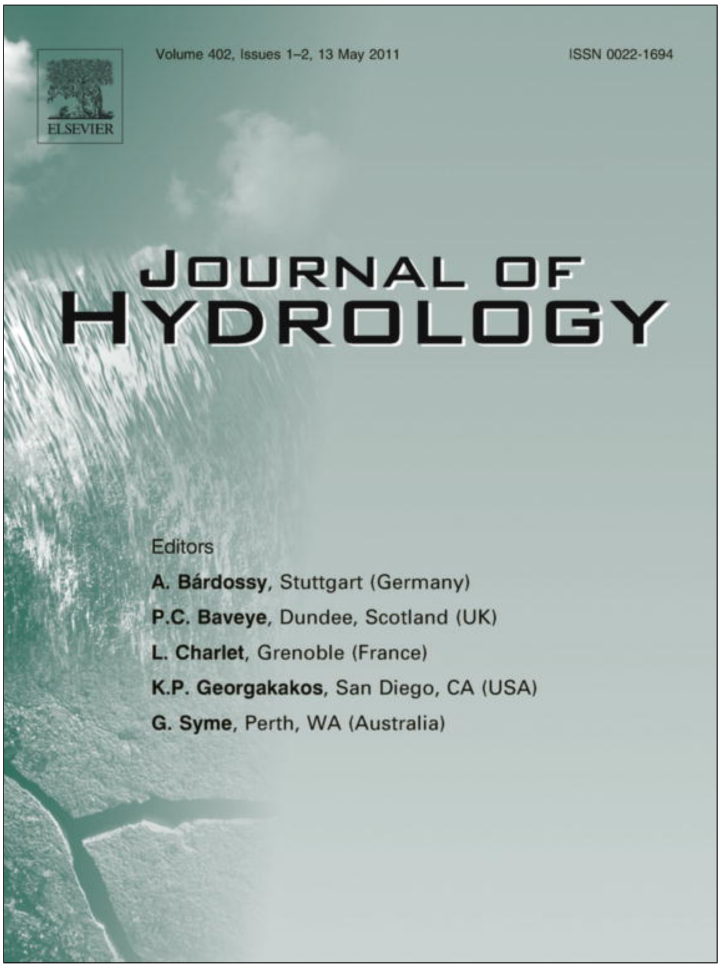
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Effect of beaver dams on the hydrology of small mountain streams: Example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium

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SUMMARY

The European beaver (*Castor fiber*) was recently reintroduced to Belgium, after an absence of more than 150 years; around 120 beaver dam systems have been established. In Europe, few studies consider the hydrological effects of those dams, and the spatial scale larger than that of one beaver pond system has not been addressed at all. This research focuses on the hydrological effects of a series of six beaver dams on the Chevral R., a second order tributary of the Ourthe Orientale R. in a forested area of the Ardennes. Thereby, also the Ourthe Orientale sub-basin itself was taken into account, being the area with probably the highest density of beaver dams in Belgium. The main research questions regarded: (1) the extent to which discharge peaks are reduced at the very location and well downstream of beaver dams and (2) the impact of the beaver dams on low flows. The first approach consisted of a temporal analysis of the Ourthe Orientale discharge and precipitation data for the periods 1978–2003 (before) and 2004–2009 (after the establishment of beaver dams in the sub-basin). The second study determined the *in situ* impact of the beaver dams: discharges were measured (September 2009–March 2010) upstream as well as downstream of the 0.52 ha beaver dam system on the Chevral river, and changes in water level within the system of six dams were monitored. Our findings indicate that there is a significant lowering of discharge peaks in the downstream river reaches due to the effect of the beaver dams. The temporal analysis of the Ourthe Orientale sub-basin shows an increase in the recurrence interval for major floods; for instance, the recurrence interval of a reference flood of 60 $m^3\ s^{-1}$ increased from 3.4 years to 5.6 years since the establishment of the beaver dams. At the scale of the Chevral beaver dams' site, we measured that the dams top off the peak flows, in addition delaying them by approximately 1 day. There are also increased low flows: Q_{355} (i.e. the discharge exceeded 355 days in a year) of the Ourthe Orientale was 0.6 (±0.15) $m^3\ s^{-1}$ before beaver dam installation and 0.88 (±0.52) $m^3\ s^{-1}$ thereafter. These findings agree with studies that suggest natural measures for flood control at the level of small mountain streams instead or in complement of building large anthropogenic constructions. Nevertheless, more studies are needed to assess the effectiveness of beaver dams in flood mitigation at the scale of sub-basins.

1. Introduction

The genus Castor comprises two species: the European beaver *Castor fiber* and the North American beaver *Castor canadensis*. Beavers (*C. canadensis*) have particularly been part of the riparian ecosystem of Northern America for centuries (Naiman et al., 1988). Ives (1942) described how beavers create an extensive artificial environment, and until major human impact took place, the changes to valley bottoms induced by beavers exceeded in magnitude those produced by humans. Though the two species cannot interbreed, they have very similar habitats, behaviour and impacts on the ecosystem (Djoshkin and Safonov, 1972; Macdonald et al., 1995).

Formerly widespread throughout much of the Palaearctic region, European beaver populations were reduced through overhunting to ca. 1200 animals, in eight isolated populations, by the end of the 19th century (Halley and Rosell, 2003). Since the 1920s, effective protection of the *C. fiber* remnant populations, the resultant natural spread, and widespread reintroductions have led to a powerful recovery both in range and in population (Halley and Rosell, 2003).

Increases in the populations and distributions of species that are able to modify ecosystems have generated much scientific interest (Rosell et al., 2005). Further, the period of rapid beaver population growth often coincides with a peak in conflicts with human land-use interests, as the colonisation of marginal habitats

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is more likely to require extensive modification by beavers (Halley and Rosell, 2003).

Since the early paper by Ruedemann and Schoonmaker (1938) in Science, it has been agreed that the most typical beaver habitat, the beaver dams, has not only nature or ecological value, but has also impact on runoff response and geomorphology. Beavers are among the few species besides humans that can significantly change river geomorphology, and consequently the hydrological characteristics (Butler and Malanson, 1995; Rosell et al., 2005). In the early Holocene, Coles (2009) argues that beavers had a greater influence on the environment than did humans, but at some point the balance shifted to humans having the greater impact. The ability of beaver ponds to effectively trap sediment, regulate the hydrology and reduce stream erosion has been demonstrated (Butler, 1995; Green and Westbrook, 2009). However, Butler (1995) estimated that "an enormous amount of work remains to be done before the effects of beavers on the landscape can be quantified".

The major local impact of beaver dams is that flow velocity is reduced and peak and low flows are regulated by beaver dams to a varying extent (Woo and Waddington, 1990). At wider scale, the beaver is considered a keystone species for water management (Angelstam et al., 2006). Although in Northern America beavers were more prevalent than today, their current induced alterations to drainage networks are not localised or unusual (Naiman et al., 1988). For instance, Woo and Waddington (1990) compared the water balance of basins with and without beaver dams and found that basins with dams lost more water to evaporation, suppressed the outflow and increased the basin water storage.

Beaver dams control the water table position in the river bed and in the adjacent alluvial plain (Westbrook et al., 2004) and create hydrologic regimes suitable for the formation and persistence of wetlands (Westbrook et al., 2006). As observed in many places, beaver activity in the Spessart (West-Germany) enhances the total water flow length by diverting water onto the floodplain, hence creating on it a multi-channelled (anastomosing) drainage network (John and Klein, 2004). Depending on the state of preservation, river flow can overtop or funnel through gaps in beaver dams, leak from the bottom of the dams or seep through the entire structure (Woo and Waddington, 1990). Beaver dams attenuate the expected water table decline in the drier summer months (Westbrook et al., 2006). The retention of event water in beaver ponds is favoured by relatively low pre-event storage (Burns and McDonnell, 1998). However, beaver dams are deemed to provide less retention during large runoff events such as snowmelt (Beedle, 1991; Burns and McDonnell, 1998). In contrast, the removal of beaver dams and subsequent change in channel structure in Sandown Creek (BC, Canada) resulted in an estimated fivefold increase in mean flow velocity (Green and Westbrook, 2009).

Most investigations on beaver impact on hydrology are dealing with impact at the local scale, and only few at the landscape or even regional scale (Ulevičius, 2009); none is known for *C. fiber*. Empirical evidence has been provided that beaver dams can influence hydrologic processes during peak- and low-flow periods on streams (Parker et al., 1985; Westbrook et al., 2004, 2006). If a single beaver dam system may only have a limited impact on discharge, a series of dams may induce a significant impact (Grasse, 1951), which will be especially pronounced in high- and low-flow periods (Duncan, 1984). Reductions in peak flows have been shown to increase as the number of ponds in a series increased (Beedle, 1991). In dry periods, the discharge of low flows is increased (Parker, 1986), what may even result in turning temporary rivers into permanent ones (Collen and Gibson, 2000; Rutherford, 1955; Yeager and Hill, 1954).

C. fiber was recently reintroduced to Belgium, after an absence of more than 150 years. Rosell et al. (2005) have suggested that beavers can create important hydrological management opportunities and the re-establishment of the beaver is deemed to be a

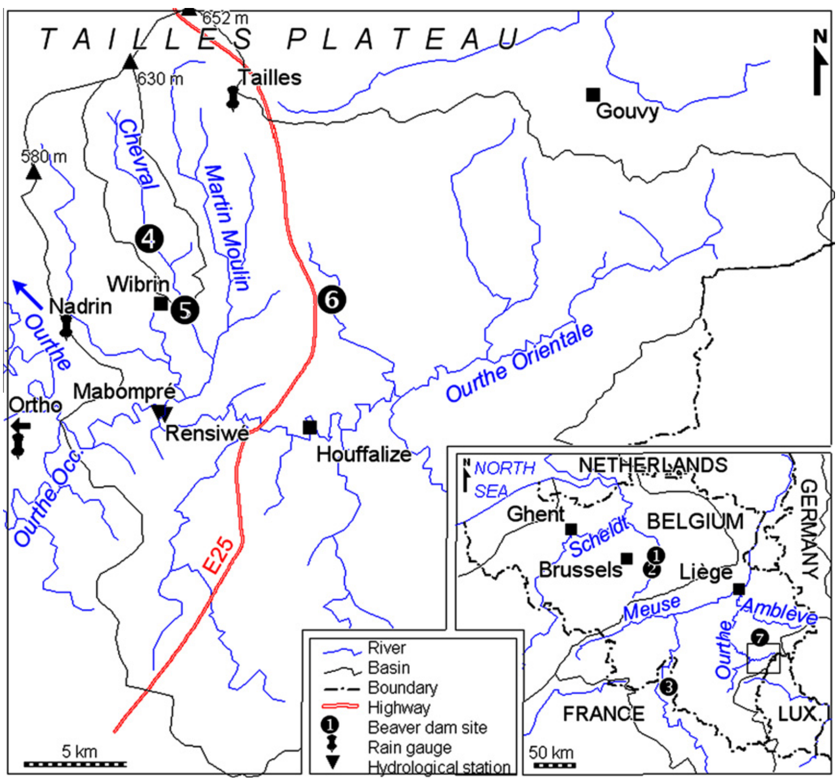


Fig. 1. The Ourthe Orientale sub-basin, hydrological and meteorological monitoring stations, and location of surveyed beaver dam systems.

way to approach good ecological status of European waters (Angelstam et al., 2006). Particularly, recent studies (e.g. Baguis et al., 2009; Boukhris et al., 2008; Willems et al., 2009) have shown that predicted changes in rainfall will lead to strongly decreased river discharges in Belgium in summer (around 50% less in dry summers by 2071–2100) (−20% in the least pessimistic scenario; −70% in the most pessimistic) and increased water shortages. Higher rainfall in winter will partially be compensated by increased evaporation; nevertheless, more frequent inundations are anticipated. Given the observations elsewhere of beaver dams that regulate river discharge and its extremes, the potential effects of beaver dam expansion on catchments runoff response in Belgium needed to be investigated. This study focuses on the hydrological effects of a series of six beaver dams on the Chevral, a second order river in the sub-basin of the Ourthe Orientale in the Central Ardennes (Fig. 1). Thereby, the Ourthe Orientale sub-basin itself is also taken into account, being the area with probably the highest density of beaver dams in Belgium. The relevance of this hydrological research is the possible regulation of stream flow, as a cumulative effect of beaver dams in the headwaters. The main research questions regarded: (1) the extent to which discharge peaks are reduced at the very location and well downstream of beaver dams and (2) the impact of the beaver dams on low flows.

2. Materials and methods

2.1. Study area

2.1.1. Beavers in Belgium

In Belgium, the beaver has recessed since the 16th century and was hunted to extinction in the mid-19th century, with the last observation in 1848 (Huijser and Nolet, 1991). Besides a few individuals that came naturally from the German Eifel to the High Ardennes (Huijser and Nolet, 1991), the actual population of beavers in Belgium are the progeny of illegal reintroductions of 100–150 beavers between 1998 and 2001. In 2003, the population was estimated at 200–300 beavers (Lempereur et al., 2003). In 2010, they were estimated around 1000 (Manet, 2010, personal communication). Signs of presence of beavers are found in sometimes distant places (up to the port of Antwerp – press reports), which indicates that the species is rapidly expanding.

Beavers live in forests or in forested buffer strips of at least 10 m width (Angst, 2009), along rivers and other water bodies, where they have full year access to sufficiently deep water or where they can develop these conditions through dam building (Stuyck and Van Den Berghe, 2008). Studies in several countries showed that beavers prefer low gradient, first and second order streams (Grubešic et al., 2006; Lizarralde et al., 2004).

Beaver dams consist of branches and twigs, sealed with mud and sometimes stones on the upstream face (Richard, 1983). Beaver dams typically have a height of around 1 m (Curry-Lindahl, 1967; Medwecka-Kornas and Hawro, 1993) and lengths often attain as much as 20 m (Medwecka-Kornas and Hawro, 1993). Small dams located in-stream can be increased systematically and then widened to expand over the alluvial plain (Richard, 1983). Woo and Waddington (1990) distinguished four ways in which water crosses the dams, related to their age and state of maintenance: (1) overflow over the whole width of the dam top, (2) gapflow or a concentrated overtopping flow at the lowest place of the dam, (3) throughflow, leaking through the dam, and (4) underflow, leaking under the dam.

The large majority of beaver dams in Belgium is located in the Ardennes and Famenne geographical regions (Plunus, 2009), 20% of the country's territory. Studies on beaver dam construction and location were carried out in the valleys of the Viroin (Van den Bergh, 1999), Ourthe Orientale (this study), Hautes Fagnes (Baguette, 1994), Dijle (Niewold, 2003), Houille (Rousseaux, 2001), and more widely in the Walloon (Lempereur et al., 2003; Libois, 2006; Plunus, 2009) and Flemish regions (Niewold and Rossaert, 2002; Stuyck and Van Den Berghe, 2008). The beavers' expansion will reasonably lead to them returning in intensively used agricultural landscapes, the hydrography of which has totally been altered in the past 150 years: drained surfaces with rectified and squeezed river beds by various engineering works (Angst, 2009).

A random sampling at seven beaver dam sites in Belgium shows that the dams had ages between 3 and 8 years and the rivers have low gradients (Table 1).

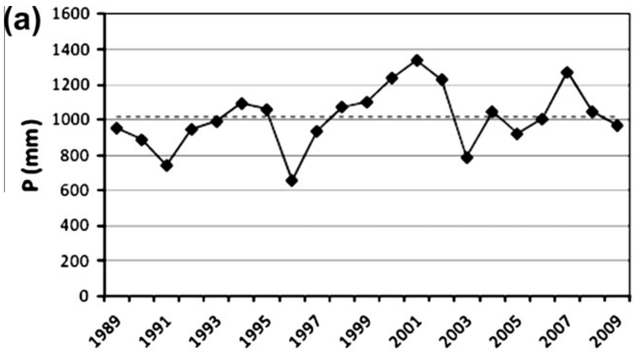
Only the beaver dams of Sint-Agatha-Rode and Pécrot were fully located in the river bed; the others expanded on the alluvial plain. The upper Chevral and Sommerain sites saw the emergence of new channels in the alluvial plain. Spectacular 2–5 ha wide inundations of the alluvial plain exist at Thilay and Lierneux, which reduced the flow in the downstream segment.

The beaver dams of our study are all located on first to third order rivers (Table 1). Similarly, Plunus (2009) in Belgium and Naiman et al. (1986) in Canada observed beaver dams in rivers of first to fourth order. Our observations also confirmed the preference for flat bottoms of U-shaped valleys or sometimes flattened V-shaped valleys (Collen and Gibson, 2000; Gurnell, 1998). The observed gradients were also consistent with Zurowski (1992)

Table 1
Characteristics of a sample of Belgian beaver dam systems.

	Location	Lat. N	Lon. E	River	Order[a]	Gradient[b] (m m^{-1})	Valley shape[b,c]	Type of dam[c]	Year of first construction[d]	Average dam height[e] (m)	Total dam length[e] (m)	Total area of beaver pond(s) [b,e] (m^2)
1	St-Agatha Rode	50°50′	4°34′	(creek)	1	<0.05	Wide alluvial plain	Small in-stream dam	2007	0.1	3	In channel
2	Pécrot	50°47′	4°39′	Petite Marbaise	1	<0.05	Wide alluvial plain	2 in-stream dams	2005	0.15	5	In channel
3	Thilay[g]	49°57	4°47′	Stole	2	0.011	U	Large dam[f]	2002	0.65	150	19,500
4	Wibrin	50°11′	5°43′	Chevral (middle)	2	0.010	V	Series of 5 dams[f]	2004 or 2005	0.6	205	3360
5	Wibrin	50°15′	5°44′	Chevral (lower)	2	0.018	Sharp V	Series of 6 dams[f]	2004	0.75	210	5200
6	Mont	50°10′	5°48′	Sommerain	1	0.007	Shallow V	Series of 4 dams[f]	2004 or 2005	0.7	55	2800
7	Lierneux	50°17′	5°48′	Lienne	3	0.005	U	Large dam[f]	2003 or 2004	0.9	90	54,000

[a] After Strahler (1952).
[b] From topographic map at scale 1/20 000, contour intervals of 5 m.
[c] Own field observations.
[d] Based on interviews with locals and guides, own observations (state of trees) and literature (Niewold, 2004).
[e] Field measurement.
[f] Dams largely expanding over the alluvial plain.
[g] Located in France, just over the border with Belgium.



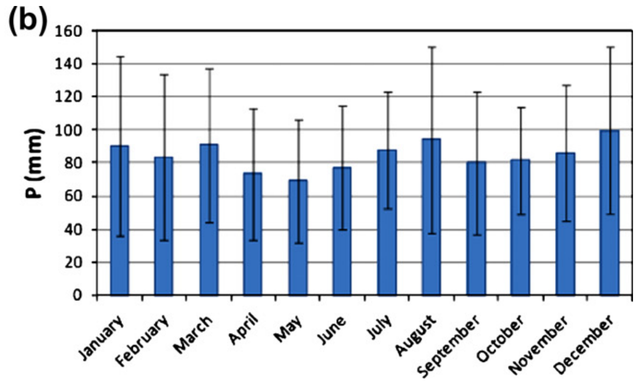


Fig. 2. Rainfall (P) variability in Ortho for 1989–2009, (a) total yearly rainfall, and (b) monthly averages with standard deviation. Data from SETHY (2010).

who stated that beaver dams generally occur on rivers with gradients <0.02.

The younger age of in-stream dams (Table 1) tends to indicate that with age, the dams expand from the river bed onto the alluvial plain. On the other hand, Pullen (1971) observed that floodplain ponds can exist for many years, whereas streamchannel ponds are typically short lived. In our study sites, interference of human activities was very limited. At the middle Chevral site, a beaver dam was built under a road bridge, leading to water flowing over the road. The dam was removed by municipal workers several times but then reconstructed by the beavers. At Thilay, a drainage pipe was installed through the beaver dam to keep the upstream water level lower.

2.1.2. The Ourthe Orientale sub-basin

The impact of beaver dams on hydrology was studied in the sub-basin of the Ourthe Orientale (Fig. 1). Since the end of 2003 the first beaver dams were observed in that sub-basin; a rough estimate indicates that in 2010 there were 120 beavers and 20 dam systems in that 317 km^2 wide sub-basin.

The Ourthe Orientale sub-basin (292–652 m a.s.l.) is part of the Central Ardennes and largely located on Siegenian formations consisting of metamorphic schists (de Béthune and Brouckaert, 1968; Goossens, 1984). The northernmost part of the sub-basin is located on Gedinnian rocks, comprising slates and phyllades. The northernmost and upper part of the sub-basin is covered by peat. Major land uses are forest and permanent meadows.

The maximum average daily discharge of the Ourthe Orientale is 35 $m^3 s^{-1}$. Average yearly rainfall is 1016 (±160) mm (Fig. 2a), which is evenly spread over the year (Fig. 2b). Large standard deviations indicate that monthly rainfall is however unpredictable.

2.1.3. The Chevral River

Within the Ourthe Orientale sub-basin, the hydrological effects were measured at the lower Chevral River, which holds a series of six cascading beaver dams (Fig. 1), with single in- and outflow locations. The Chevral takes its source on the Tailles plateau (Fig. 1), which forms the northern axis of the Ardennes anticlinorium (Demoulin, 1995). The catchment area is 14 km^2 and is essentially forested (Table 2). This second order river is a tributary to the Martin Moulin R., which, near Rensiwé, flows as a third order stream into the Ourthe Orientale (Fig. 1).

2.2. Analysis of the hydrological time series of the Ourthe Orientale River

Systematic statistical analyses have been carried out on existing river discharge data and temporally correlated to the establishment of beaver dam systems in the Ourthe Orientale sub-basin. Average daily discharges were obtained for the Ourthe Orientale at Mabompré for 1978–2009 (SETHY, 2010) and for the Martin Moulin (2004–2010), a tributary to the Ourthe Orientale, at Rensiwé, 4 km downstream of the studied beaver dam site (Aqualim, 2010). Both stations are located nearby each other (Fig. 1), and were visited in 2009 and 2010, whereby proper functioning was observed. The daily discharges at both stations for the 2004–2009 interval have similar patterns and are highly correlated (determination coefficient R^2 of 0.81).

To analyse possible changes over time in high flows, their frequency, expressed in terms of recurrence interval (*tr*) was determined. For both periods, before beaver dam installation (BBD; 1978–2003) and after (ABD; 2004–2009), the flood frequency curve was obtained by using the highest annual daily discharge (Q_{max}) (Bras, 1990):

$$tr = (N + 1)/m \quad (1)$$

where N is number of ranked flood values, and m is the rank of a specific value. The recurrence time interval *tr* corresponds to the inverse of the probability for a flood to occur and equals the time statistically expected between occurrences of a flood with a given discharge. The temporal division leads inevitably to incorporating a period after beaver dams of only 6 years (2004–2009).

Further, time series of yearly maximal flow (Q_{max}), the discharge exceeded five (Q_5), ten (Q_{10}) and 355 days a year (Q_{355}) were plotted and compared between the periods BBD and ABD. Q_{355} is taken as a low flow index (Billi and Paris, 1992). To comprehend the impact of beaver dam construction on rainfall–runoff relationships, daily rainfall data were also obtained for the Ortho station (293 m a.s.l.) for 1987–2009 (SETHY, 2010) and monthly rainfall data for the Nadrin station (402 m a.s.l.) for 1978–2009 (RMI, 2010). Both stations are located slightly out of the Ourthe Orientale sub-basin at a distance of 8–10 km from its centre, taking into account that daily rainfall in the study area does not vary significantly over such distances (Ly et al., 2010). Rainfall data were not available at hourly increment which made that rain intensity could not be taken into account. To allow the comparison with rain

Table 2
Land cover in the Chevral catchment, as derived from topographic maps (NGI, 2005, 2007) and field observations.

Land cover class	%
Coniferous forest	47.0
Id., clear cut in 2009	0.3
Deciduous forest	15.7
Mixed forest	15.8
Permanent meadow	17.6
Farmland	0.6
Marsh	0.4
Water body	0.2
Build-up area	2.4

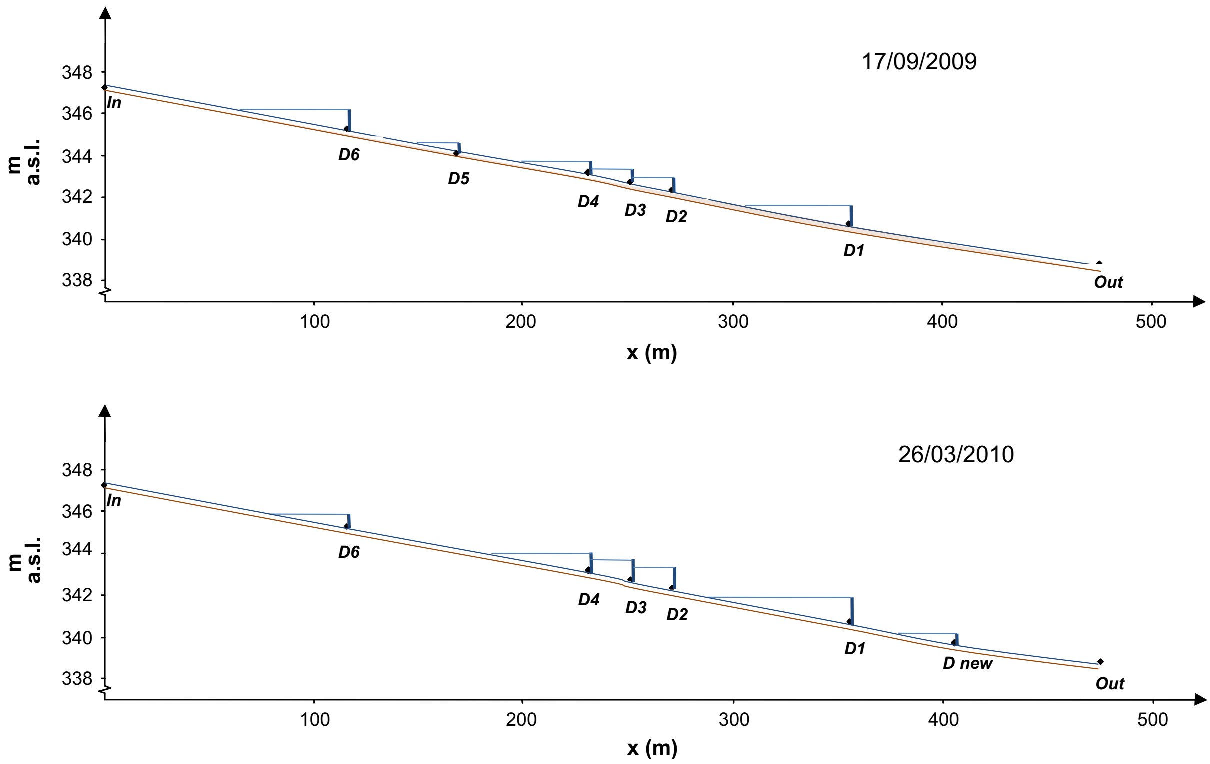


Fig. 3. Longitudinal profiles of the Chevral beaver dam system (vertical exaggeration: 10×), as measured with 6 months interval.

depths, daily discharge values were expressed as runoff depths. For every month, maximal and minimal daily discharges as well as average monthly discharge were expressed as a fraction of the total rain depth of that month. To allow a comparison over time, discharge and discharge divided by rain (Q/P) values were standardised over the whole period:

$$z = (x - \mu)/\sigma \quad (2)$$

where z = standardised value, x = measured value, μ = average of the time series, and σ = standard deviation.

2.3. Hydrological monitoring on the Chevral River

The Chevral catchment is fully located on Siegenian formations composed of schists. The stony valley bottom is surrounded by valley flanks with stone-rich loamy colluvium (Deckers and Tavernier, 1958). The series of six dams on the lower Chevral is reported to have been installed in 2004 and is occupied by one beaver family (Mahaux, personal communication, 23 August 2009). The fact that all trees in the pond system have died, but some have not yet fallen, confirms this age. The beaver dam system was very dynamic throughout the 7 months of observation. Some dams disappeared while others were newly built, changed in height (Fig. 3), breached (Fig. 4) and were eventually repaired.

Discharges on the lower Chevral were measured on 7 days, between September 2009 and March 2010, at 100 m upstream of the uppermost dam (inflow), and 100 m downstream of the lowermost (outflow). The difference in time between the two measurements was approx. 30′.

Between the inflow and outflow measurement locations, the Chevral has a streambed gradient of 0.018 (Fig. 3). Field measurements were done on 30 September, 9 and 12 October, 1 and 17 November 2009, 24 January and 26 March 2010. Most field days were dry, except 17 November 2009 (heavy rain) and 26 March 2010 (drizzle).

Discharge measurements at the inflow and outflow locations were done by the river flow continuity equation,

$$Q = vA, \quad (3)$$

in which Q is flow discharge ($m^3\,s^{-1}$), v is mean flow velocity ($m\,s^{-1}$) and A is the area of the cross-section (m^2). The float method was used to measure the reach average flow velocity by means of a sequence of ten individual floats of wine corks for each measurement over a predefined river reach length and measuring the geometry of a reach representative cross-section. Measurements in which the float was obstructed by rocks or got trapped in small swirls were discarded and started over. The very shallow flow depth (typically a few centimeters – 40 cm at most) and the common occurrence of upcurrent surface swirls suggested to apply no correction coefficient to the surface velocity measurements in order to not underestimate flow discharge.

The sample of 7 days on-site measurements of outflow from the beaver dam system was correlated with data from the 4 km downstream Rensiwé hydrological measurement station on the Martin Moulin; the high determination coefficient (R^2 = 0.82) shows that our discharge measurements are consistent. The obtained regression allowed extrapolating the daily discharges (Q_{out}) at the beaver dam site for each day of the study period. Then we sought correlations between the seven measured inflow discharges and the Q_{out}'s of the day itself and the following days, in order to allow reconstructing the daily discharges at the inflow location of the beaver dam system (Q_{in}).

To monitor the stored water volumes in the pond system, we measured the vertical distance between the water level and nails driven into trees standing in the water near the left bank. As 30 September 2009 was the day with the lowest water level, the subsequent measurements were expressed as increases relatively to the lowest level. To calculate the volumes of stored water, the coordinates of 32 points on the contour of the flooded area were recorded by hand-held GPS (with EGNOS correction) and distome-

Fig. 4. Changes, within a few months, in 'dam 4' on the Chevral. In summer (23/08/2009), the dam was nearly watertight; on 17/11/2009 there was overflow with beginning breaching; gapflow (arrow) on 26/03/2010. On 04/08/2010 the gap was again fully closed.

ter (Leica Disto TM Lite); the latter was particularly used for inaccessible areas where the beaver pond extended up to rocky crags. As valley flanks are steep, the variation in ponded area with rising water levels was considered negligible. A multiplication of pond area with area-weighted average height of the water for each observation day (using Thiessen polygons – Fig. 5) allowed determining the volume of water stored in the system (beyond the residual volume, corresponding to the day with lowest water levels) on each of the measurement days. A correlation of these seven storage volumes with Q_{out} of the corresponding day allowed to tentatively reconstructing a timeline of stored water volume.

3. Results

3.1. Hydrology of the Ourthe Orientale River before and after beaver dam installation

The first approach consisted of a temporal analysis of the Ourthe Orientale discharges at the middle-long term, for the periods 1978–2003 (before) and 2004–2009 (since the establishment of beaver dams in the sub-basin), using discharge and precipitation data. The normalised (z) values of maximal daily discharges Q_{max}, Q_5 and Q_{10} (i.e. the discharge exceeded 5 and 10 days in a year) (Fig. 6a) of the last 5 years after beaver dam establishment (ABD) are all negative, hence lower than the long term average. In the whole time series, there is no other period of >3 years with negative values. For the minimal discharges Q_{355} (Fig. 6b) the years 1987, 2007 and 2008 have very high z values, which lead to most other years having only slightly negative z values. There are three periods with average to well above average low flow, two BBD (1980–1982, 1987–1988) and one ABD (2006–2009). On average, Q_{355} increased from 0.6 (±0.15) $m^3 s^{-1}$ in the last 6 years BBD to 0.88 (±0.52) $m^3 s^{-1}$ in the 6 years ABD.

The slopes of the trendlines on these normalised (z) values of discharges at Mabompré (Table 3) indicate that before the beaver dams the flow variability around the mean showed no trend whereas after beaver dams the high discharges tend to decrease and the low flows tend to increase.

For the calculation of the recurrence interval (Fig. 7) of maximum average daily discharges BBD and ABD, given the small size of the ABD data series (whereby the use of extreme values analysis such as Gumbel's or Pearson's makes little sense), the log-normal law was considered (R^2 = 0.94 and 0.84). One may further observe the decrease in slope of the logarithmic regression lines, from 32.1 BBD to 26.1 ABD. Based on this analysis, the recurrence interval of

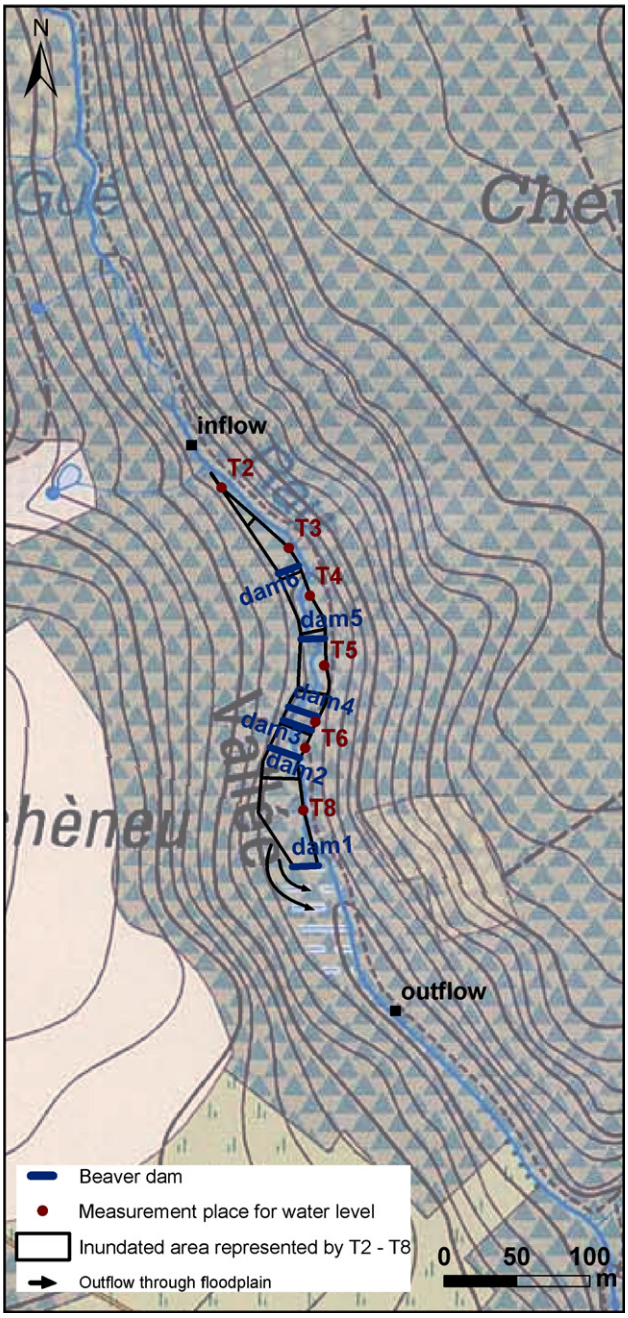


Fig. 5. Location of beaver dams in the lower Chevral valley, with indication of measurement points for the water level (T2–T8). The beaver pond system has been divided into polygons, each represented by one measuring point. Situation on 17 November 2009. Background map: NGI (2006).

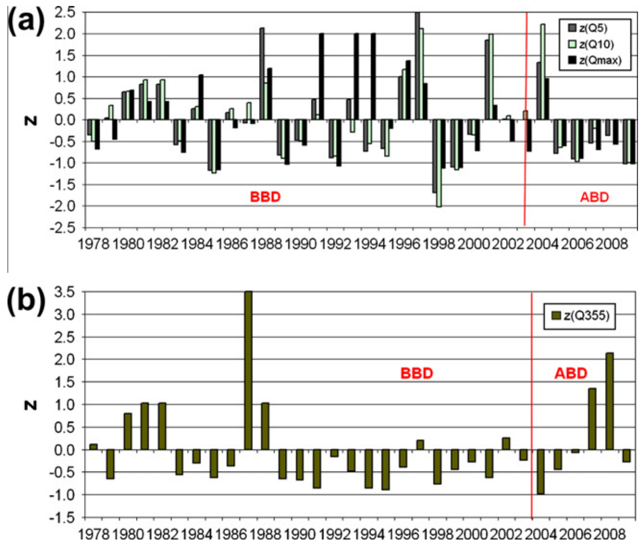


Fig. 6. Normalised (z) values of yearly discharges of the Ourthe Orientale at Mabompré since 1978, with vertical line indicating the installation of beaver dams in the basin: (a) maximal discharges (Q_{max}, Q_5, Q_{10}), and (b) minimal discharges (Q_{355}). (BBD: before beaver dams; ABD: after beaver dams). *Source*: own processing of existing dataset (SETHY, 2010).

Table 3
Slope (a) of the trendlines on normalised (z) values of discharges ($z = ax + b$, with x = time in years) before beaver dam installation (BBD) and after (ABD).

	a (BBD)	a (ABD)
Q_5	−0.0018	−0.316
Q_{10}	−0.0049	−0.397
Q_{max}	−0.0055	−0.311
Q_{355}	−0.0351	0.792

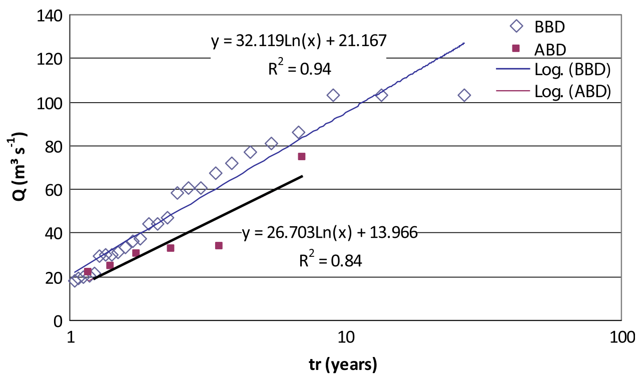


Fig. 7. Flood frequency curves of the Ourthe Orientale at Mabompré as a function of recurrence interval (tr) for the periods before (BBD; 1978–2003) and after beaver dam installation (ABD; 2004–2009). *Source*: own processing of existing dataset (SETHY, 2010).

a reference flood of 40 $m^3 s^{-1}$ was 1.8 years BBD and 2.7 years ABD, for a flood of 60 $m^3 s^{-1}$ it was 3.4 years BBD and 5.6 years ABD (Fig. 7). The short observation time ABD does not allow predicting changes in the recurrence interval of larger discharges.

The time series of standardised ratios of discharge (at Mabompré) to monthly rainfall (at Nadrin) show that the average z values are positive BBD and negative ABD. Average z value of Q_{max}/P (Fig. 8a) is 0.038 BBD and −0.166 ABD and that of Q_{mean}/P (Fig. 8b) is 0.026 BBD and −0.114 ABD. Further, both parameters have no positive (unexpectedly high) values in the period ABD, in contrast to the period BBD. The negative z values of Q_{max}/P are almost invariable (Fig. 8a), for Q_{mean}/P they vary a bit more (Fig. 8b) but not as strongly as the positive z values. Similar analysis was not done for the low flows as, in the study area, the capacity of 1 month of rainfall to affect the base flow of the month itself is minimal.

The timeline of daily discharges of the Ourthe Orientale (not represented) peaks yearly; the peak floods were higher before 2004, though such was not the case for peaks in rainfall. At first sight, decreased peak discharges after 2004 might be attributed to the establishment of many beaver dams in the sub-basin, but it appears that also in small rivers without beaver dams in their basin (Bocq, Mehaigne, Dendre Occidentale, Molignée) and in the

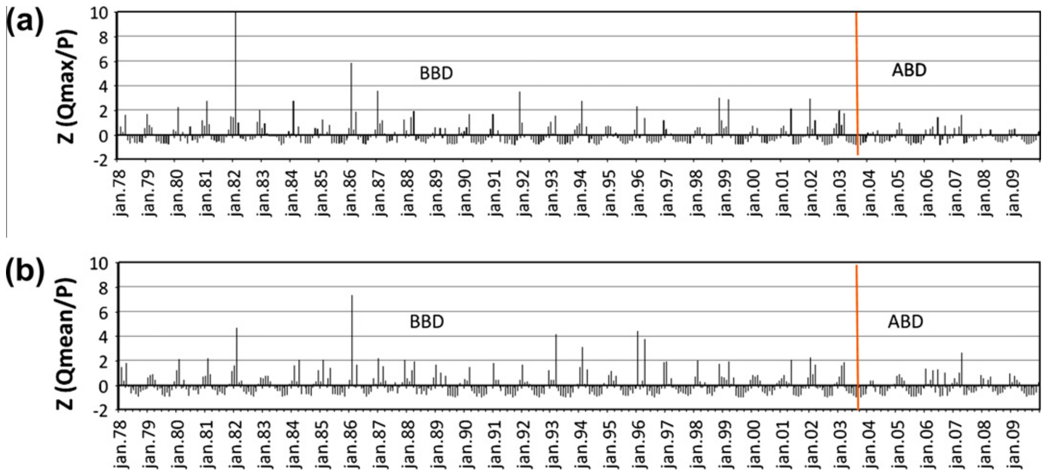


Fig. 8. z-Values for the ratio of discharge (Q in mm, Mabompré station on the Ourthe Orientale) to total rainfall (P in mm, Nadrin station) of the same month, before (BBD) and after beaver dam construction (ABD): (a) for monthly maximum of average daily discharges (Q_{max}), and (b) for average discharges (Q_{mean}). Source: own processing of existing datasets (RMI, 2010; SETHY, 2010).

Table 4
Results of hydrological measurements at the lower Chevral beaver dam system.

Date	Discharge into the beaver system Q_{in} ($m^3 s^{-1}$)	Discharge out of the beaver dam system Q_{out} ($m^3 s^{-1}$)	Q_{in}–Q_{out} ($m^3 s^{-1}$)	Water volume stored in the beaver ponds[a] V (m^3)
30/9/2009	0.08	0.11	−0.03	0
9/10/2009	0.16	0.26	−0.10	43
12/10/2009	0.35	0.62	−0.27	202
1/11/2009	0.20	0.20	0.00	75
17/11/2009	0.76	0.66	0.09	310
24/1/2010	0.75	1.16	−0.41	163
26/3/2010	0.96	1.01	−0.05	59

[a] As compared to the volume on 30/9/2009, date with lowest water level.

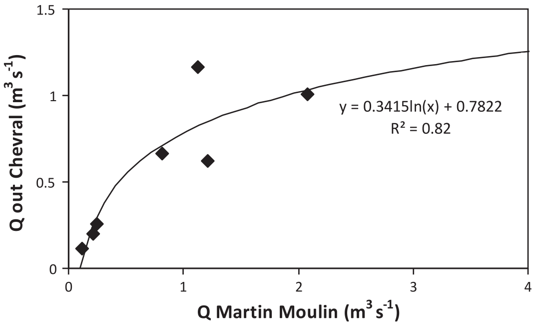


Fig. 9. Instant discharges (Q_{out}) at the lower Chevral beaver dam site (own measurements) vs average daily discharges, 4 km downstream on the Martin Moulin River at Rensiwé (Aqualim, 2010) for the same dates.

Meuse river (all data from SETHY, 2010), there is a general absence of high peaks in 2004–2009.

3.2. Hydrology of the lower Chevral beaver dam system

In the second approach, an *in situ* study was done to determine the impact of the beaver dams: discharges upstream and downstream of the beaver dam system on the Chevral river, and changes in water level within the system were measured (Table 4). On six of the seven observation days, the outflow was larger than or equal to the inflow. The volume stored in the 0.52 ha beaver dam system was largest on 17 November 2009.

The correlation between daily average discharge values measured on the Martin Moulin for the 7 days of field measurements and our own instantaneous measurements at the outflow of the Chevral beaver dam system (Fig. 9) was fitted by a logarithmic trend ($R^2 = 0.82$). This correlation allowed an extrapolation for Q_{out} over the study period (Fig. 10, lower curve). The inflow discharges Q_{in} were positively correlated ($R^2 = 0.80$) with Q_{out} of the same day, and showed even a better correlation ($R^2 = 0.85$) with the calculated outflow discharges of the next day (Fig. 11). This exponential function allowed extrapolating the results of the inflow measurements over the whole study period (Fig. 12) and comparing them to the calculated outflow discharges.

The monitored volumes of stored water in the Thiessen polygons around the measurement sites for water level generally show parallel trends to which one sharply decreasing water volume in one polygon (related to the breach presented in Fig. 4) on 26 March 2010 is an outlier.

The Chevral beaver dam system was measured to temporarily store up to 310 m^3 of water on top of the volume that is permanently stored, represented by the measurement of the water level

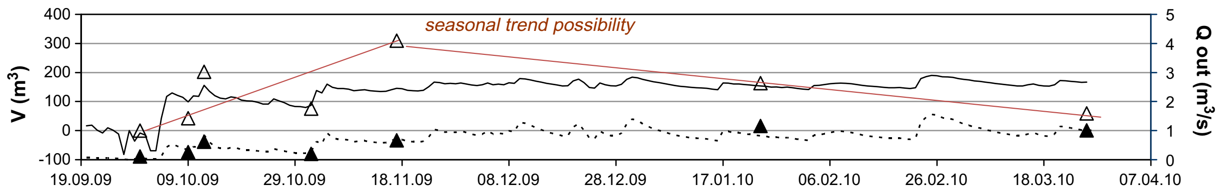


Fig. 10. Observed (triangles) and calculated (curves) hydrological parameters of the beaver pond system on the Chevral. Lower curve and filled triangles represent discharge at the outlet of the beaver dam system (Q_{out}); upper curve and open triangles represent water volume stored (V), in respect to the situation on 30/9/2009. Hypothesised seasonal trend is indicated.

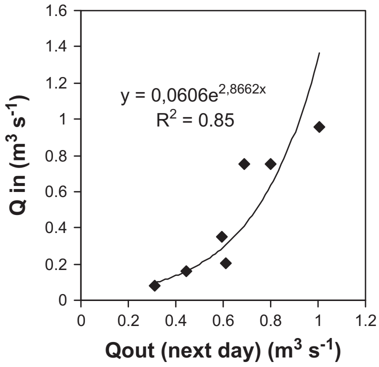


Fig. 11. Measured inflow in the Chevral beaver dam system (Q_{in}) vs. calculated outflow (Q_{out}) of the next day.

when it is lowest (Table 4). Volumes of stored water are positively correlated to outflow discharges ($R^2 = 0.32$), where the one measurement with highest stored volume of water (on 18.11.2009) is responsible for the weak correlation (Fig. 10).

4. Discussion

The impact of beaver dams on discharge was considered at two spatial scales, that of the Ourthe Orientale sub-basin, which has probably the highest density of dams in Belgium, and that of the embedded Chevral site. In the first case, the study was done at mid-long term (1978–2009), while the Chevral was studied over a season (September 2009–March 2010).

4.1. The coming of beavers in the Ourthe Orientale sub-basin has smoothened the hydrograph

The analysis of the time series of Ourthe Orientale discharges shows some tendencies that may be related to the establishment of beaver dams in its basin. The maximum discharges Q_{max}, Q_5 and Q_{10} in the years 2005–2009 were all less than the average maximum discharges of the full time series (1978–2009) (Fig. 6a). As the first 25 years of the series comprise only one period of three consecutive years with below average maximum discharges, the occurrence of five continuous years of low maximum discharges after 2005 seems to indicate that the beaver dams have contributed to such reduction of the maximum discharges.

Similar conclusions can be drawn from the flood frequency curves (Fig. 7) and the slopes of the logarithmic regression lines of the periods before and after beaver dam installation. The same maximal discharges have a greater recurrence period after beaver dam installation, and this difference becomes larger when the maximum discharges are extremer (with greater return periods). This approach confirms the flattening of hydrographs due to introduction of beaver dams (Burns and McDonnell, 1998; Gurnell, 1998; Woo and Waddington, 1990). Given the recent introduction of beavers and dam building, their effect could only be observed over a statistically short observation period.

We could not find, for the study period (June 1987–2009) any correlation between daily rainfall and discharge. This may be explained by the fact that we could not bring into account: (1) rainfall intensity and (2) detailed soil moisture and vegetation characteristics. Small mountain rivers usually react rapidly on intense storms as compared to rivers of higher order, but when the same rain depth is spread over several hours, such effect is not observed (Billi and Paris, 1992). In the studied Ardennes massif, covered by forests and meadows, the linkage of runoff to rainfall requires complex analyses whereby antecedent moisture conditions should be taken into account, as well as evaporation which is linked to relative humidity and air temperature (Petit, 1995).

At monthly scale the normalised values of Q_{max}/P for the periods before and after beaver dam installation show a remarkable difference whereby no more peaks occurred after 2004 (Fig. 8a).

The slopes of the trendlines on the *z*-scores for BBD and ABD time spans (Table 3) allowed sorting out the decreasing or increasing trend rates, and quantifying the changes in the natural trend after the appearance of beaver dams. Though the two time spans are very different in terms of number of observations, the values of the rates of change on discharge *z*-scores at Mabompré (Table 3) do support the findings of an effect of beaver dams in reducing the high flows and increasing the low flows in the dry periods.

These findings confirm that beaver dams can contribute to decrease flood risk, thereby confirming the "headwater" paradigm (Haigh, 2009; Haigh et al., 2005) that stresses the potential of temporary water storage in low order river basins.

The average low discharge (Q_{355}) of the Ourthe Orientale was 0.6 (±0.15) $m^3 s^{-1}$ BBD and increased to 0.88 (±0.52) $m^3 s^{-1}$ ABD. Hence, the duality in water retention (Gurnell, 1998) could be observed at the scale of the Ourthe Orientale sub-basin.

4.2. Trends in water storage and release in the Chevral beaver system

The results of hydrological measurements on the Chevral (Table 4) show greater outflow than inflow on most days, except when rain occurred. Obviously in dry periods the dam system releases water to the lower river reach, whereas on rainy days the flood is buffered. In line with this thought, we could best correlate the incoming discharge with the outgoing discharge of the next day (Fig. 11). The capacity of the dam system for temporary water storage is particularly illustrated in Fig. 12. Between 17 November 2009 and 24 January 2010, when the extrapolated Q_{out} curve shows

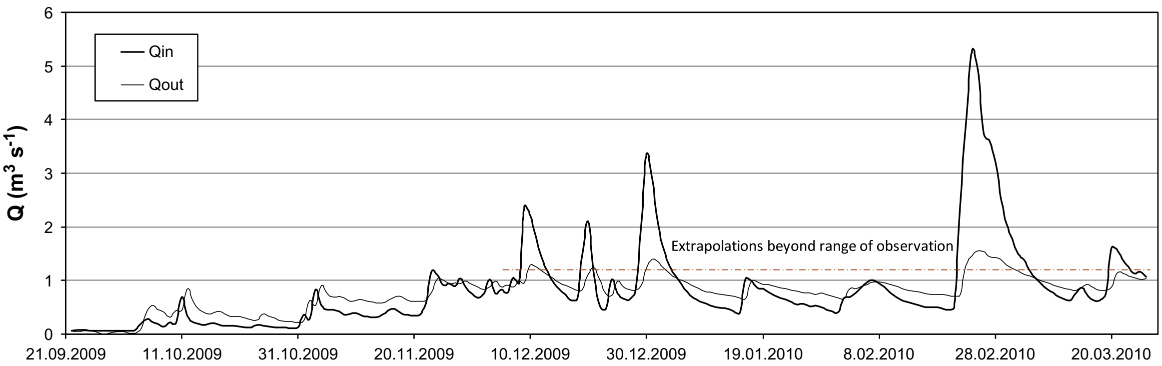


Fig. 12. Comparison over time of the calculated curves for inflow (Q_{in}) and outflow (Q_{out}) in the Chevral beaver dam system. The Q_{out} curve is flattened and delayed as compared to the Q_{in} curve. The dotted horizontal line indicates discharge of 1.2 $m^3 s^{-1}$, the upper end of the range of our measurements (Table 4).

some peaks, no field measurements were done. Also for the largest peak of the end of February 2010, there was no field measurement, though the extrapolated peaks are estimated to correspond to reality, when considering the downstream Martin Moulin daily discharges (Rensiwé station). For the magnitude of the largest peaks in Q_{in}, we should bear in mind that inflow discharges were extrapolated using a power relation equation (though with a high R^2 of 0.85) what may have lead to some exaggeration of the peaks in Q_{in}. It is however clear that the highest discharges, after crossing the series of six beaver dams, are topped off while the low flows are increased after passing through the dam system. With regard to decreased outflow, Meentemeyer and Butler (1999) showed that beaver dam emplacement may even lead to the fact that in some cases no discernible outflow occurs. Similarly to the wider Ourthe Orientale sub-basin, at the scale of the studied Chevral catchment the duality of water retention was observed, in line with findings by Burns and McDonnell (1998) and Gurnell (1998).

The increase in low flow discharges is explained by the release of water that was stored in the beaver ponds as well as from the optimally filled ground water reserve (John and Klein, 2004).

The estimated stored water volume (relatively to the lowest observed water level on 30 September 2009; Fig. 10, upper) was up to 310 m^3 for a 0.52 ha area and evidences the buffering capacity of the beaver dam system. With two exceptions, the extrapolated pond volumes are in line with the observed volumes. The extrapolation of the obtained equation to the whole time series (Fig. 10, upper curve) clearly underestimates the stored volume on 17 November 2009 and overestimates it on 26 March 2010. This observation, combined with field observations on the physical quality of the dams over time (Fig. 4), led to the hypothesis that besides the correlation with incoming discharges, there is a seasonal tendency in water volume, as indicated by the hypothesised trendline in Fig. 10. This outlier and the observed low stand at the end of the observation period tend to indicate that the stored volumes in the pond system are related to more than the outflow discharges only, and that at least a second parameter should be accounted for. Field observations on the state of the dams (Fig. 4) suggest that the effectiveness of the dam system is linked to a seasonal trend with decreased beaver activity in winter, when they lower food intake and feed on previously stored branches (Aleksiuk, 1970; Novakowski, 1967) and when water levels are generally high anyway.

The spectacular lowering of the stored volume around one measurement point was caused by a long lasting breach in dam 4, with a leakage that started on 17 November, a breach that was noted on 24 January and not yet restored on 26 March 2010. These changes are not a sign of beaver site abandonment, as a new dam (Fig. 3) was initiated in the same period, and by summer 2010 dam 4 had been fully restored. All this indicates that for detailed measurements at the scale of a beaver dam system, the *bio*-physical character needs to be incorporated in the analysis. Increased breaching in winter may further also be related to higher discharges that can be related to less evaporation, periods with frozen ground and snow melt.

5. Conclusions

In this first hydrological study after beaver reintroduction in Western Europe, we could compare hydrographs that were not influenced by beaver activity until 2003, with those after the first dams were built in 2004. Our findings at the scale of the Ourthe Orientale sub-basin indicate that there is a lowering of discharge peaks due to the effect of the beaver dams. The temporal analysis of the Ourthe Orientale sub-basin suggests an increase in the recurrence interval for major floods since the establishment of the beaver dams, by more than 50%. Both the temporal observations of change in the Ourthe Orientale discharges, and the variation between inflow and outflow at the Chevral beaver dam system, show a duality of water retention similarly to what was observed by Burns and McDonnell (1998)and by Gurnell (1998).

At the level of the Chevral beaver dams' site, we measured that the dams top off the peak flows, in addition delaying them by approximately 1 day. The Chevral beaver dam system led also to increased low flows.

These findings also tend to agree with studies that suggest natural measures for river restoration at the level of small mountain streams, instead or in complement of engineering works downstream in order to reduce flooding (Haigh, 2009; Haigh et al., 2005; van Winden et al., 2003). Though, more studies and a longer observation period are needed to make prognoses concerning flood prevention, for instance for the entire Ourthe–Amblève basin (2751 km^2), and to compare the hydrological impacts of dam building by *C. fiber* and *C. canadensis*.

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