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Spatio-temporal sedimentation patterns in beaver ponds along the Chevral River, Ardennes, Belgium

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Abstract

With the recovery of the European beaver (*Castor fiber*) and their capacity to engineer fluvial landscapes, questions arise as to how they influence sediment transport, including the spatio-temporal trends and patterns of sedimentation in beaver ponds. The Chevral river (Ardennes, Belgium) contains two beaver dam sequences which appeared in 2004. Volumes of sediment deposited behind the dams were measured and grain size distribution patterns were determined. Flow discharges and sediment fluxes were measured at the in- and outflow of each dam sequence. Between 2004 and 2011, 1710.1 m³ of sediment were deposited behind the beaver dams, with an average sediment thickness of 25.1 cm. The thickness of the sediment layer was significantly ($p < 0.001$) related to the area of the beaver ponds. Along the stream, beaver pond sediment thickness displayed a sinusoidal deposition pattern, in which ponds with thick sediment layers were preceded by a series of ponds with thinner sediment layers. A downstream textural coarsening in the dam sequences was also observed, probably due to dam failures subsequent to surges. Differences in sediment flux between the in- and outflow at the beaver pond sequence were related to the river hydrograph, with deposition taking place during the rising limbs and slight erosion during the falling limbs. The seven-year-old sequences have filtered 190.19 tons of sediment out of the Chevral river, which is of the same order of magnitude as the 374.4 tons measured in pond deposits, with the difference between the values corresponding to beaver excavations (60.24 tons), inflow from small tributaries, and runoff from the valley flanks. Hydrogeomorphic effects of *C. fiber* and *C. canadensis* activity are similar in magnitude. The detailed analysis of sedimentation in beaver pond sequences confirms the potential of beavers to contribute to river and wetland restoration and catchment management.

Key words: *Castor fiber,* sediment deposition, suspended sediment, zoogeography, headwaters, hydrograph

1. Introduction

The European beaver (*Castor fiber*) has recently reappeared in the northwest European fluvial landscape and has begun to exert a hydrologic impact. These rodents can attain 15-35 kg in body weight and are closely related to the North American beaver *Castor canadensis* (Lavrov and Orlov 1973). *C. fiber* was once widespread throughout the Eurasian continent, inhabiting river valleys in forested regions (Zharkov and Sokolov 1967; Djoshkin and Safonov 1972). At the end of the 19th century, their population had declined to ca. 1200 beavers (Halley and Rosell 2003), mainly due to overhunting. Management measures (including strict hunting regulations) and reintroduction led to the recovery of the populations, allowing the beaver to recolonise much of its former habitat, including areas where it had been absent for centuries (Nolet and Rosell 1998; Halley and Rosell 2003). In Belgium, *Castor fiber* was reintroduced in the 1990s (Huijser and Nolet 1991; Libois 1993).

Beavers have an important influence on their environment by creating dams, canals, and other structures to control water flow. They construct dams to guarantee a stable water level so that their lodge and burrow entrances stay below the water level without inundation of the nest chambers (Gurnell, 1998). These activities affect the hydro-geomorphology of catchments (Gurney and Lawton 1996; Rosell *et al.* 2005). The construction of dams is their most remarkable activity (Butler 1991), as it influences the discharge flow and sediment flux of the stream. Beaver dams store water during peak flows so that in dry periods the stored water is released gradually, guaranteeing higher water levels during dry periods (Yeager and Hill 1954; Rutherford 1955; Parker 1986; Gurnell 1998; Nyssen *et al.* 2011). The capacity of the stream to transport sediment is also affected by beaver dams. Dams favour upstream sediment accumulation (Naiman *et al.* 1988; Butler and Malanson 1995) with the eventual development of meadows (Ruedemann and Schoonmaker 1938; Kurstjens and Calle 2009). However, few beaver ponds undergo complete infilling since dam failures occurring during high flows cause outburst floods that erode beaver pond deposits (Butler 1989; Meentemeyer and Butler 1999; Green and Westbrook 2009).

Few studies have examined sedimentation in beaver ponds, and they focused on *C. canadensis* (Naiman et al. 1986; Butler and Malanson 1995; Meentemeyer and Butler 1999; Pollock et al. 2007). Butler and Malanson (1995) correlated pond area and sediment volume with beaver dam age. They observed that sediment accumulation rate decreased with increasing age of the pond (Butler and Malanson 1995; Pollock et al. 2007). Beaver pond deposits not only contain sediment deposited from upstream, but also material of local origin mobilized by beaver activities (Butler 1991). By examining the grain size distribution, Butler and Malanson (1995) determined that the sediment in older ponds was finer than in younger ponds. An expected downstream sediment fining effect was not found by Bigler et al. (2001). Within a beaver pond, the surface layer sediment becomes finer downstream except near the dam, where coarser sediment is again deposited (Butler and Malanson 1995). Most of these studies concerned single beaver ponds, and sequences of dams have generally not been investigated.

It has been suggested that *C. fiber* engineer fluvial landscapes differently that *C. canadensis* since they construct less extensive dams (Gurnell 1998). However, the hydrogeomorphic aspects of dams constructed by *C. fiber* have been studied only once (John and Klein 2004) and in that study the focus was on changes to floodplain morphology.

Building upon earlier studies (Nyssen et al. 2011) related to the influence of beaver (*C. fiber*) dams on the flow regime of the Chevral river (Ardennes, Belgium), this research focuses on the influence of sequential dams on sediment fluxes. The main research questions concerned (1) the amount of sediment deposited upstream of the beaver dams, (2) spatio-temporal trends and patterns of sedimentation, and (3) the impact of the beaver dams on suspended sediment transport.

2. Materials and methods

2.1. Study area

The beaver dams studied in 2009-2011 were located in the valley of the Chevral, a sub-basin of the Ourthe Orientale (Fig. 1). This second order stream is a tributary to the Martin Moulin river, near Rensiwé, which flows as a third order stream into the Ourthe Orientale. The 317 km² 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 Chevral river originates in the northernmost part of the Chevral sub-basin, which is located on Gedinnian rocks consisting of peat-covered slates and phyllades (Fig. 1). Major land uses are forest and permanent meadows. The alluvial plain adjacent to the stream is characterized by gleyification (Deckers et al. 1957). The average annual rainfall is 1016 (± 160) mm, which is evenly spread over the year (Nyssen et al. 2011).

The first beaver dams in the Ourthe Orientale sub-basin were observed at the end of 2003. By 2010 there were approximately 120 beavers and 20 dam systems (Nyssen et al. 2011). Within the sub-basin, the Chevral river holds two sequences of beaver dams (Fig. 1), which were first observed in 2004. The first sequence consists of seven beaver dams, and its hydrology was studied by Nyssen et al. (2011). This sequence is located furthest downstream and the catchment area at the outflow is 14 km².

*** Figure 1 approximately here ***

2.2. Measurements of sediment deposition rates in beaver ponds

The location of each dam was established based on GPS. Pond length and width were determined using a measuring tape. The volume and mass of pond deposits upstream of the beaver dams were measured during summer 2010. This was accomplished by wading through the ponds and using a graduated rod (resolution 0.5 cm) to measure the depth from the water surface to the top of the sediment layer and the depth to the interface between the sediment layer and the underlying stream bed, soil A horizon, or buried bedrock at several points (Fig. 2). Because the transition from the unconsolidated sediment layer to the underlying layer is characterized by a marked difference in resistance, we could accurately determine when the stick reached the bottom of the sediment layer. The sediment thickness at that point was calculated from the difference between the two depths. The average measurement error was reasonably estimated at +/- 2 cm. The measurements were performed in an upstream direction to avoid interference with the downstream sediment.

*** Figure 2 approximately here ***

The location of the measurement points was dependent on the shape of the beaver ponds. When the pond was elongated and clearly followed the old stream bed, the measurement points were located along a longitudinal transect and a few transverse transects (see further, Fig. 4). If the pond width was such that the old stream course could not be recognised, the measurement points were positioned according to a regular grid scheme laid out with the help of measuring tapes and stakes. If the old stream channel became evident at a certain distance upstream of the beaver dam, a combination of both methods was used.

In sequence 1 there was one recent beaver dam that did not hold an upstream sediment layer, and in sequence 2 two ponds did not hold sediment. One of these was very small and one had burst. In total, sediment measurements were carried out in 34 beaver ponds (Table 1).

*** Table 1 approximately here ***

A few months after these sediment measurements, dam 2.16 burst and the upstream sediment layer surfaced. A discontinuous buried A horizon, ca. 5 cm thick, was observed beneath the sediment layer (Fig. 3). To verify whether the sediment measurements really measured the depth of the bottom of the sediment layer and not the bottom of the A horizon, control measurements were executed in the surfacing sediment layer together with a soil coring to determine which interface was measured. However, a clear soil profile could be obtained based on the soil coring for only two control measurements. In one control measurement the depth of the bottom of the sediment layer was sounded, but in the other control measurement the depth of the bottom of the A horizon was sounded. The possible error was within the range of the average estimated error of 2 cm, given that the A horizon was discontinuous and limited in thickness. In addition, this possible error only occurred in sediment measurements outside the old stream bed. Such errors are not possible in measurements within the old stream bed as the difference in resistance between the unconsolidated sediment and the stony stream bed is unequivocal.

*** Figure 3 approximately here ***

Two sediment samples were collected in each of three ponds in sequence 1 and six ponds in sequence 2. The samples were obtained just upstream of the beaver dams, one at the centre and one at the side of the pond. The dry bulk density was determined, and the textures of samples from sequence 2 were determined by means of wet sieving and sedigraph (Micromeritics Sedigraph III).

The areas of the beaver ponds and the volumes of the sediment layers were calculated in a GI-System (ArcMap 9.3) based on the field measurements. Rather than interpolating between the measurement locations, as for instance done by Westbrook et al. (2011), we chose to take into account the boundaries of the original river morphology, and the sediment volumes were calculated using a weighted mean based on Thiessen polygons created around the sediment measurement points (Fig. 4). For the creation of the Thiessen polygons, measurement points located in the old stream bed – considered 3 m wide – and points located outside the old stream bed were contrasted, as it was assumed that the deeper stream bed would produce a different sedimentation pattern. Of course, this distinction could only be made for beaver ponds where the old stream course was still observable; in locations where the measurement points were located on a regular grid, this distinction was not made.

*** Figure 4 approximately here ***

The sediment volume (V) in each beaver pond was calculated from:

$$\mathbf{V} = \sum_{\mathbf{i}=1}^{\mathbf{n}} \mathbf{A_i} \, . \, \mathbf{t_i} \qquad (1)$$

where n is the number of Thiessen polygons within the pond, A_i is the area of Thiessen polygon i [m²], and t_i is the thickness of the sediment for Thiessen polygon i [m].

The average sediment thickness per beaver pond was calculated as:

$$\bar{\mathbf{t}} = \mathbf{VA^{-1}} \qquad (2)$$

To gain insight into the variability of the sediment thickness within a particular pond, it was necessary to normalize it for the length of the beaver ponds. Therefore, a grid with pixels of 2 m by 2 m was created for each pond, and a value for the sediment thickness was attributed to each pixel corresponding to that of the nearest measurement. The average sediment thickness was calculated every 2 m upstream of the beaver dam (Fig. 5). After converting the length to 100%, an average sediment thickness was obtained for every 5% of the pond length based on the nearest value. As this value for the sediment thickness was obtained at twenty locations for each pond, regularly spread along their length, these thicknesses could be converted into relative values:

$$T_i = t_i / \bar{t} \qquad (3)$$

in which T_i is the dimensionless sediment thickness parameter at location i, t_i is the sediment thickness at location i [m], and i is the sequential number of the location along the pond, every 5% of its length (projected on a straight line between the centre of the downstream dam and the inflow location or centre of the bordering upstream dam).

Using this approach, only the relative variability of sediment thickness within the beaver ponds is represented, enabling the variability within all ponds to be compared.

*** Figure 5 approximately here ***

In addition to sedimentation in the beaver ponds, deposition took also place in periodically flooded areas along the ponds. The presence of deposited sediment in these areas was locally observed, but no suitable method was devised to measure the volume of these deposits. Beavers also cause erosion, and canals excavated by beavers were observed in the periodically flooded alluvial plains (Fig. 6). The volume of these canals was quantified in order to assess erosion by beaver activity: canal lengths, widths, and depths were measured at two to five locations. Other forms of erosion such as bank slides and burrows were not observed. Dam failures occurring during periods of high flow in the winter of 2010-11 were also recorded.

*** Figure 6 approximately here ***

2.3. Hydrological monitoring of the Chevral river

Hydrological measurements were executed on six days between October 2010 and March 2011 at four straight stream segments, located for sequence 1 at 100 m upstream of the uppermost dam (inflow) and 300 m downstream of the lowermost dam (outflow), and for sequence 2 at 600 m upstream of the uppermost dam and 100 m downstream of the lowermost dam. Between the in- and outflow point of sequence 2, two tributaries flow into the Chevral R., whereas sequence 1 has no tributaries. Discharges at the in- and outflow locations were calculated using the river flow continuity equation,

$$Q = v\ S \qquad (4)$$

in which Q is the discharge flow [$m^3\ s^{-1}$], v is the mean flow velocity [$m\ s^{-1}$], and S is the cross-sectional area [m^2]. The float method was used to measure the reach average flow velocity with ten individual floats of wine corks for each measurement. The measurements were performed over a predefined stream length and the geometry of a representative cross-section of each reach was measured. Measurements in which the float was obstructed by rocks or was trapped in small swirls were discarded and repeated. The float method is commonly restricted to straight reaches with a uniform cross-section and assumes a logarithmic distribution of velocity through depth. The calculations incorporate a correction factor of approximately 0.84 depending on the float shape and its submerged fraction (Linsley et al, 1988). This is correct for relatively deep (1 - 2 m) and smooth channels. Due to the very shallow flow depth (typically 10 - 40 cm), the rough bed with protruding boulders, a turbulent, highly-mixed flow, and the common occurrence of downward flow and upcurrent surface swirls, no correction coefficient was applied to the surface velocity measurements in order to prevent underestimation of the discharge flow.

The suspended sediment concentration was obtained by centrifugation of a depth-integrated water sample. The concentration was used to calculate the suspended sediment flux:

$$Qs = CQ \qquad (5)$$

where Qs is the suspended sediment discharge [$g\ s^{-1}$] and C is the suspended sediment concentration [$mg\ l^{-1}$].

In addition, the same hydrological measurements had previously been performed on seven days between September 2009 – March 2010 at sequence 1 (Nyssen et al. 2011), making the observation periods 13 months at sequence 1 and 6 months at sequence 2.

The 13 days of on-site flow discharge measurements at the outflow point of sequence 1 were correlated with data from the Rensiwé flow gauge located 4 km downstream on the Martin Moulin R. (Aqualim 2011); the high determination coefficient ($r^2 = 0.86$) indicates that our discharge measurements were consistent. The established relationship between these measurements permitted interpolation of the discharge flow (Qout) at sequence 1 for each day of the study period. The same was done for the six days of on-site flow measurements at the outflow point of sequence 2. The daily discharges (Qout) were obtained based on regression ($r^2 = 0.92$) with the flow gauge data.

3. Results

3.1. Situation and dynamics of the beaver ponds

Beaver dam systems comprise beaver ponds, areas along the ponds that are periodically flooded, and beaver canals (Fig. 7). The pond numbers used in this article are composed of the sequence number (1 or 2) and a number for the pond. The average pond area in sequence 1 was 345.2 m^2 (± 368.6 m^2), with the smallest being pond 1.5 (131 m^2) and the largest being pond 1.4 (1 092 m^2). In sequence 2, the average pond area was 169.4 m^2 (± 209.8 m^2). Pond 2.30 (8 m^2) was the smallest and pond 2.21 (941 m^2) the largest. Periodic flooding was induced by the beaver dams over an area of 4812 m^2 along sequence 1 and 8192 m^2 along sequence 2.

*** Figure 7 approximately here ***

A comparison of the state of the beaver ponds in April 2011 with their state during summer 2010 (Fig. 7) revealed that several dams had failed over the winter due to high flows. During the earliest high-flow period (November 2010), no dam failures were observed, only dam overflows. The failures occurred during a second period in January 2011 (Fig. 8).

*** Figure 8 approximately here ***

In sequence 2, the dam failures were mainly located in the middle of the sequence (Fig. 7), and all dams from 2.12 to 2.18 were burst. This series of dam failures is possibly due in part to the removal of dams 2.16 and 2.17 by municipal workers to protect a road from flooding (Fig. 9). This may have led to a cascade effect (Butler 1989) destroying dams 2.15 to 2.12.

*** Figure 9 approximately here ***

3.2. Sediment in dam systems

The addition of pond deposits resulted in sediment volumes of 419.2 m^3 in sequence 1 and 1290.9 m^3 in sequence 2, for a total of 1710 m^3 and an average sediment thickness in the ponds of 25.1 cm (Table 2). As the beaver dams were first observed in 2004, the average sediment deposition rate over seven years was 2.9 cm yr^{-1} in sequence 1, 3.9 cm yr^{-1} in sequence 2, and 3.6 cm yr^{-1} on average. The sediment mass was calculated using the average dry bulk density of 0.29 (± 0.02) g cm^{-3} obtained from all sediment samples – no significant difference ($p > 0.05$) was observed between the bulk densities of sequence 1 and sequence 2. The total sediment mass deposited in both dam sequences was 495.9 tons. As a result of the sediment sampling method, only the bulk density of the upper sediment layer was determined. However, Marsh et al. (1999) found an increasing bulk density with increasing sediment depth, and our sediment mass is probably slightly underestimated.

*** Table 2 approximately here ***

A portion of the deposited sediment was generated by the beavers themselves through canal excavation (Fig. 6). In the study area, 37 canals were observed and measured, 9 in sequence 1 and 28 in sequence 2 (Fig. 7). On average, these canals were 11.6 m long, 28.9 cm deep, and 49.1 cm wide. For each pond we calculated the sediment mass that was transported into it from the adjacent canals (Table 3). A total of 14.73 m^3 of sediment was excavated along sequence 1 (40 m^3 km^{-1}) and 42.43 m^3 along sequence 2 (35 m^3 km^{-1}). Assuming a bulk density of 1.42 g cm^{-3} in the alluvial plain (Rommens et al. 2006) the total mass of excavated alluvium amounted to 81.16 tons.

*** Table 3 approximately here ***

3.3. Sediment deposition patterns

Sediment deposit volumes varied widely between beaver ponds. In sequence 1, the average sediment thickness varied between 7.3 cm (pond 1.2) and 27.1 cm (pond 1.4) and in sequence 2, from 1.2 cm (pond 2.25) to 50.7 cm (pond 2.11), excluding beaver pond 2.26. A similar variability occurred in the volume of the sediment, which in sequence 1 varied between 10.9 m^3 (pond 1.5) and 296.4 m^3 (pond 1.4), and in sequence 2 between 0.4 m^3 (pond 2.30) and 411.0 m^3 (pond 2.21).

Based on field observations, the variability in average sediment thickness between the beaver ponds was due to four factors: (1) the area of the beaver pond (as a proxy for sediment trapping efficiency), (2) the sediment volume released into the pond from the excavated canals, (3) the distance between the beaver dam and the inflow point into the dam sequence, and (4) the quality of the beaver dams, which could only be qualitatively assessed. Beaver ponds 2.9, 2.10, 2.11, and 2.22 were fed by tributaries of the Chevral R. and water diverted by upstream beaver dams. Because they were not situated in the old stream bed, their position compared to the beginning of the sequence could not be determined. As a result, these ponds were not included in this analysis. Based on Kolmogorov-Smirnov tests, all observations were normally distributed, except for the sediment volumes delivered into the ponds from the canals. Pearson's correlation coefficients between the average sediment thickness and the other three factors were calculated. The area of the beaver pond was the only factor with a significant correlation with the average sediment thickness ($r^2 = 0.53$; $p < 0.001$) (Fig. 10). Correlations with the location of the pond in the sequence and with beaver excavations in the adjacent alluvial plain were weak and insignificant ($p > 0.05$).

*** Figure 10 approximately here ***

It is possible a more complex sinusoidal relationship exists between the thickness of the sediment layer and the location of the beaver pond within the dam sequence (Fig. 11), in which ponds with a thick sediment layer are preceded by ponds with a thin sediment layer.

*** Figure 11 approximately here ***

The longitudinal variation in sediment thickness within beaver ponds (shown by means of the average values of the sediment thickness parameter T_i – eq. 3) was assessed by comparing the actually computed value to the expected value of this parameter in the case of evenly distributed sediment thickness, normalized to 100. An analysis of all beaver ponds (Fig. 12, curve (a)) revealed that the sediment layer was thinner than average at the upstream end of the pond and became increasingly thicker close to the dam. A t-test indicated that the relative sediment thickness was significantly different ($p < 0.05$) from 100 at the lower and upper ends of the beaver pond.

The average pattern corresponded well to the pattern of sediment thickness in ponds connected to a stream section at the upper end (Fig. 12, curve (b)). Ponds bordered both upstream and downstream by beaver dams (Fig. 12, curve (c)) had more constant sediment thickness, and a significant difference ($p < 0.05$) from 100 occurred at only 1 of the 20 locations examined.

*** Figure 12 approximately here ***

The twelve sediment samples collected at sequence 2 were characterized by a small clay fraction: 5.6% (± 1.8%). A greater variability was observed in the silt and sand fractions of the sediment samples with an average silt fraction of 59.3% (± 17.4%) and an average sand fraction of 35.1% (± 18.7%). The cumulative grain size distribution curves for all of the sediment samples (Fig. 13) indicate that the sediment within the dam sequence becomes coarser when it is deposited further downstream in the sequence. Sediment samples from ponds 2.1, 2.6, and 2.13 had larger sand fractions than samples from ponds 2.15, 2.21, and 2.28, which were predominantly silt.

*** Figure 13 approximately here ***

We found no significant differences between the texture of sediment deposited at the centre and sediment deposited at the side of the ponds. Further, no significant difference was found between the sediment texture in large and small ponds, or between the texture of thick and thin sediment layers (all $p > 0.05$).

3.4 Flow discharge and sediment flux

To study the impact of the beaver dams on suspended sediment transport, hydrological measurements were carried out on the Chevral river. (Table 4). There were two days of high flow discharge (14 November 2010 and 12 January 2011). The first high flood occurred just after a period of heavy rainfall and the second during a period of snowmelt. On both days, greater flow was also recorded at the lower measurement stations. A similar downstream increase in flow was observed on most measurement days and may be explained by the two tributaries flowing into the Chevral R. between the inflow and outflow point of sequence 2 and the three tributaries situated between the two dam sequences. On average no significant differences ($p > 0.05$) were observed between the incoming and outgoing suspended sediment concentration or sediment flux. However, a significant difference ($p = 0.020$) was noted between the suspended sediment concentrations in September 2009 to March 2010 and those in October 2010 to March 2011. This is probably due to forest management activities in the Chevral R. basin during these periods. Greater sediment concentrations and fluxes at the inflow point than at the outflow point were recorded for sequence 1 on 17 November 2009 and for sequence 2 on 6 November 2010. These two days were also the only field days in which measurements were carried out during rainfall.

Low sediment fluxes were observed (around 5 g s^{-1}) on other days except those with high flow discharge (14 November 2010 and 12 January 2011).

*** Table 4 approximately here ***

A logarithmic regression was established between daily average flow values measured at the downstream Rensiwé flow gauge on the Martin Moulin R. for the thirteen days of field measurements and our own instantaneous measurements at the outflow point of sequence 1 ($r^2 = 0.86$), which enabled interpolation of the outflow of sequence 1 over the period September 2009 – March 2011 (Fig. 14). The same process was performed for the outflow of sequence 2 ($r^2 = 0.92$) based on six instantaneous field measurements, permitting interpolation of outflow measurements at sequence 2 between October 2010 and March 2011 (Fig. 15a). Due to the occurrence of high flow on two of the field days, nearly the entire flow range was included in these analyses, which strengthened both regressions and interpolations.

*** Figure 14 approximately here ***

*** Figure 15 approximately here ***

The hydrological measurements were also analyzed with regard to position on the hydrograph (Fig. 16). When the flow was in a rising phase, suspended sediment was deposited in the ponds of sequence 2, while in the falling limbs, slight removal of sediment occurred.

*** Figure 16 approximately here ***

Using the trends established for sequence 2, the sediment deposited in this sequence during the study period could be estimated. The average sedimentation during the rising phases of the flow was 12.44 g s^{-1} and the average erosion during the declining phases was 1.21 g s^{-1} (Fig. 15b). For undetermined phases and also for minima and maxima in the flow (occurring at transitions between rising and declining phases) the sedimentation rate was equalled to 0 g s^{-1}. By plotting and integrating the cumulative sedimentation in sequence (Fig. 15c) it was found that 13.12 tons of suspended sediment was filtered from the Chevral R. during the six-month study period. Extrapolation back to 2004 when the beaver dams were constructed reveals that 190.19 tons of sediment transported by the Chevral R. would have been deposited in sequence 2.

4. Discussion

4.1. Spatial trends and patterns in deposited sediment

The average annual beaver pond sedimentation rate of 3.6 cm yr^{-1} in this river draining a forested catchment is within the range measured in North America (Butler and Malanson 2005). The significant correlation between average sediment thickness in beaver ponds and pond area ($r^2 = 0.73$; $p < 0.001$) (Fig. 10) may be explained by the relationship between the area of a beaver pond and the age of the dam, as described by Butler and Malanson (1995). Richard (1967) reported that beavers progressively enlarge their dams both in height and laterally across the adjacent floodplain. As the dam is enlarged, not only is more water stored, but also more sediment is deposited. Furthermore, after building their dams with branches the beavers use mud to fill the gaps between the branches (Richard 1955). These gaps become better filled over the years until the dam is abandoned (Woo and Waddington 1990), strengthening the dam and resulting in higher sediment deposition.

High flows can play an important part in the redistribution of sediment between beaver ponds in a dam sequence. These will cause gap flows and eventual dam failures (as observed in January 2011 in the study area), which can trigger a domino effect on downstream dams impacted by water-sediment surges (Marston 1994). For rivers like the Chevral that are situated in a rather moderate relief, these outbursts will not have the catastrophic consequences (Harthun 2000) described by Butler (1989), and the domino effect may be stopped at larger ponds that will weaken the surge. Dam failure may explain the pattern in average sediment thickness for successive beaver ponds (Fig. 11). Ponds with a thin sediment layer would be located upstream of dams which are less resistant to high flows, while ponds with a thick deposit are located upstream of dams that are more resistant to surges and capable of retaining the sediment influx. This is consistent with our interpretation of the correlative relationship between sediment thickness and pond area (Fig. 7). On the other hand, visual interpretation of the locations of lateral inflow of water and sediment during storms does not show a link between these locations and the wave pattern of sediment deposition.

Similarly to Bigler (2001), we did not observe downpond sediment fining. Dam failures are also a possible explanation for coarsening of the sediment texture in a dam sequence. The more downstream a dam is located within a sequence, the greater the chance that a dam failure occurred upstream in an earlier period, causing a water-sediment surge and transporting coarser sediment mobilized from the stream bed into the pond. However, beaver ponds 2.21 and 2.28 had a thick sediment layer with a fine texture, demonstrating that factors other than dam failure may determine the spatial distribution of sediment in beaver dam sequences.

There was also a systematic variation in the sediment thickness within the ponds. Overall, the sediment layer was thickest just behind the dams and became thinner upstream (Fig. 12, curve (a)). No evidence of deltas was present in the beaver pond intakes, possibly because of the large silt fraction in the sediment while deltas are mainly built up from sand. The variability in sediment thickness was different between ponds connected to a stream section at the upper side (Fig. 12, curve (b)) and ponds bordered by a beaver dam both upstream and downstream (Fig. 12, curve (c)). For the first group of ponds the sediment layer was thickest at the upper side of the beaver dams and gradually decreased in thickness upstream. Ponds enclosed within two beaver dams had a more even distribution of sediment thickness. Two differences between these pond types provide an explanation for the difference in sediment distribution. First, one may expect that the flow velocity in ponds bordered by only one dam will decrease gradually as the pond broadens, so most sedimentation will occur near the beaver dam, while for ponds bordered by dams at both ends, the inflowing water is already slowed by the upstream dam, yielding a more constant flow velocity and consequently more even sediment deposition. Secondly, in these latter ponds there are no fluctuations in pond length between dry and wet periods, in contrast to ponds that are bordered at one end by a stream section that expands or shrinks depending on the water level. In wet periods, the sedimentation in these ponds will begin further upstream from the dam than in dry periods because a fraction of the ponds will constantly fluctuate between stream and pond conditions. Hence, no thick sediment layer will accumulate in the most upstream portion of these ponds, as the sediment deposited during a wet period will be washed downstream during low pond stands.

4.2. Temporal trends and patterns in suspended sediment flux

In sequence 2, a net deposition (average of 12.44 g s^{-1}) took place in the rising phase of floods, while an average net erosion of 1.21 g s^{-1} took place in the declining phases. In contrast to what would be expected, beaver dams do not carry out constant sediment filtering, but instead have a similar effect on discharge as on suspended sediment flux. At high discharges water will be stored within a dam system and large fractions of the suspended sediment will be deposited, while during low flow discharges water will be released from the dam system, not only increasing downstream flow discharges (Gurnell 1998; Nyssen et al. 2011) but also remobilising sediment for transport out of the system. This relation was not observed in sequence 1, probably because the sediment fluxes at the inflow point of sequence 1 were already influenced by sequence 2.

4.3 Sediment budget of the Chevral beaver dam system

The relation between the suspended sediment fluxes and the position on the hydrograph provided an estimate for the amount of sediment filtered out of the Chevral R. by dam sequence 2 during the six-month study period of 13.12 tons. This could be extrapolated to 190.19 tons during the seven years the dams were in existence. The sediment mass obtained by this method could be compared with the deposited sediment mass of 374.4 tons (Table 2).

The difference between sediment masses (Fig. 17) is assumed to result from (a) excavations by beavers, which were measured to be 60.24 tons (Table 3) at sequence 2, (b) the inflow of two tributaries of the Chevral R. as well as the incoming runoff from slopes and dirt roads along the 1.8 km length of sequence 2, and (c) differences in rainfall pattern and variability of the flow discharges between the study period and the preceding seven years as well as in dam retention capacities and in the intensity of forest management activities in the catchment.

The fact that sequence 2 filtered 190.19 tons of sediment plus the sediment from the slopes of the Chevral R. in seven years may not be interpreted as an equivalent decrease in sediment inflow to the main river of the basin. The downstream effect of beaver dams is too complex for such a conclusion to be drawn. On one hand, it has been demonstrated that beaver dams reduce the flow velocity (Meentemeyer and Butler 1999), which diminishes the erosion capabilities of the river in downstream reaches. On the other hand, a clear water effect may occur due to sedimentation in the upstream beaver dams (Meentemeyer and Butler 1999) which could increase the erosive capacity of the stream. Consequently, there is a need for further research into the downstream effect of beaver dams on the sediment fluxes of high order rivers.

5. Conclusion

The two beaver dam sequences on the Chevral R. together retained 1710.1 m³ of sediment in seven years, with an average thickness for all pond deposits of 25.1 cm. Variations in sediment thickness between ponds could be explained by the area of the beaver ponds ($r^2 = 0.53$) (Fig. 7), and a pattern in the average sediment thickness of successive ponds (Fig. 11) was also observed. Both findings might be linked to the solidity of the beaver dams; the more the gaps within a dam are filled with mud by the beavers, the more incoming sediment is retained. In addition, solid dams may be more resistant to surges and receive sediment from upstream ponds having less resistant dams. It is possible the downstream coarsening of sediments in a dam sequence is due to erosive surges arising after dam failures or breaching.

Trends in sediment thickness within beaver ponds were also examined. It was striking that no deltas were observed and that the sediment layer was thickest just upstream of the beaver dams. It was also found that ponds bordered by two dams had a more even sediment thickness than ponds bordered by a beaver dam only on the downstream end. This may be attributed to the difference in flow velocities through these ponds and seasonal variations in pond area.

In sequence 2, the difference between the in- and outflowing suspended sediment fluxes was linked to the hydrograph of the Chevral R.: during rising limbs, deposition (average 12.44 g s^{-1}) occurred, while during the falling limbs slight erosion (average 1.21 g s^{-1}) took place. Based on this, it was calculated that 190.19 tons of sediment were filtered from the Chevral R. by the beaver dams of sequence 2 over seven years. The deposited sediment mass measured on-site in the beaver ponds was 374.4 tons. The difference between these values could be explained by erosion caused by beavers, inflow from small tributaries, and runoff from the valley flanks (Fig. 17).

The findings in this study confirm the results of a recent study (Burchsted et al., 2010) which stresses the potential for beavers to contribute to river and wetland restoration as well as for catchment management. Further, the study of dam sequences reinforces the fact that sediment inputs and outputs from one beaver pond cannot be understood without studying the sequence as a whole. Quantitative measurements of sediment deposition will be more reliable if an entire sequence of ponds is considered rather than an individual beaver dam pond given the high variability of sediment trapping in these ponds (Fig. 11). Finally, a comparison of sediment deposition rates in ponds constructed by *C. fiber* and those constructed by *C. canadensis* suggests that there is little difference in how the two species influence the hydrogeomorphology of fluvial systems.

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Figure captions

Fig. 1. The Ourthe Orientale sub-basin, with location of flow gauge and beaver dam sequences on the Chevral R.

Fig. 2. Measurement of sediment thickness in beaver ponds, in which a graduated stick was first inserted to the top of the sediment and then to the interface between the sediment and *in situ* material.

Fig. 3. Soil profile in beaver pond 2.16, with a buried A horizon and soil with gleyic properties (observation after dam breaching).

Fig. 4. Location of measurement points and examples of Thiessen polygons used in three scenarios: (a) in the course of the Chevral R. (e.g. pond 1.2); (b) regular grid used when the pond occupied the previous floodplain (e.g. pond 1.3); (c) combination of the two previous methods (e.g. pond 2.21).

Fig. 5. Thickness of sediment layer (in cm) on 2 m x 2 m grid points (e.g. pond 1.2) used for calculating average sediment thickness at 1 m, 3 m, 5 m, etc. upstream of beaver dams based on thickness measured at nearest measurement point. Darker grey tones indicate thicker sediment deposits.

Fig. 6. Canals excavated by beavers in the floodplain near pond 1.1.

Fig. 7. Situation of the surveyed beaver dam systems; all ponds were present in October 2010; ponds reduced in size or eliminated due to breaching in winter 2010-2011 are indicated. Arrows mark locations of lateral inflows from (temporary) rivers and roads during storms.

Fig. 8. Changes to beaver dam and pond 2.14. Clockwise: dam and pond were intact in August 2010; dam failure (circled) in January 2011 (the snow-free area indicates the maximum extent of the water, just before breaching); pond became empty by March 2011; breach repaired and pond filled in October 2011.

Fig. 9. Failure of beaver dam 2.17 in January 2011; the wood pieces (middle) are remnants of dam material removed from the stream bed by municipal workers (recent traces of machinery) to protect a road (behind the photographer) from flooding. The dam was destroyed at a high water level (probably the maximum of the flood) as can be observed from the extent of the snow-free area and from humidity on standing trees.

Fig. 10. Average sediment thickness as a function of pond area. Labels indicate pond number. Sequential numbers are displayed for ponds with a thick sediment layer as compared to the nearby ponds (Fig. 11) and/or ponds where sediment was sampled.

Fig. 11. Average sediment thickness per beaver pond vs. distance from the inflow point of sequence 2; labels indicate sequential number of ponds with a thick sediment layer compared to nearby ponds. Beaver dams without ponds and those located in the alluvial plain away from the main stream are not indicated. Large dots at the bottom of the graphs indicate locations with major lateral inflow of water and sediment during storms.

Fig. 12. Average relative sediment thickness (eq. 3) in beaver ponds as a function of distance behind the dam: (a) for all ponds (n = 34), (b) for ponds bordered by a beaver dam at the lower side only (n = 26), and (c) for ponds bordered both downstream and upstream by a beaver dam (n = 8). The flow direction is from right to left on the diagram. Values that are significantly different from 100 ($p < 0.05$) are indicated by a small square.

Fig. 13. Cumulative particle size distribution of all analyzed sediment samples (beaver pond sequence 2). Labels indicate pond number followed by c for centre and s for side of the pond.

Fig. 14. Observed and calculated outflow at beaver pond sequence 1.

Fig. 15. Calculation of sediment deposition in pond sequence 2 during the study period: (a) the flow (Q) at the outflow of sequence 2, (b) expected rate of sediment deposition or erosion (ΔQs) as a function of the rising and falling limbs of the hydrograph based on field measurements reported in Fig. 16. For undetermined phases and for minima and maxima in the flow discharge the sedimentation rate was set to 0 g s^{-1}, (c) cumulative sedimentation based on eq. (5) or the product of (a) and (b).

Fig. 16. Difference between suspended sediment flux at the in- and outflow points (ΔQs) of pond sequence 2 vs. the average flow discharge at these two measurement points. Observations were separated according to rising and falling limbs of the hydrograph.

Fig. 17. Sediment budget for the beaver pond system 2 (2004 – 2011, in %), in which A = suspended sediment of the Chevral R. that was deposited (ΔQs), B = sediment originating from beaver canals (measured in situ), C = assumed input from side catchment, small tributaries, and adjacent rural roads, and D = possible errors in measurement and extrapolation. The sum of all fractions corresponds to the total mass of pond deposits in the dams of sequence 2 (374.4 tons).

Figures

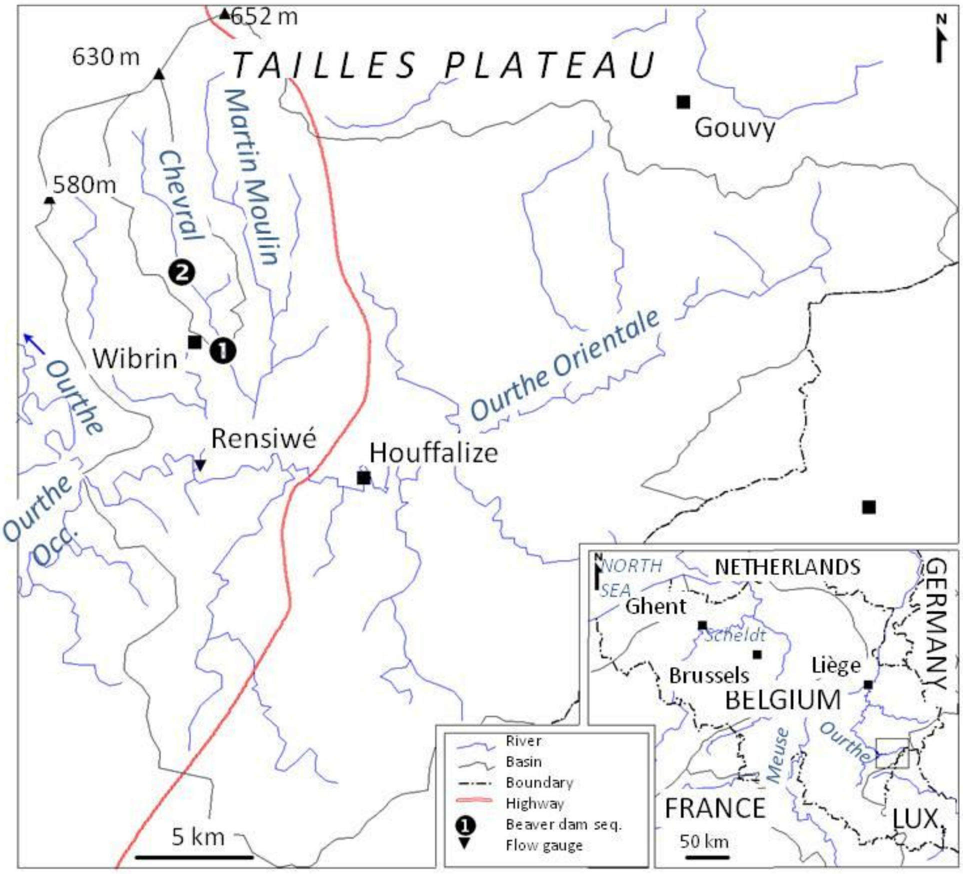


Figure 1.

Figure 2.

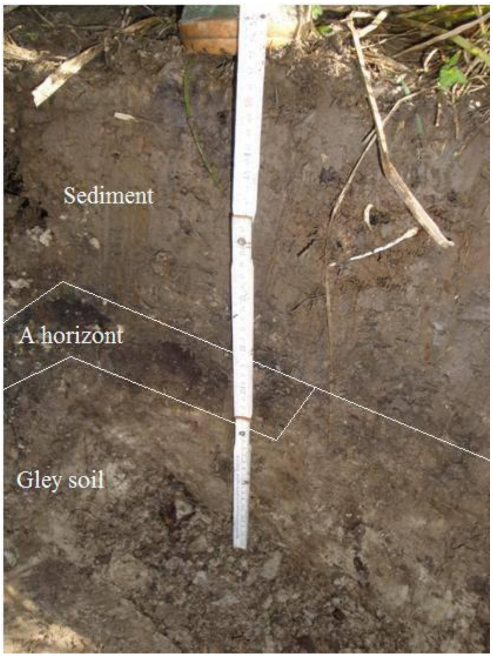
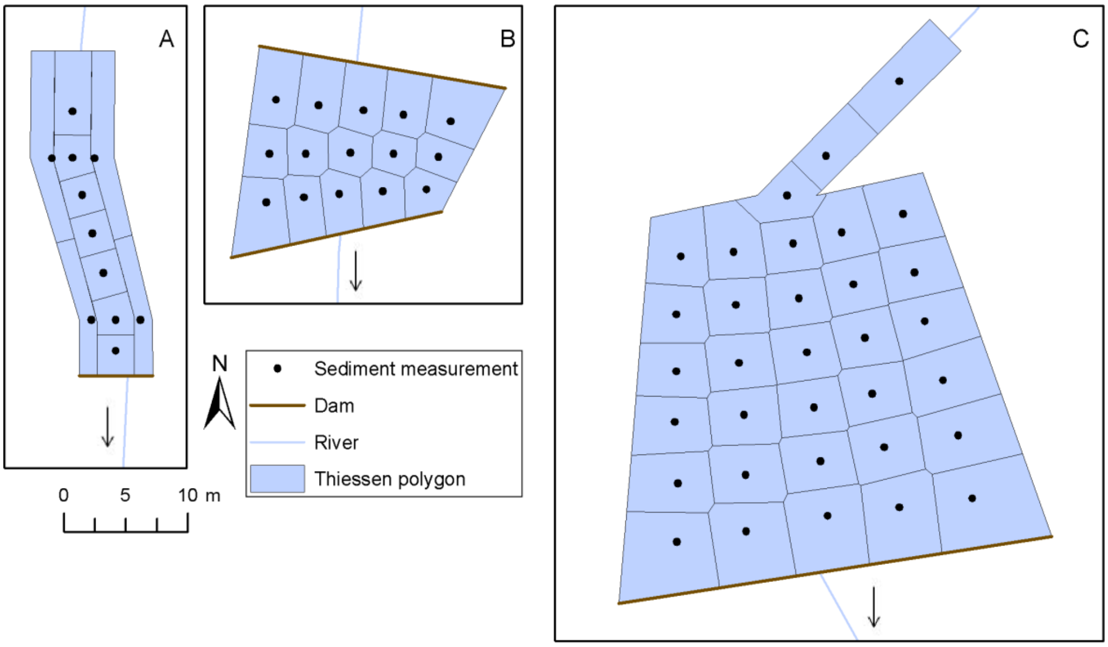


Figure 3



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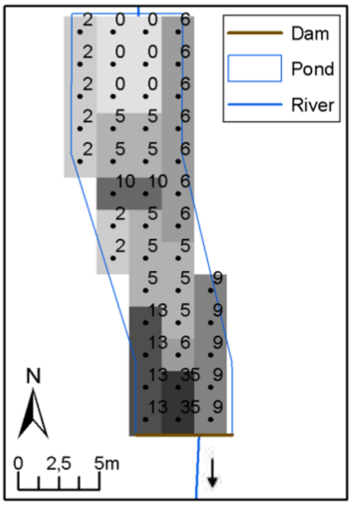
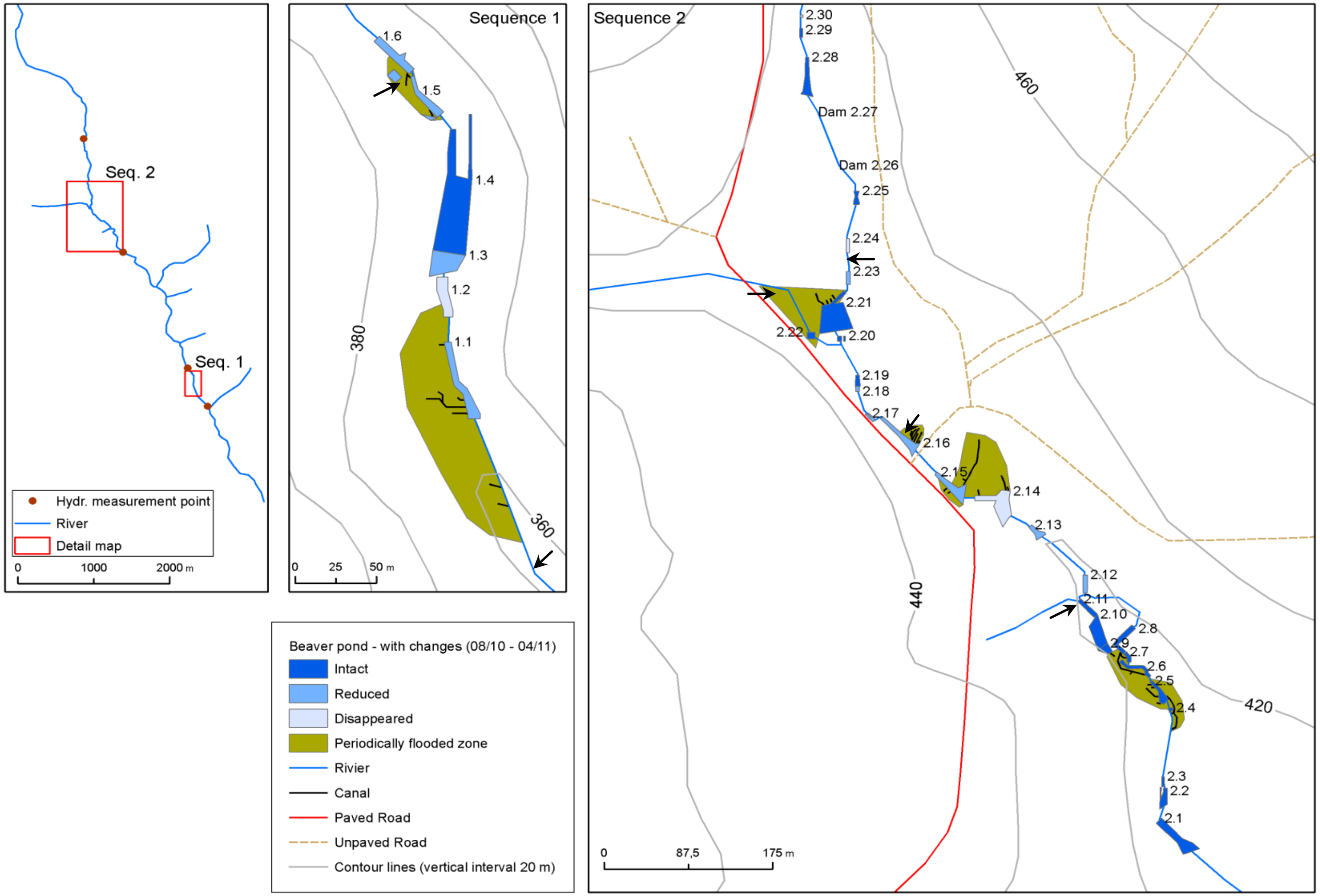


Figure 5.

Figure 6.

Figure 7.


Seq. 2
Seq. 1
Hydr. measurement point
River
Detail map
0
1000
2000 m
Sequence 1
1.6
1.5
1.4
1.3
1.2
1.1
380
360
0
25
50 m
Sequence 2
2.30
2.29
2.28
Dam 2.27
Dam 2.26
2.25
2.24
2.23
2.21
2.22
2.20
2.19
2.18
2.17
2.16
2.15
2.14
2.13
2.12
2.11
2.10
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
460
440
420
0
87,5
175 m
Beaver pond - with changes (08/10 - 04/11)
Intact
Reduced
Disappeared
Periodically flooded zone
Rivier
Canal
Paved Road
Unpaved Road
Contour lines (vertical interval 20 m)

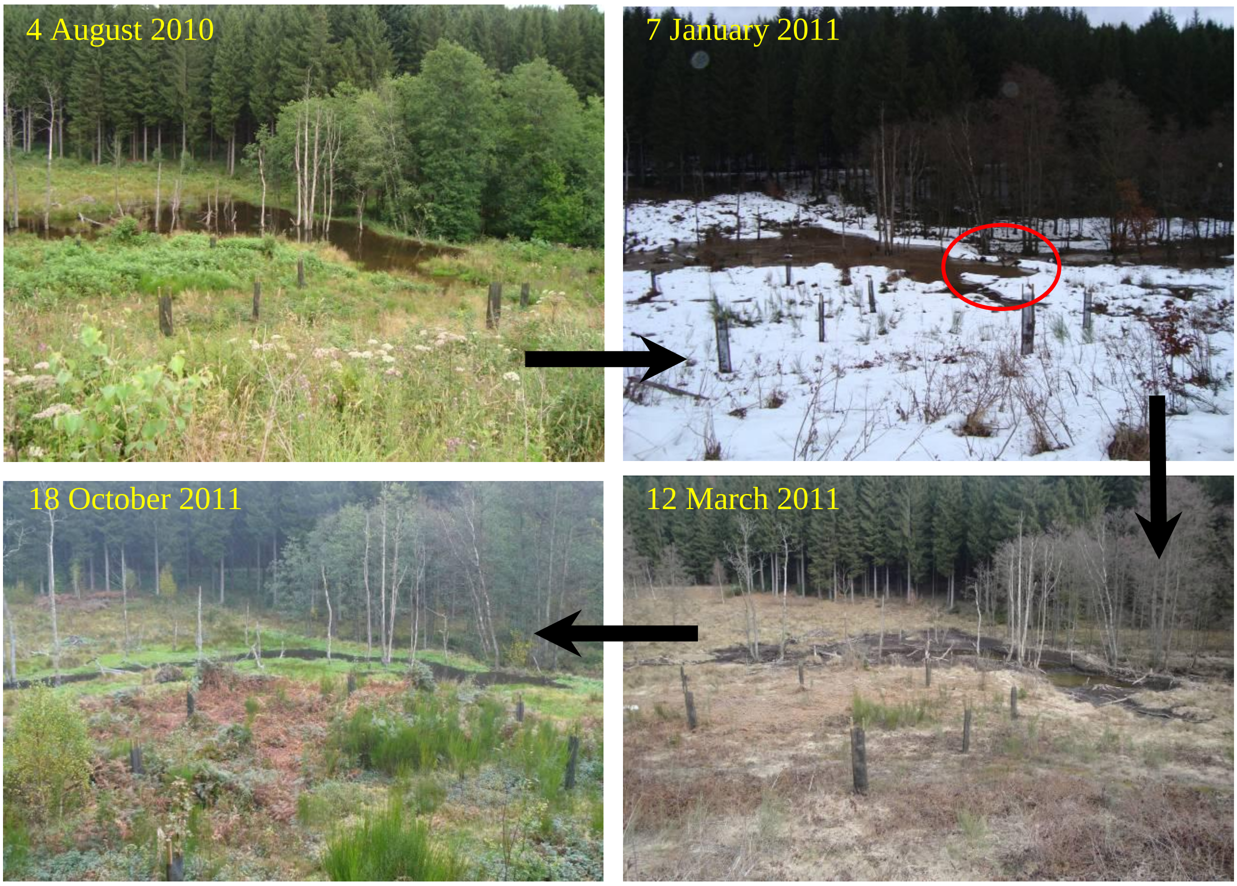


Figure 8.

Figure 9.

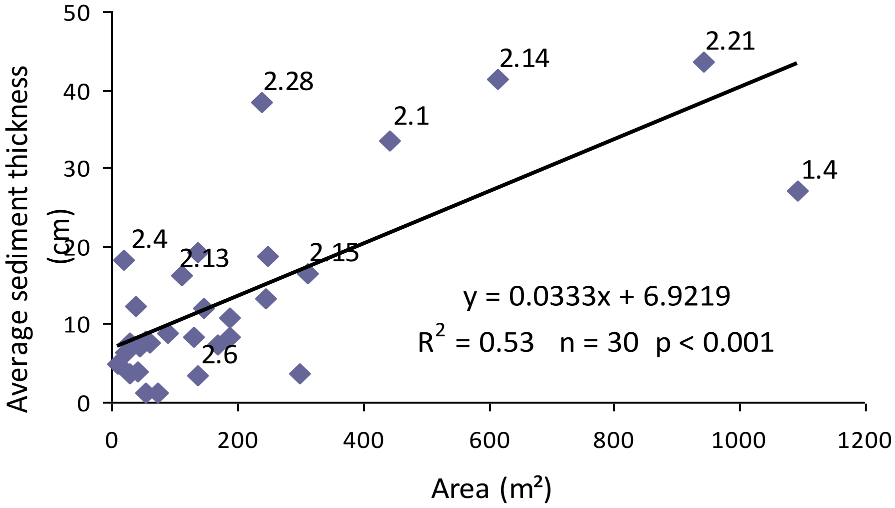
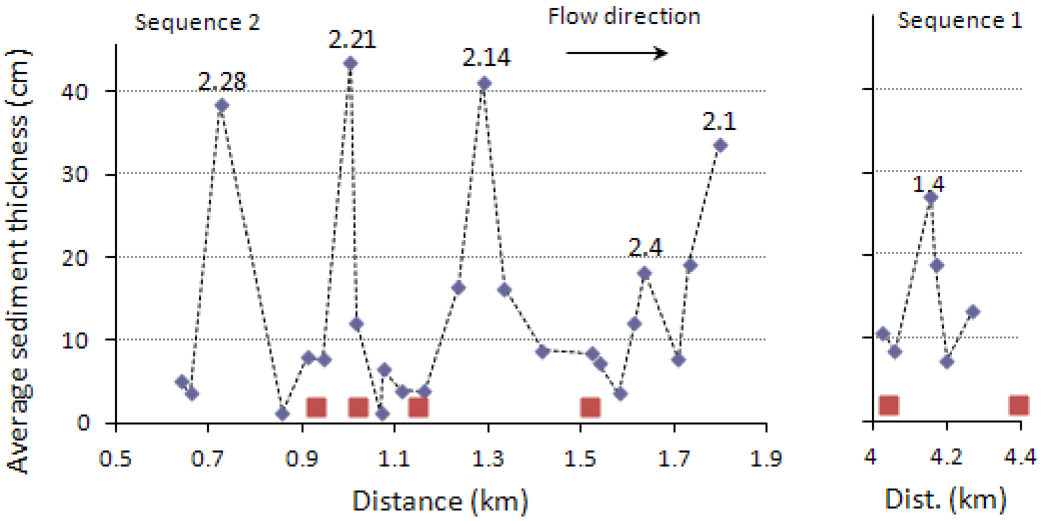


Figure 10.



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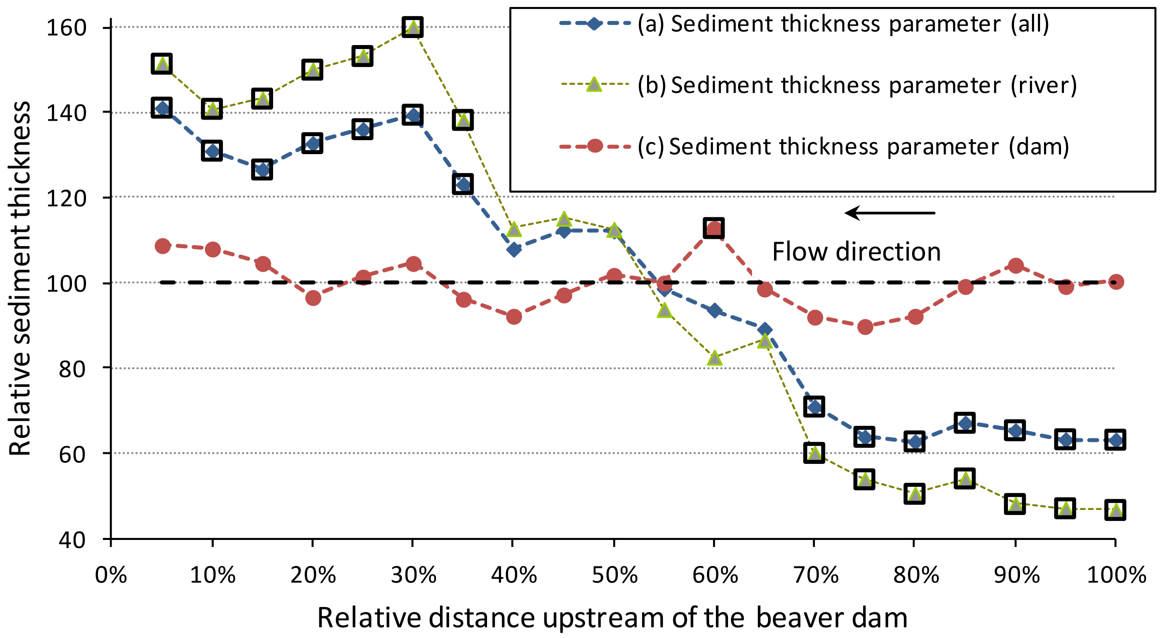

Figure 12.

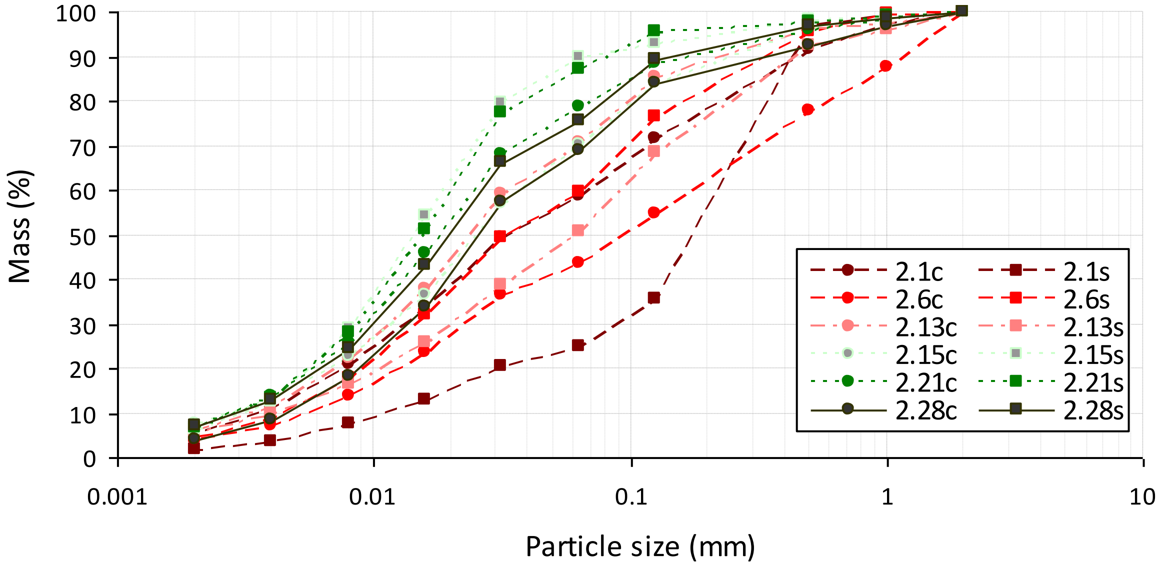

Figure 13.

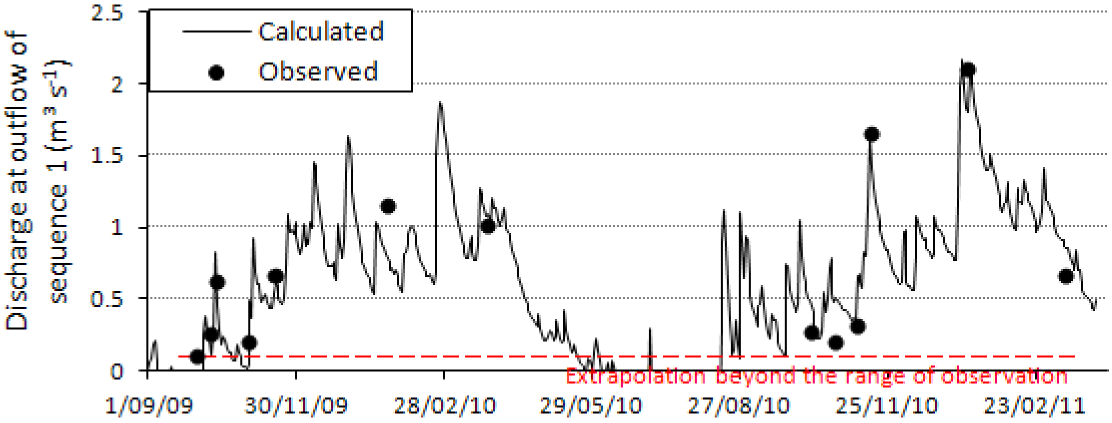

Figure 14.

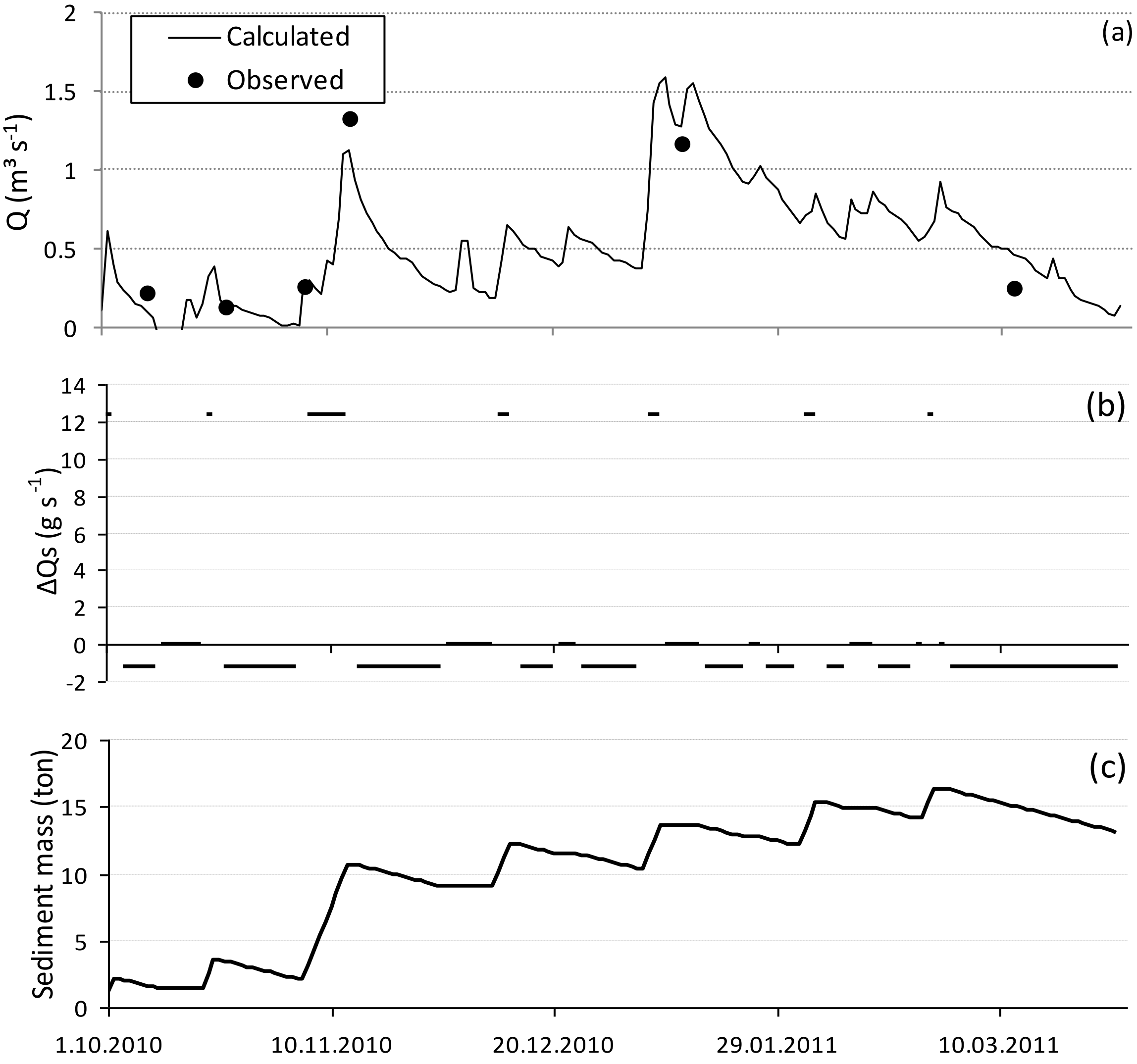

Figure 15.

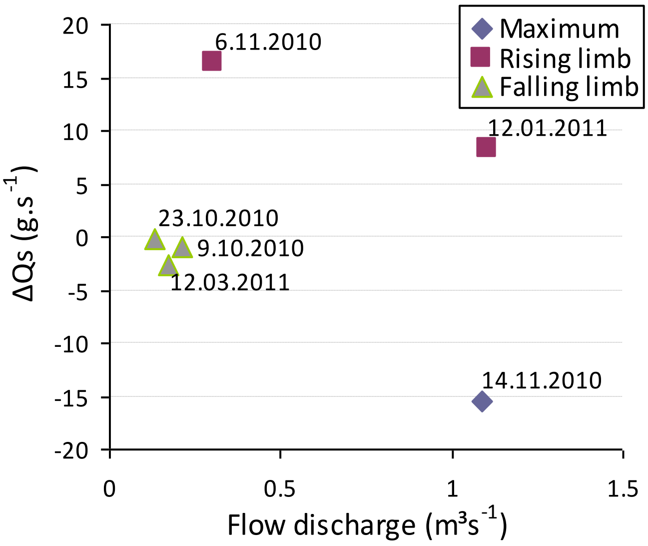

Figure 16.

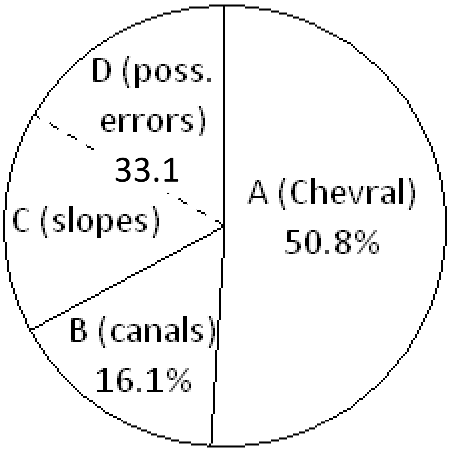

Figure 17.

Tables

Table 1. Deposited sediment thickness in beaver ponds.

	Number of ponds with measurements	Number of measurement points	Average number of measurement points by pond
Sequence 1	6	117	19.5
Sequence 2	28	254	9.1
Total	34	371	10.9

Table 2. Mass and volume of beaver pond deposits.

	n	Average pond area (m²)	Average sediment volume by pond (m³)	Average sediment mass by pond (ton)	Average sediment thickness (cm)
Sequence 1	6	345.2	69.9	20.3	20.2
Sequence 2	28	169.4	46.1	13.4	27.2
Total	34	200.4	50.3	14.6	25.1

Table 3. Volumes of beaver excavations and estimated mass produced between 2004 and 2011, listed by beaver pond in which it was presumably deposited.

Beaver pond	Soil volume (m³)	Soil mass (ton)
Sequence 1		
Downstream of pond 1.1	2.09	2.97
Pond 1.1	10.61	15.06
Pond 1.5	1.50	2.13
Unclear	0.53	0.75
Total sequence 1	**14.73**	20.92
Sequence 2		
Pond 2.3	4.37	6.21
Pond 2.5	4.84	6.87
Pond 2.6	3.73	5.30
Pond 2.7	0.94	1.33
Pond 2.12	3.41	4.85
Pond 2.13	9.30	13.20
Pond 2.14	9.35	13.28
Pond 2.19	5.82	8.27
Unclear	0.67	0.95
Total sequence 2	**42.43**	60.24
Total both sequences	**57.16**	81.16

Table 4. Measured stream and suspended sediment fluxes at the in- and outflow points of both sequences

	Sequence 2						Sequence 1					
	Inflow point			Outflow point			Inflow point			Outflow point		
Date	Q ($m^3 s^{-1}$)	C ($mg l^{-1}$)	Qs ($g s^{-1}$)	Q ($m^3 s^{-1}$)	C ($mg l^{-1}$)	Qs ($g s^{-1}$)	Q ($m^3 s^{-1}$)	C ($mg l^{-1}$)	Qs ($g s^{-1}$)	Q ($m^3 s^{-1}$)	C ($mg l^{-1}$)	Qs ($g s^{-1}$)
30/09/2009							0.08	4.20	0.34	0.11	8.60	0.95
9/10/2009							0.16	2.50	0.40	0.26	6.30	1.64
12/10/2009							0.35	12.30	4.31	0.62	8.70	5.39
1/11/2009							0.20	0.90	0.18	0.20	2.00	0.40
17/11/2009							0.76	28.30	21.51	0.66	4.70	3.10
24/01/2010							0.75	5.10	3.83	1.16	3.80	4.41
26/03/2010							0.96	8.80	8.45	1.01	5.50	5.56
9/10/2010	0.20	16.80	3.36	0.22	19.50	4.29	0.24	15.70	3.77	0.27	17.30	4.67
23/10/2010	0.13	14.70	1.91	0.13	15.70	2.04	0.29	15.40	4.47	0.20	15.50	3.10
6/11/2010	0.35	74.20	25.97	0.26	36.40	9.46	0.28	22.50	6.30	0.31	19.60	6.08
14/11/2010	0.84	35.50	29.82	1.33	34.00	45.22	1.45	30.20	43.79	1.66	32.80	54.45
12/01/2011	1.04	33.70	35.05	1.17	22.80	26.68	1.68	24.60	41.33	2.11	21.10	44.52
12/03/2011	0.09	14.60	1.31	0.25	15.50	3.88	0.21	16.30	3.42	0.67	18.40	12.33

Q = stream discharge; C = suspended sediment concentration; Qs = suspended sediment flux