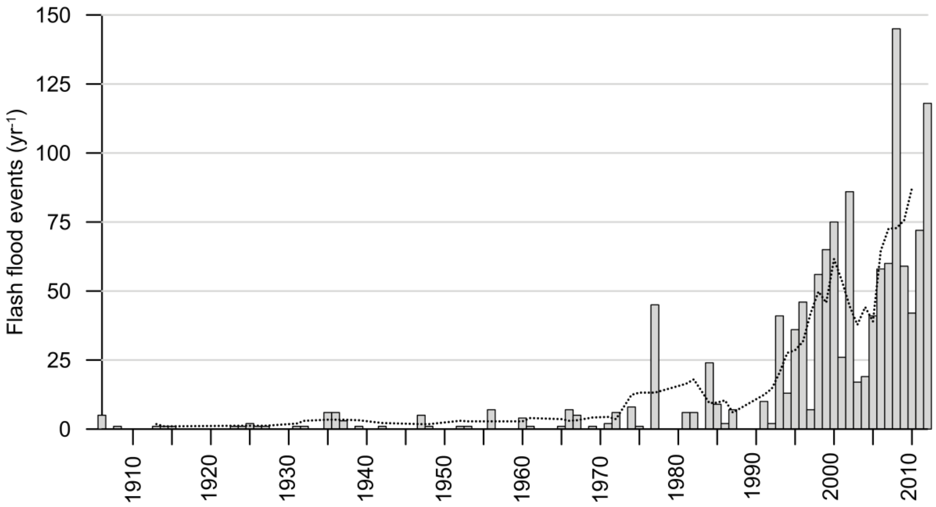
SOURCE: NATIONAL INSTITUTE OF STATISTICS AND LOCATION OF THE RIVERS AND TOWNS MENTIONED IN THE TEXT (B: BASSENGE, H: HÉLÉCINE, J: JODOIGNE, L: LINCENT, O: ORP-JAUCHE, R: REMICOURT, T: TUBIZE, W: WASSEIGES)

44 The high variability of the area of Walloon municipalities makes the use of a non-straightforward density unit mandatory to get comparable results. At the municipality scale, the mean areal density of flash floods in Wallonia between 1906 and 2013 reaches 0.07 event.km^{-2} (standard deviation: 0.10 event.km^{-2}). Eight municipalities present a flash flood density superior to 0.20 event.km^{-2} on this period of 107 years. They are located on Figure **7**, showing the population density of each municipality of Wallonia. Hélécine and Lincent are the most affected areas, with 0.83 and 0.68 event.km^{-2} respectively, corresponding to 14 and 10 recorded events. Orp-Jauche and Jodoigne, with 24 and 28 recorded events respectively, also suffered many times of intense flash floods in this area focusing flow runoff from surrounding agricultural areas (see zoom on Figure **6**). The other municipalities with high density are Remicourt, Wasseiges, Tubize and Bassenge, corresponding to 7 to 9 events. All these municipalities belong to the Hesbaye region, constituted of arable lands, divided in large plots on a loamy substrate and the Brabant Plateau, where sandy soils are also covered by loess deposits (Christians & Daels, 1988). The least affected municipalities are located in Central Ardennes, East Belgium (essentially covered with forested areas and grassland) and western parts of the Fagne and Famenne subareas (mainly devoted to grassland).

45 Assessing the temporal evolution of the number of flash floods and muddy floods in a large area is a difficult task due to the possible incompleteness of the database in older times or in low population density zones (Figure **7**). The analysis of press records seems to indicate that the database only shows major events in urban areas before the year 1965; only a few events are documented each year (Figure **8**). Between 1965 and 1988, a low increase of the yearly occurrence is noticeable. From 1991, the number of recorded flash floods rises sharply to several dozen per year. The peak is reached in 2008 with almost 200 events recorded this year. The meteorological station of Uccle (near Brussels) recorded this year 861.0 mm of precipitations. Two other peaks of events occurred in

1977 (855.9 mm) and 2012 (976.5 mm). Normal value on the period 1981-2010 reaches 852.4 mm.

Figure 8. Temporal evolution of flash floods and muddy floods documented in press archives (Wallonia, 1906-2013) and running average (5-year window).



46 The running average shows the huge increase of the number of flash floods in the 1990s. This is concomitant with the emergence of digital archives on the Internet but this effect could not explain this massive increase, because paper archives were also analysed. After a small decrease, another rise is observed in the second part of the 2000s. Despite the impossibility to guaranty a completeness of the dataset, especially before the 1970s, a clear increase of the occurrence of events is noticeable in press records. Several hypotheses may underlie this increase: 1) a real increase of the flash flood events, due to an increased sealing of the urban and field soils and/or an increased rainfall intensity and amount; 2) a rise in the number of people affected by the flash floods, due to the urbanization of small valleys that concentrate runoff water downstream of monoculture crops. Larger field plots and the removal of hedgerows at parcel boundaries may have important effects on soil erosion and peak flow (Beuselinck *et al.*, 2000); 3) the awareness of the press to document any event, even minor which was not the case earlier in the century. Gérard (2013) tried to correlate the rainfall intensity with the occurrence of flash floods, but the spatial variability of the rainfall events that generate the floods is huge. Radar rainfall images are needed to push forward this study, the density of the rain gauges network in Wallonia is not dense enough to characterise the causes of each flash flood event.

Flash flood vulnerability, hazard and risk mitigation in Wallonia

47 During the period 1969-2007, every municipality in Wallonia has been affected by at least one major damage caused by flooding (all caused combined) and included in a Royal Decree as a national disaster (SPW, 2008). According to the information available for this period, in a third of cases floods were caused by watercourses overflowing and in the remaining cases, by water runoff on agricultural land or blocked sewers. From 2003, the P.L.U.I.E.S. Plan ("*Prévention et Lutte contre les Inondations et leurs Effets sur les Sinistrés*")

works as an integrated and multi-disciplinary strategy that contains 30 actions aiming to reduce the risk of flood damage (SPW, 2008). The actions include building restrictions in flood prone areas. In addition to overflowing areas, concentrated runoff axes were added to the flood vulnerability and risk maps in Wallonia, taking into account the small valleys susceptible to generate heavy damage in case of flash floods. Some specific watercourses affected in the past by intense flash floods causing fatalities were equipped with early alarm systems and real-time message to the surrounding population, such as the Biesme River which killed three people in Gerpinnes during the flood of August 1987. A higher density of monitoring stations is required to reduce the risk. In Europe, 52 casualties per year due to flash floods are reported in average, representing 40% of the overall casualties due to all the types of floods (Borga *et al.*, 2011). Major events with documented characteristics such as the case study reported in the urban area of Liège in 2008 should allow the development of urban layout strategies to reduce the risk of submersion.

48 Uncertainties in long-term climate scenarios do not give a clear vision of the evolution of flash flood and muddy flood damage in the future. Many authors link the climate warming to the intensification of heavy precipitation events over roughly two-thirds of the continental Northern Hemisphere (Andersen & Marshall Shepherd, 2013). In Belgium, a statistical analysis of 44 regional and 69 global climate model runs, based on three different emission scenarios (A1, A1B, B1) showed that the 10-year design storm intensity can increase up to about 50% till 2100. Systems currently designed for a 20-year return period of flooding, might flood with a mean recurrence interval of about 5 years. It is found that increase in storage capacity of 11-51% is required to keep the overflow frequency to the current level (Willems, 2013). Design parameters for urban drainage systems and IDF curves need to be revised to account for this evolution (Andersen & Marshall Shepherd, 2013).

Conclusion

49 The major flash flood event that occurred in Liège on May 29, 2008 was analysed from geomorphologic evidences. Tree trunk injuries, flood marks, block deposits and fine sediment accumulations allowed the reconstruction of the hydrological characteristics of the flood in these ungauged watersheds. A multi-disciplinary approach allowed the comparison of several peak discharge estimations using flood marks, block size and hydraulic models. This flood has shown its exceptional intensity through the sediment transport rates that were estimated in the affected watersheds, reaching 440 $t.km^{-2}$ of suspended load transport and 51 $t.km^{-2}$ of bed load mobilization. Values with one order of magnitude greater than usual floods in Wallonia were measured. The analysis of the spatial repartition of flash floods in Wallonia has shown that the well-known mud flow prone areas, in the loamy region, are not the only territories where extreme events can occur. In addition to the main valleys of the Gette, Geer, Mehaigne and Senne rivers, the tributaries of the Sambre and the Meuse rivers have been affected by these phenomena. The threshold of 40 $mm.day^{-1}$ has been highlighted as the main triggering factor, in conjunction with a hazardous urbanization, especially downstream of large monoculture crops. Despite the incompleteness of the database acquired from press archives, the temporal evolution of the number of flash flood cases shows a significant increase from the 1990s. Finally, the vulnerability of the Walloon territory to flash flood hazard was

highlighted and mitigation strategies have been developed in the frame of the recrudescence of extreme rainfall events.

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NOTES

1. Archives and availability period of each source at the Royal Library of Brussels: *Le Soir* (1900-2013), *La Meuse* (1900-2013), *La Libre Belgique* (1918-2013), *La Dernière Heure* (1907-2013), *Vers l'Avenir* (1918-2013), *La Wallonie* (1921-1950), *Journal de Verviers* (1940-1943), *La Lanterne* (1944-1950) , *La Légia* (1940-1942), *Mons-Tournai* (1941-1942), *Le Nouveau Journal* (1941-1942), *Province de Namur* (1942-1944), *Le Quotidien* (1914-1915), *La Région de Charleroi* (1915-1918), *L'Écho de Liège* (1915), *Journal du Borinage* (1943), *Journal de Namur* (1940).
2. Web-based archives: *La Libre Belgique* (2001-2013), *Le Soir* (1995-2013), *La Dernière Heure* (2001-2013), *7sur7* (2008-2013), *L'Avenir* (2007-2013), *RTL* (2008-2013), *RTBF* (2008-2013), *Le Vif* (2011-2013), *SudPress* (2006-2013).

ABSTRACTS

Flash floods and muddy floods may cause severe human and material damage despite their small spatial extent and low occurrence. In late May 2008, a major event has affected the area of Liège. This paper describes the methodology used to reconstruct the hydrosedimentological parameters of the flood from the geomorphological evidences observed in the field. Bed load and suspended load transport rates estimated during this extreme event were compared to the average values observed in other Walloon rivers and more specifically in the Ardennes Massif. The spatial distribution and the temporal evolution of the flash flood and muddy flood events are then analysed across Wallonia based on several works compiling press archives since the early twentieth century. The biases associated with this type of historical sources and the consequences of flash floods and muddy floods on the vulnerability and the risk of flooding in Wallonia are finally addressed.

Les crues éclairs et les coulées boueuses, malgré leur extension spatiale réduite et leur occurrence peu fréquente, peuvent être à l'origine de dégâts importants tant sur le plan matériel que sur le plan humain. Fin mai 2008, un événement majeur a affecté la région liégeoise. Ce papier décrit la méthodologie employée pour reconstituer, en milieu forestier, ses paramètres hydrosédimentologiques à partir des éléments géomorphologiques observés sur le terrain. Les taux de transport de la charge de fond et de la charge en suspension au cours de cet événement extrême sont comparés aux valeurs moyennes observées dans d'autres rivières wallonnes et plus spécifiquement dans le massif ardennais. La répartition spatiale et l'évolution temporelle des crues éclairs sont ensuite analysées à l'échelle de la Wallonie sur base de plusieurs travaux académiques compilant l'ensemble des événements recensés dans la presse depuis le début du XX ème siècle. Les biais liés à ce type de sources historiques sont abordés ainsi que les conséquences des crues éclairs sur la vulnérabilité et le risque d'inondation soudaine en Wallonie.

INDEX

Mots-clés: crue éclair, coulée boueuse, laisses de crue, reconstitution des débits, gestion des risques d'inondation
Keywords: flash flood, muddy flood, flood marks, discharge reconstruction, flood risk management

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