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Environmental conditions as explanatory factors for the distribution of beaver dams in Flanders

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Abstract

The beaver (*Castor fiber*) has re-established in Flanders after 150 year absence. Overhunting caused the species' extinction in Belgium and in the largest part of Eurasia. Protection and reintroduction led to the remarkable return. By their dam building behaviour beavers can flood surrounding areas which are often valuable lands for agriculture or urban areas. To handle these conflicts, it is important to analyse in which conditions beavers will build a dam. Therefore, this research focussed on determining differences between areas where beavers settle with and without dam building. Significant differences were found in water depth, stream width, stream velocity, bank height and distance from a dam or burrow/lodge to vegetation. The analysis of these five environmental conditions led to the construction of a linear model which was able to make a distinction between dam and no-dam areas ($p < 0.05$). With a classification tree, a distinction is made with 97% certainty between dam and no-dam areas based only on a water depth with a threshold value of 65 cm. This analysis can now be used as a base to predict if a waterway will be suitable for dam building during the ongoing colonisation of the beaver. The examination of the effects of dam building is essential in assessing the flooding-risk in a certain area when dam building occurs. With an average increase of 47 cm of the water level, flooding can occur at places where the bank height too low. This examination on the effects of dam building can be used to assess the sensitivity of possible conflicting areas. These findings will be important in the policy development to realise a harmonic relation between the highly urbanised Flanders and this remarkable and valuable species for nature.

Summary

The beaver is Europe's largest rodent and is well known because of its dam building. The beaver went extinct in Flanders and in the largest part in Europe 150 years ago because of overhunting for its fur and meat. Protection, reintroduction of the species and nature conservation in Flanders led to the return of the species. The beaver is a valuable species in nature as it increases the species richness of its surroundings because it creates a new environment by dam building. The beaver does not always build a dam, only if the water level is not sufficient to keep the entrance of its lodge under water (which is important for protection against predators), they will build a dam to increase the water level. If a water way is sufficiently deep, the beaver will settle in a lodge or burrow in the river bank without dam building. Dam building is frequently the cause of conflicts with humans because they can flood agricultural land or risk flooding of urban area. Therefore this study was intended to find out which conditions led to dam building. It was found that water depth, stream width, stream velocity, bank height and distance from the dam or the lodge to the nearest woody vegetation differed between areas where they build dams and where beavers settle without dams. These five factors led to the construction of a model which can make a distinction for a particular waterway if it is suitable for beavers with dam building or not. This model can now be used to evaluate waterways which are likely to be colonised by beavers in the future. If a certain waterway is predicted to be suitable for dam building, measures can be taken to prevent dam building and therefore prevent conflicts with the surrounding human population.

Introduction

General introduction of *Castor fiber*

Biology

The Eurasian beaver (*Castor fiber*) is Europe's largest rodent (Nolet and Rosell, 1998). The species is herbivorous, has a semi-aquatic lifestyle and is mainly nocturnal (Buech, 1995). Beavers mostly live in family groups around a freshwater system and within a territory; this beaver group is called a colony (Jenkins, 1979). A colony has a specific composition of a monogamous couple together with the one to three young of the current year and those of the previous year (Wilson, 1971 cited in Nolet and Rosell, 1998). Territories are defended by aggression and scent marking (Rosell 2001; Nolet and Rosell, 1998). The available habitat limits the viable population in an area and therefore also the quantity and size of colonies (Maringer and Slotta, 2006).

Beavers have a semi-aquatic life style in which freshwater systems are essential for settlement, also trees are part of the required conditions for suitable habitat (Nolet and Rosell, 1998). This makes riparian woods important habitat (Nolet and Rosell, 1998). Herbaceous material available in spring and summer is an important additional part of the beavers' diet (Jenkins, 1979). Beavers generally live seven to eight years (Heidecke, 1991 cited in Nolet and Rosell, 1998). They are of monogamous nature and there is no sexual dimorphism in morphology and behaviour (Herr and Rosell, 2004). The beaver's main predator is the wolf (*Canis lupus*) but both species do not always live in the same areas (Voigt et al., 1976). Where they co-occur, the wolf can have a significant effect on population regulation of the beaver (Baker and Hill, 2003). Other predators can be the lynx (*Lynx rufus*), wolverine (*Gulo gulo*), bear (*Ursus spp.*) and river otter (*Lontra canadensis*) but are of minor importance and are not typical predators of the beaver (Baker and Hill, 2003; Loforth et. al.,2007; Rosell and Czech, 2000).

Ecology

The beaver is a generalist herbivore, mainly eating the bark, shoots and leaves of woody plants (Jenkins, 1975; Nolet et al., 1995), also aquatic, agricultural and other herbaceous

plants are an essential part of the beavers' diet (Jenkins, 1979; Parker et al., 2007; Nolet and Rosel, 1998). Coniferous trees are rarely used as a food source (Maringer and Slotta, 2006).
The beaver is often seen as an ecosystem engineer as they modulate the availability of resources to other species by causing physical state changes in biotic or abiotic material and thereby modify, maintain and create habitats by the construction of dams (Jones et al., 1994). The beaver can change the geomorphological, hydrological and biological properties of a landscape (Gurney & Lawton, 1996). Beavers increase landscape heterogeneity, habitat and species diversity (Rosell et al., 2005). By their specific foraging method, the beaver also has an impact on the ecological succession in riparian forests, species composition and the structure of plant communities (Rosell et al., 2005). For this reason they are also frequently seen as keystone species (Naiman, 1986). Their presence is crucial in maintaining the organization and diversity of ecological communities and is exceptionally important compared to other present species (Mills et al., 1993). By selective feeding on woody plants, beavers shape riparian forests and increase the herbaceous richness by creating distinct plant communities (Anderson et al., 2006; Naiman, 1986). Nevertheless, it must be mentioned that the beaver's status as ecosystem engineer or key stone species is sometimes questioned (Donkor and Fryxell, 1999) as they can decrease the species richness at lower trophic levels. But the ability to modify ecosystems clearly generates considerable scientific and management interest (Nyssen et al., 2011; Rosell et al. 2005).

Beaver dams

A dam is a structure that beavers build in a waterway with flowing water and mainly exists out of woody material which can be supported by sediments, rocks and herbaceous materials. Functional dams cause an increase in water depth upstream of the dam. Dam construction behaviour has an important adaptive significance. This is mainly because the created beaver pond increases the access to food, provides an environment for food storage and a water level sufficient to keep the entrance of the lodge under water which is important because it reduces the predation risk (Anderson, 2010; Zurowski, 1992 cited in Rosell et al., 2005). Therefore, beavers often re-establish destroyed dams (Bhat et al, 1993).

Dam building activities affect hydrology, sediment transport, debris accumulation (Rosell et al., 2005) and the shape of the valley (Johnston and Naiman, 1987). Beaver dams and the accompanied pond increase the area of riparian habitat (Johnston and Naiman, 1987; Pollock et al., 2007; Cunningham et al., 2006). The effect of dams on the water flow varies due to the location in the catchment and the topography of the environment (Rosell et al., 2005). In narrow valleys, beaver ponds are small. In wide flood plains, the surrounding area is flooded sooner and a large beaver pond is created (Johnston and Naiman, 1987). Beaver ponds are sediment traps (Rosell et al., 2005; Butler and Malanson, 1995). The older a dam gets, the more efficiently stream velocity is reduced (Meentemeyer and Butler, 1999 cited in Rosell et al., 2005) and the more sediment it contains (Rosell et al., 2005). The amount of accumulated sediment in a beaver pond varies with stream discharge, slope gradient and upstream surface material (Meentemeyer and Butler, 1999 cited in Rosell et al., 2005). Beaver ponds also accumulate organic matter (Pollock et al., 2003) which locally increases the nitrogen and phosphor concentrations which influences these nutrient cycles (Rosell et. al., 2005). The velocity and the discharge of the water before the dam in the beaver pond is reduced. In contrast to this, downstream from the dam, there is an increased erosion due to fast flowing water coming from the dam (Rosell et al., 2005). Another consequence of a dam is that the water table is elevated (Johnston and Naiman, 1987) which causes saturating of surrounding areas which can result in the decline in available agricultural land.

According to the way water crosses the dam, four different dam types can be distinguished (Woo and Waddington, 1990; Nyssen et al., 2011). A ‘overflow type’ dam where water flows over the dam, a ‘gapflow type’ where water flows through a gap, a ‘throughflow type’ where water discharges through the dam or a ‘underflow type’ where water flows through the bottom of the dam.

Castor fiber and Castor canadensis

The genus *Castor* consist of two species, *Castor fiber* which occurs in Eurasia and *Castor canadensis* which originally occurs in the North American continent but has historically also been introduced in Europe (Nolet and Rosell, 1998; Parker et al., 2012) before genetic analysis in 1973 revealed that they should be distinguished as separate species (Parker et al., 2012). *Castor fiber* has 48 chromosomes and *Castor canadensis* has 40 chromosomes (Lavrov & Orlov, 1973 cited in Halley and Rosell, 2002). Morphologically, these two species are extremely difficult to distinguish (Novak, 1987 cited in Rosell et al., 2005). Also differences in ecology or behaviour are found to be minor as their dam construction activity is similar (Danilov et al., 2011) which results in a nearly complete niche overlap (Parker et al., 2012; Nolet and Rosell, 1998, Rosell et al., 2005). Until now, apart from Finland, it is not completely clear where the non-native *Castor canadensis* is present in Europe (but see Parker et al., 2012 for an overview). Also for Belgium, the current presence or absence of *Castor canadensis* is unclear though *Castor canadensis* individuals have been found in the past (Dewas et al., 2012).

The re-establishment of the beaver after near-extinction

Short history

The Eurasian beaver once was widespread in Europe and Asia (Nolet and Rosell 1998). But due to severe overhunting for its fur, meat and castoreum (a chemical substance from the castor sacs for territorial marking often used as a medicine or as a base aroma in perfume) in the 19th century, the Eurasian beaver decreased drastically until only 1200 Eurasian beavers were left in the beginning of the 20th century living in eight relict populations in Europe and Asia (Nolet and Rosell 1998).

To save the species from extinction, hunting restrictions and protection programs started and re-establishment began. Early reintroductions were aimed for the re-establishment of the beaver and with the purpose of reintroducing a future game species to be harvested for its fur (Nolet and Rosell 1998). But since the 1970s, reintroduction was focused on ecological reasons because of its important function as ecosystem engineer (Nolet and Rosell 1998; Nolet et al., 1995). Currently, the Eurasian beaver is becoming re-established over the largest part of its former range in Europe except for Portugal, Italy and the Southern Balkans (Halley et. al., 2012). In Asia, the relict populations are still rather small (Nolet and Rosell 1998) although recent data is lacking. The present population of Eurasian beavers is still increasing and is currently estimated at 1,04 million individuals (Halley et. al., 2012).

Previously, eight subspecies of *Castor fiber* were distinguished based on skull measurements (Heidecke, 1986 cited in Nolet and Rosell 1998). These 8 subspecies represented the eight relict populations of Europe and Asia when the species was driven near extinction (Nolet and Rosell 1998). The genetic base of these eight subspecies has been examined on several occasions but most recently only two evolutionary significant units are distinguished, namely the western and eastern haplogroup (Durka et al., 2005). Still, it is important to sustain the biological diversity of these eight relict populations within *Castor fiber*, so management goals should include the maintenance of viable populations in the eight areas where the original unmixed populations live (Nolet and Rosell 1998).

Current situation in Belgium and Flanders

In Belgium, the Eurasian beaver went extinct in 1848. After that, the first observed beaver was found in the Ruhr river in 1990 (Huyser and Nolet 1991 cited in Niewold and Rossaert, 2002) which probably originated from the Eifel region in Germany (Dalbeck et al., 2011). Reintroductions without official authorisation started between 1998 and 2001 in Wallonia (Dewas et al., 2012). 101 beavers were released in several sites (Van den Bergh and Manet, 2003). The re-establishment of the beaver in Flanders started in 2000. 20 individuals from Bavaria (Germany) were released in the Dyle in Southern Flanders in 2003 (Verbeylen, 2003). In addition, beavers which were reintroduced in the South of the Netherlands (Limburg) started to disperse via the Meuse to Flanders (Kurtjens et al., 2009). The Belgium population contains different geographic forms because of different origins of all releases and dispersals (Durka et al., 2005). The Belgian population is currently being estimated at 1400 - 1800 animals ranging over 370 sites while expansions continues of which the population in the Walloon area is estimated at 1200-1500 individuals distributed over 309 territories (Benoit Manet, personal communication) and the Flemish population is estimated at 180 to 300 individuals distributed over 60 territories (Kristijn Swinnen, personal communication).

As one of the eight relict populations was left in France in the lower Rhöne (figure 1), protection started in 1909 which resulted in the successful re-establishment of the beaver and a present population of 10 000 to 15 000 individuals (Halley et. al., 2012). Dispersal between Belgium (Wallonia) and France has been recorded (Halley et al.,2012). Germany also had one of the eight remnant populations left in the Elbe in the beginning of the 20th century. Present numbers are estimated at 8000 – 10000 and the mixed Bavarian population has been the source of beaver reintroductions in Belgium (Van den Bergh and Manet, 2003). Reintroductions in the Netherlands already started in 1988 which resulted there in a successful re-establishment and a dispersal of Southern populations to Flanders (Halley et. al., 2012). In Luxembourg, 15 *Castor canadensis* had established which had probably escaped from a zoo (Schley et. al., 2001) and are eradicated (Schley, personal communication), currently no *Castor fiber* populations are known.

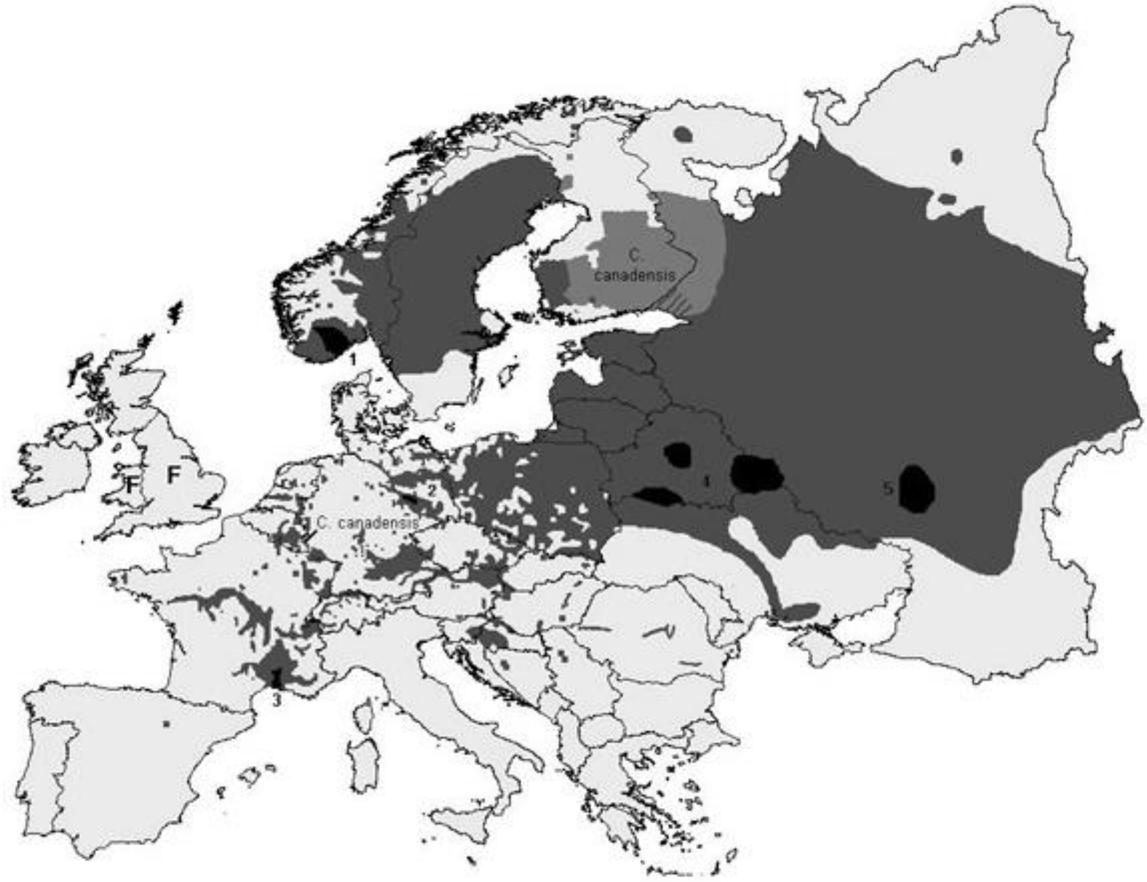


Figure 1: Present distribution of *Castor fiber* (dark grey) and *Castor canadensis* (light grey) in Europe. Location of the relict populations are marked in black (Halley et al., 2012).

Being listed in annex II and IV of the EU-habitat directive of 1992 (Maringer and Slotta, 2006), beavers are strictly protected and protection zones are required. In Flanders, the beaver is added to the list of protected species since July 2001. This means that it is forbidden to kill, hunt, catch or keep animals, it is also not allowed to destroy or disturb their territory. (Niewold and Rossaert, 2002). Since 2008 is the beaver reclassified by IUCN as least concern thanks to the successful re-establishment of the species in most parts of their original range (Halley et. al., 2012).

Human- wildlife conflicts

In Belgium, human population densities are extremely high (366 persons/km², FOD economy Belgium) and the landscape is intensively managed; this is the landscape that is currently being recolonized by the beaver. This demonstrates that beavers do not require large undisturbed areas to survive (Halley and Rosell, 2002). But this also means that beavers activities come in contact with human activities which leads to frequent human-wildlife conflicts (Halley and Rosell, 2002).

The beaver is a protected species so damage control and management is important (Nolet and Rosell, 1998). Because the wolf (as the main predator of the beaver) is absent in the largest part of Europe, the beaver populations will continue to grow and populations are only limited by their food supply (Nolet and Rosell, 1998). Belgian landowners often have negative perceptions towards beavers (Van den Bergh and Manet, 2003; Verbeylen, 2003), beavers were found shot dead and sudden disappearances from problematic sites are no exception (Van den Bergh and Manet, 2003). Measures to limit damage by beavers have been considered in order to keep public opinion in favour of beavers (Nolet and Rosell, 1998). In Flanders, a couple of solutions in these conflict zones have already been suggested and used.

Most beaver damage is related to the feeding activity on cultivated plants and the flooding consequences of dam building (Heidecke and Klenner-Fringes, 1992 cited in Nolet and Rosell, 1998). Damage to agricultural fields can locally be very prominent (Rosell and Parker, 1995). Most damage (>75%) occurs in the narrow riparian zone within 20m of the water edge (Nolet and Rosell, 1998; Heidecke and Klenner-fringes, 1992 cited in Halley and Rosell, 2002). Restoration of a 20 m wide zone of natural vegetation along the banks of waterways can be a durable solution to the problem of feeding damage (Nolet and Rosell, 1998) although probably not realistic in Flanders. Physical barriers like fencing to protect crops has proven to be a useful solution in agricultural areas (Dewas et al., 2012).

Flooding can sometimes be prevented by the use of overflow pipes (flow devices) (Heidecke and Klenner-Fringes, 1992 cited in Nolet and Rosell, 1998). Removing dams from territories is usually not a good solution as beavers will rebuild their dam at the same location.

Regulated hunting has also been suggested (Halley and Rosell, 2002) but because these animals are very sensitive to overhunting, this will stay a difficult balance both from ethical and conservational view.

Digging in banks of a waterway or in dikes which protects surrounding buildings can also be a cause of conflicts (Niewold and Rossaert, 2002) but this digging can be easily located so measures can be taken by refilling of the holes in the dikes or banks and protect them by stones or iron nets.

Better education to landowners is also seen as an important part to help improving the acceptance of the beaver. (Dewas et al., 2012; Halley and Rosell 2002). Wildlife tourism is seen as helping foster positive attitudes to beavers from society (Halley and Rosell, 2002), this is essential in realizing feasible management plans. However, managing wildlife in urban areas is increasingly problematic in modern society (Jonker et al., 2006). In such areas which are intensively managed, human-wildlife conflicts should be anticipated and management policies established (Maringer and Slotta, 2006). Beavers should be managed in a framework that makes beavers a normal part of the cultural landscape (Halley and Rosell, 2002). The management helps in preventing conflicts with human activities but it also has as a goal to contribute to nature conservation objectives such as the implementation of the Natura 2000 program (Van den Bergh and Manet, 2003).

Research goal

Beavers do not establish a home range in a random site (John and Kostkan, 2009). So, which aspects of the environment determine the suitability of an area for the settlement of beavers? This question has been assessed numerous times (Maringer and Slotta, 2006; Curtis and Jensen, 2004; John and Kostkan, 2009; Barnes and Mallik, 1997; Mckinstry et. al., 2001; Allen, 1983; Jakes et. al., 2007) and research has been conducted from different approaches. Key habitat features have been examined in different ecosystems and models based on these environmental parameters (HSI or Habitat Suitability Indices) have been developed for specific areas (Maringer and Slotta, 2006; John and Kostkan, 2009; Barnes and Mallik, 1997). Topography, hydrology and vegetation are mainly seen as influencing beaver distribution (Maringer and Slotta, 2006).

But more important, considering the impact that beaver dams have on their surroundings and the conflicts it can cause, it is of great importance to have more detailed information on which environmental conditions influence beaver dam construction (Hartman & Tornlov, 2006). Revealing potential dam building areas is therefore necessary and that is the goal of this research. The central question in this thesis is: under which conditions do beavers build a dam in Flanders and when not? Being able to answer the central research question for a specific area will lead to the development of a model which is able to predict if a certain waterway with specific conditions is suitable for dam building or not. This is based on the understanding of the ecological relationships of the engineering effects on the habitat and the understanding of the landscape context (Mckinstry et. al., 2001).

Dam modelling studies (Hartman and Törnlöv, 2006; McComb et al.,1990; Barnes an Mallik, 1996; Suzuki and McComb, 1998; Curtis and Jensen, 2004) have already been conducted but these studies lack a consensus about the contribution of different environmental conditions. This is partly due to habitat differences among study areas but partly also due to differences in approaches. This is why caution against extrapolation of these models in other areas is needed. Validation of these models in different environments is first required and depending on differences in habitat quality because variables influencing beaver habitat use may vary across regions.

Since there is no model yet for Flanders, Western Europe or another area resembling Flanders to predict the occurrence of beaver dams; and this while human-wildlife conflicts are increasing and the inquiry for a model is rising, this master thesis will focus on the development of such a model. Moreover, the hydrological and geological effects of a dam will be examined in order to analyse the flooding risk with dam building. Therefore, this thesis will focus on 3 questions:

- Under which environmental conditions will beavers build a dam?
- Where specifically in an area with suitable environmental conditions will a dam be built?
- What are the hydrological and geological effects of a dam?

Material and methods

Study area

Data were collected in beaver territories in Flanders, the Northern part of Belgium, in the Walloon area at sites which were topographically comparable to Flanders and in one territory in the Netherlands. In total 33 dams were measured and 13 control areas where beaver territories were situated without dams (figure 2). Measurements were taken in July, August and October 2013 to minimize the effects of variable rainfall over the year. The study area in Belgium is topographically fairly flat and is divided in the Scheldt basin in the West and Meuse basin in the East.

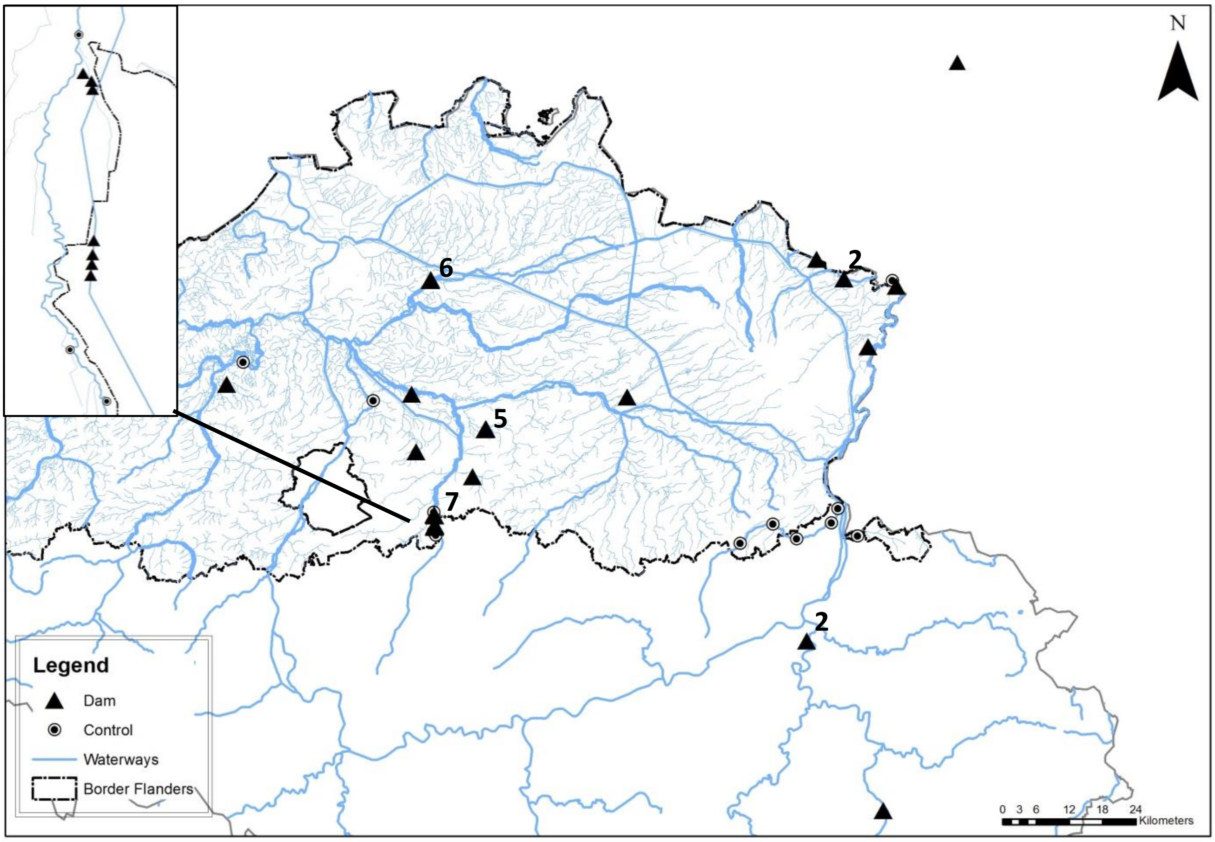


Figure 2: 28 Sampled beaver territories in Flanders and the Walloon area. 33 dams (triangles) in 15 territories and 13 territories without dams (dots) were measured. Places with multiple dams are marked by the number of measured dams in these sites. The territories around the Dijle are shown in detail because they consist of dam and no-dam areas.

Fieldwork

Six of the 15 dam sites comprised multiple dams (table 1). Sites with dams are considered independent if they are not influenced by another dam or if they are situated on separate waterways. Certain dams caused conflicts with the surrounding population, other dams were built in the surroundings of human influence (table 1). In certain dams, a flow device was installed to lower the water level which causes an effect on the dam measurements (table 1). Coordinates of the dam locations are not given as was agreed with local managers of the areas where dams were located. The 13 sites without dams were all considered independent from each other as they are each colonised by separate beaver colonies (table 2).

Table 1: Overview of territories with dams

Territory	Waterway	Number of dams	Independent dam	Upstream flooding	Conflicts	Human influence	Flow device
Bocholt	Lozerbroekbeek	1	Yes	Yes	Yes	No	No
Bree	Oude Lossing	2	Yes	No	No	No	No
Colonster	Trou du chien	2	No	No	No	No	No
Dilsen-Stokkem	Kogbeek	1	Yes	No	Yes	No	No
Erps-Kwerps	Molenbeek	1	Yes	No	Yes	Yes, in surroundings of train	Yes
Huldenberg	Grote Marbaise	3	2 dams are influencing each other, 1 independent	No	No	No	No
Holsbeek	Leigracht	5	No	Yes	Yes	No	Yes (2)
Kinrooi	Itterbeek	1	Yes	No	Yes	No	No
Liènne	Lienne	1	Yes	No	No	No	No
Lummen	Goerbeek	1	Yes	Yes	Yes	No	No
Pécrot	Petite Marbaise	5	No	No	Yes	Yes, fishing activity	Yes (2)
Bonheiden	Binnenbeek	1	Yes	No	Yes	No	Yes
Dendermonde	Vondelbeek	1	Yes	No	No	No	No
Venray	Oostrumsebeek	1	Yes	Yes	No	Yes, in surroundings of roads	No
Zandhoven	Kleine beek	6	No	Yes	Yes	Yes, in surroundings of roads	Yes (1)

Table 2: overview of beaver territories without dams

Territory without dam	Waterway
Bassenge (Boirs)	Jeker
Huldenberg (Ottenburg)	Dijle
Huldenberg (Sint Agatha Rode)	Dijle
Oud-Heverlee	Dijle
Bassenge (Eben-Emael)	Jeker
Bierbeek	Molenbeek
Tongeren (Lauw)	Jeker
Tongeren	Jeker
Kinrooi (Kessenich)	Itterbeek
Dendermonde	Beek van de kleine Sluis
Voeren	Berwijn
Bassenge (Wonc)	Jeker
Zemst	Zenne

Six environmental conditions, hypothesised determinant for necessity of a waterway for beaver dam building and based on other dam studies (Hartman and Törnlöv, 2006; McComb et al.,1990; Barnes an Mallik, 1996; Suzuki and McComb, 1998; Curtis and Jensen, 2004) were measured at water ways with and without dams: stream width, stream depth, stream velocity, bank profile, distance from dam to the nearest woody vegetation and distance until the embranchment upstream of the dam if present. Another environmental condition was registered to determine the effect of a dam at territories with dams: height difference of water level at dam.

At each territory the same method was used for data collection. The distance from the dam àr burrow/lodge to nearest vegetation was measured (1 m accuracy). Stream velocity was calculated from the time needed (0.1 seconds accuracy) for a floating object (a piece of cork or a branch) to move 1 to 10 m (small distances were used for slow flowing rivers) at least 20 m downstream from the dam.

Measurements at dam territories started with measuring the width of the dam with a tape measure (Stanley 30 m 34-792 fiberglass measure rod (Stanley, Born, Netherlands), 1 cm accuracy). The height difference of the water level just before and after the dam was measured by holding a measuring rod (Geo Fennel TN 14 Telescopic Measuring rod, length 4 meter (Geo Fennel, Baunatal, Germany), 1 cm accuracy) horizontal over the dam (controlled with a level (Stanley 42-294 Torpedo level (Stanley, Born, Netherlands)) and measuring the distance from the rod to the water surface on both sides of the dam (figure 3). The difference between these two measurements is the height difference between the upstream and downstream side of the dam. This measurement was done twice on the top of the dam (potential depressions were not included in this measurement as this could be a consequence of temporal damage of the dam) and the average was taken.

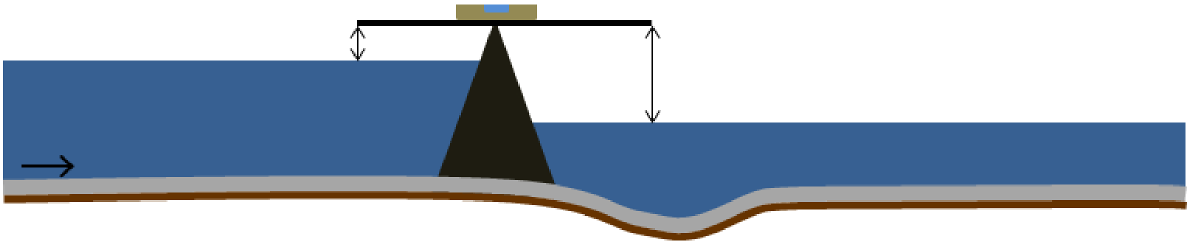


Figure 3: measurement of height difference just before and after the dam (black triangle). By holding a measuring rod horizontally, the distance from the rod to the water surface at both sides of the dam was measured with a measure tape. By this the influence of dam by means of increasing water level is measured. The arrow indicates the flow direction.

Then, the remaining measurements were conducted for territories with dams from 100 m upstream till 100 m downstream of the dam. For sites without dams, the measurements were conducted from 50 m upstream the lodge or burrow until 50 m downstream. The stream width, stream depth and bank profile were measured with the following procedure. At 5 m, 10 m, and then every 10 m until 100 m or 50 m (depending on the type of territory) both downstream and upstream of the dam or burrow/lodge, the stream width was measured with the tape measure from bank to bank at the water surface. At these points, also the stream depth was measured in the middle of the stream, 1m left and 1m right of the middle to examine the effect of variations of water depths influencing dam building. The depth was measured with a measure rod from the water surface until the bottom of the stream without pushing into the sediment. Then the rod was pushed into the sediment until the bedrock which is the measure for the depth with sediment (figure 4). Rivers were crossed by waders, swimming or canoe.

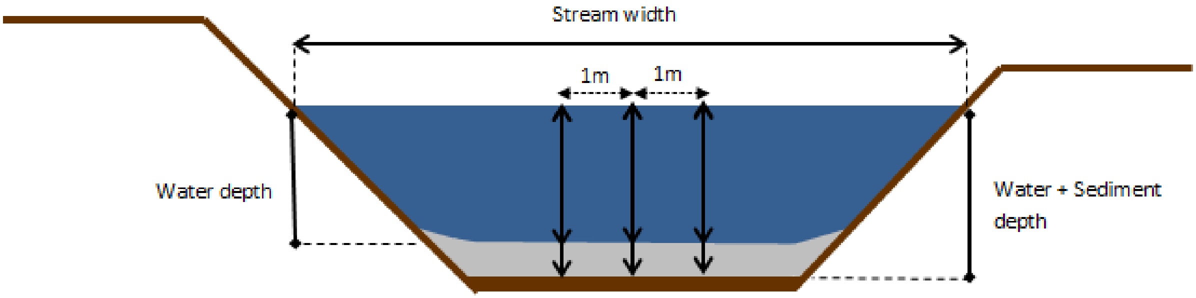


Figure 4: measuring stream width and stream depth. Stream depth is measured in the middle, 1 m left of the middle and 1 m right of the middle. Both the depth of the water level and the thickness of the sediment is measured. Stream width is measured from bank to bank at the water surface.

Bank profiles were measured at the two banks. To define the bank profile, the breakpoint where the sloping bank shifts to the flat bottom of the river was determined by scanning the bottom by feet at both sides. The bank profile was then defined by three measurements (figure 5): the distance from the breakpoint at the water surface until the bank (BB); the height from the breakpoint at water surface to top of the bank (HBT); the distance from breakpoint to top of the bank (BT). These three measurements were chosen as a sufficient description of the bank profile and a practical achievable procedure to conduct at all measuring points. The measurements were carried out with the measuring tape, measure rod and a level so measurements were horizontal.

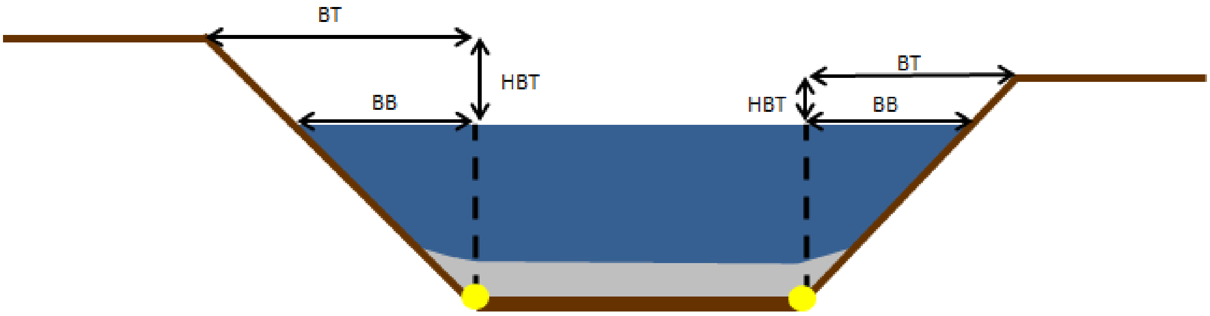


Figure 5: measuring the bank profile. From the breakpoint (yellow dot) the distance at the water surface until the riverbank (BB), the height from the top of the bank to the water surface (HBT) and the distance from the top of the bank to the breakpoint at water surface (BT) is measured at both sides of the river.

A detailed measurements form which was used during the measurements can be found in annex 1.

GIS analysis

The percentage of woody vegetation around dam and control areas was calculated using ArcGIS (ESRI, Redlands, United States of America). Infra-red aerial photographs (Agiv, Agentschap voor Geografische Informatie Vlaanderen, Gent, Belgium, Summer 2012) of each site were analysed by the help of supervised maximum likelihood classification to classify the picture into water, woody vegetation and other vegetation (and possibly buildings, motorways or shade) after which the percentage of wood was calculated (figure 6). This analysis was done from 50 m upstream to 50 m downstream of the dam or burrow/lodge and in a buffer of 15 m around the water way. The maximum likelihood classification was believed to be the most accurate method to determine the percentage of woody vegetation as it was also checked by a field visit during measurements.

Figure 6: An example of the calculation of the percentage of woody vegetation in the control site of Tongeren by the help of maximum likelihood classification in ArcGIS on Infra-Red air photographs. Light green areas are grass, dark green areas are woody vegetation and blue areas are water. The analysis was done from 50 m upstream to 50 m downstream of the lodge and in a buffer of 15 m around the water way.

Data analysis

Preliminary analysis

Statistical analysis has been conducted with the statistical program R (The R Foundation for Statistical Computing, Vienna, Austria). Significance is regarded when p-values were lower than 0.05. Significance levels <0.05 are visualised with *, significance levels <0.01 are visualised with ** and significance levels <0.001 are visualised with ***. When data were not normally distributed, non-parametric tests were used.

Water depths, measured at each measuring point at the left, in the middle and at the right of the waterway (figure 4) were checked for significant differences.

A upstream confluence was found in ten of the 33 measured dams. First, the effect of a confluence upstream needed to be examined to know how these data should be handled further. The average values of the water depth and water width were compared between left and right stream.

Characteristics of dam occurrence

In this analysis, for sites with multiple dams, only the measurements of the oldest dam (known from observations of local land managers) were included as this was seen as the original situation when a dam was constructed. Dams with flow device were also included because no effects of dam construction were analysed in this part. This resulted in a total of 18 dams which were used in this analyses.

A statistical analysis of the following seven environmental conditions was conducted to analyse the differences between dam areas and control areas:

- Water depth at 10 m downstream of the dam or at the burrow at a control area
- Water width at 10 m downstream of the dam or at the burrow
- Distance from the dam or burrow/lodge until the nearest woody vegetation
- Stream velocity
- Average bank height from 50 m upstream to 50 m downstream of the dam or burrow
- Average bank slope from 50 m upstream to 50 m downstream of the dam or burrow
- Percentage of woody vegetation in a buffer of 15 m around the waterway from 50 m upstream to 50 m downstream of the dam or burrow/lodge

The values for water depth and width 10 m downstream of the dam were chosen because analysis of the effect of dams revealed that the depth and width do not differ anymore from 10 m to 100 m downstream (see results). 10 m downstream specifically is chosen to make comparison possible with the research of Hartman and Törnlöv (2006) where they also examined the effect of water depth and width at beaver dams and control areas.

Correlations between the environmental conditions were tested after which a PCA analysis was conducted. Only environmental conditions which differed significantly between dam and control areas were used in the PCA analysis. Afterwards, a generalised linear model was set up to be able make a distinction between dam and control areas.

The environmental conditions which differed significantly between dam and control areas were also plotted in binomial distribution graphs after which threshold values for each environmental condition could be calculated (value of environmental condition with a dam certainty of 50%). These threshold values are determinant for the presence or absence of a dam. The threshold values are calculated using the formula of a logistic regression equitation:

$$y = \frac{e^{b+ax}}{1+ e^{b+ax}} \qquad \rightarrow \qquad x = \frac{1}{a}.\left(\ln(y) - \ln(1-y) - b\right)$$

Where y is the chance of construction of a dam, x is the value of the environmental conditions associated with this y, a is the slope of the logistic curve and b is the intercept.

Based on the threshold values, 4 conditions can be distinguished for the data points in the binomial graphs (figure 7): true positive (dams which are predicted correctly, dam areas on the left of the threshold line on the binomial graph), true negative (non-dam areas which are predicted correctly, non-dam areas on the right of the threshold line on the binomial graph), false positive (non-dam areas which are predicted to be dam areas, non-dam areas on the left of the threshold line on the binomial graph) and false positive (dam areas which are predicted to be non-dam areas, dams on the right of the threshold line on the binomial graph).

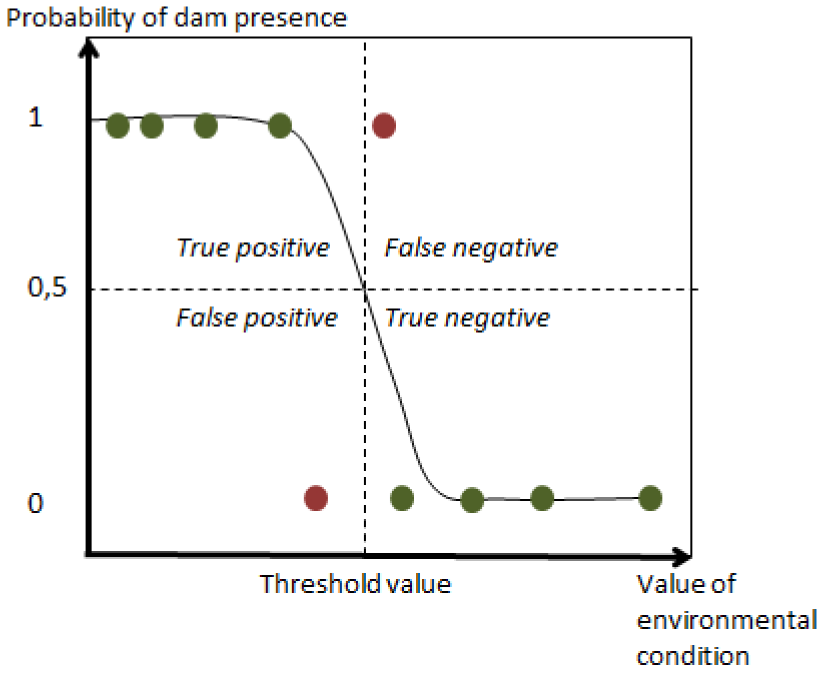


Figure 7: scheme of a binomial graph for dam presence (1) and dam absence (0) with the 4 possible conditions: true positive, true negative, false positive, false negative. The threshold value is given by the value of the environmental condition on the x-axes connected to a value of 0,5 (50% chance on dam construction) on the y-axes.

Afterwards, a classification tree (package 'Party', R statistics, Hothorn et al., 2014), is set up. This tree makes it possible to make a distinction between dam and no-dam areas based on the combination of the environmental conditions and their combined threshold values favouring the most important environmental conditions.

Dam localisation

Is the occurrence of a dam at a certain place determined by very local conditions and therefore specifically localised or could the dam also be situated on a other place in the waterway? To answer this question, an analysis was performed to determine the variance in bank slope, bank height and the distance to a possible confluence upstream. In this analysis, at sites with multiple dams, only the measurements of the oldest dam were included as this was seen as the original situation when a dam was constructed. Dams with flow device were also included because no effects of dam construction were analysed in this part. This results in a total of 18 dams which are analysed. To analyse the effect of a possible confluence upstream, the distance from a dam to the confluence upstream is compared to the distance of the nearest confluence downstream of the dam. This was considered because of the more efficient increase of the water level when dam construction is situated just after a confluence and the water level in two waterways will be raised resulting in an effect on a larger area. For this, the distance from the dam to the downstream confluence is measured using ArcGIS.

To examine if the location of the dam is specified by very local conditions, bank height and bank slope are calculated. The specific location of the dam was expected to be specified by the lowest bank height and bank slope in the watershed area because a low bank height and slope are optimal conditions for the upstream area to flood so dam building would be optimal. Bank height is defined as the sum of sediment depth, water depth and the height from the breakpoint at water surface to top of the bank (HBT in figure 5). Bank slope is defined as the tangent of the angle between the bank height and the distance from the breakpoint at the water surface until the bank (BB in figure 5). At each measure point, the minimum value of these slopes and bank heights was defined of both bank sides. Then, the whole measuring transect of each dam was divided in five parts: from 100 m upstream to 60 m upstream, from 60 m to 20 m upstream, from 20 m upstream to 20 m downstream, from 20 m to 60 m downstream and from 60 m to 100 m downstream (figure 8). Next, for each part, an average value for the bank slope and bank height was calculated. In this way, for each dam, five values for both factors were analysed by the help of a generalised mixed model for differences between the five parts.

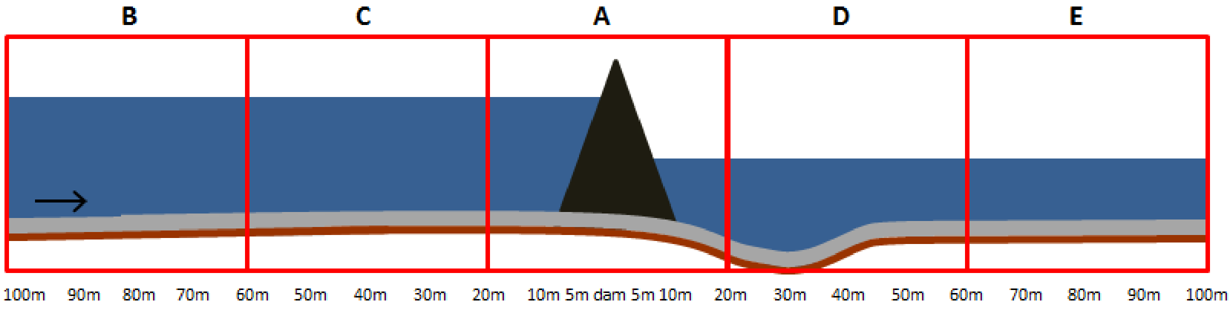


Figure 8: the division of the 200 m long transect around the dam in five equal parts for the measurements of bank height and bank slope in order to examine possible differences between these parts which define the specific location of the dam.

Effects of a dam

In this analysis, dams with flow device were excluded because they did not reflect the normal effect of a dam anymore. Sites with multiple dams were analyses in as follows: each of these sites was treated as one dam where the upstream- measurements of the dam most upstream and the downstream- measurements of the dam most downstream were used. In this way, dams in between were considered not to have an influence on these measurements which were used. This resulted in a total of 16 dams which were used in this analyses.

As a first effect of a dam, the average profile of the water depth at dam areas was analysed. All measurements were converted to relative values i.e. as the proportional ratio to the depth at 100m downstream of the dam so comparison between dams is possible. The average profile of the water width at dam areas was also analysed. All measurements were converted to relative values i.e. as the proportional ratio to the width at 100 m downstream of the dam so comparison is possible. To analyse the territories without dams, measurements were converted to relative values i.e. as the proportional ratio to the depth and width at 50 m downstream of the burrow or lodge.

The average increase of the water level was calculated by the average difference of the two measurements of the height difference just before and after the dam measured horizontally over the dam. For the 16 dam sites, for each place, the height difference of the dam and the resulting water depth upstream of the dam were calculated.

Another important consequence of dam building is the effect of rising of the water level on the flooding risk of the area. For this analysis, the upstream lowest bank height (HBT) per dam was used because at this point, the flooding will occur first.

As a consequence of a dam, the sedimentation patterns will change because of the decrease of stream velocity just before the dam and the increase of stream velocity after the dam. Therefore, a higher sediment layer just before the dam and a lower sedimentation just after the dam is expected. To test this hypothesis, sedimentation depths are calculated as the difference between the total water depth when the measure stick was pushed into the sediment and the water depth where the stick was not pushed into the sediment (figure 4). All measurements were converted to relative values i.e. as the proportional ratio to the sediment depth at 100 m downstream of the dam so comparison was possible. Because data were not normally distributed, no averages over dams were taken but medians were calculated by the help of bootstrap analysis. A sample of 16 measurements was randomly sampled with replacement and was repeated a 1000 times.

Results

Preliminary analysis

All gathered data can be found in annex 2, table A1 to A10.

Water depths were averaged because no significant differences (t-test) were found between left, middle and right measurements (table A1). With these findings, for the rest of the analysis, averages of the left, middle and right measurements are used.

In the t-test analysis of the effect of a upstream confluence (table A2), differences between left and right streams both for water depth and water width were found not to be significant. With this result, for the rest of the analysis an average of both streams for all measurements was calculated for each of the ten dam sites which had a upstream confluence.

Characteristics of dam occurrence

Differences of the environmental conditions (table A3) between dam areas and control areas were tested (figure 9). Differences for water width ($p < 0.001$, t- test), water depth ($p < 0.001$, Wilcoxon test), distance from vegetation ($p < 0.01$, t-test), stream velocity ($p < 0.01$, t-test) and bank height ($p < 0.01$, t-test) are significant. Difference in bank slope is not significant ($p > 0.05$, Wilcoxon test), the percentage of woody vegetation was also found not to be significant ($p > 0.05$, t-test).

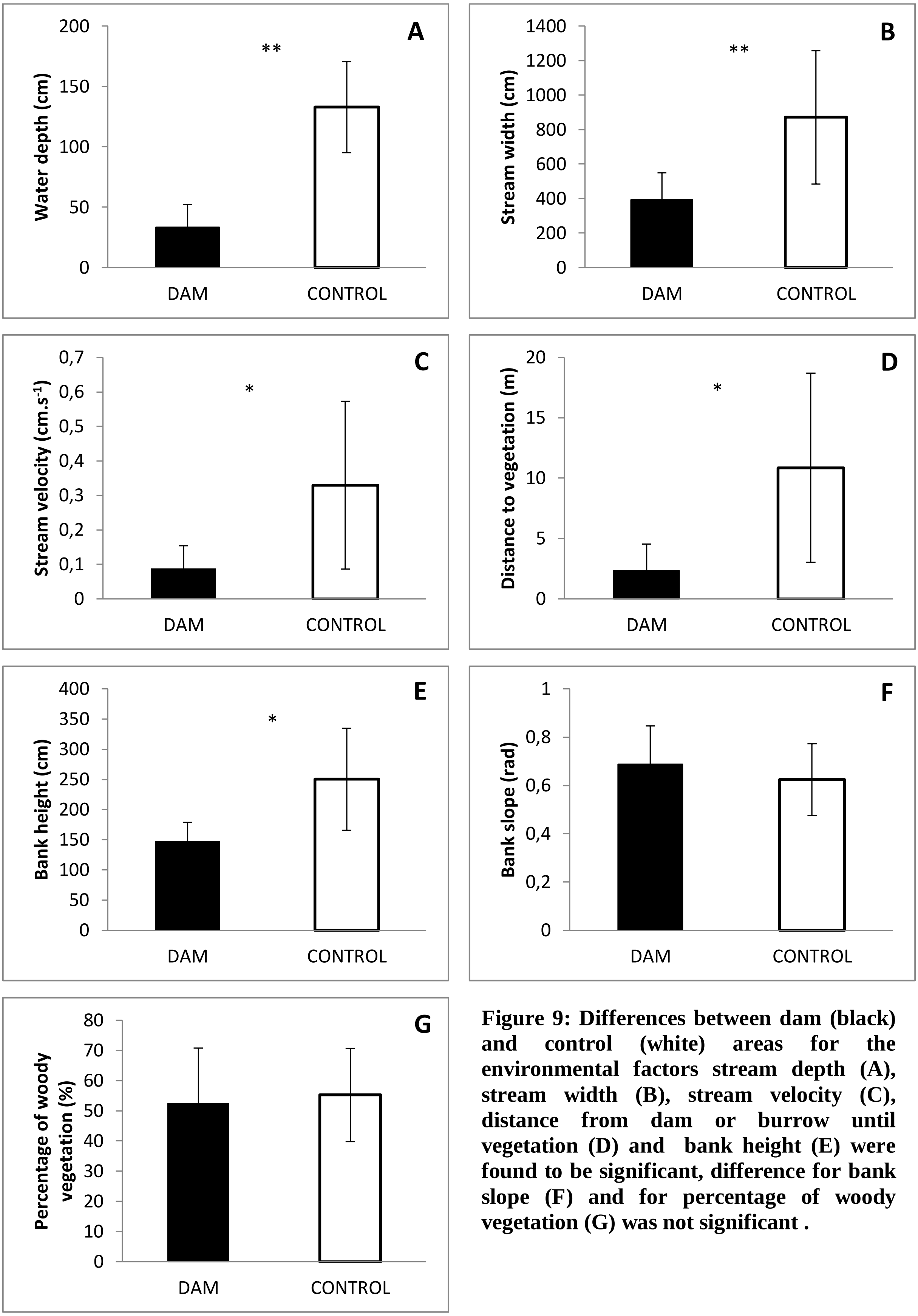


Figure 9: Differences between dam (black) and control (white) areas for the environmental factors stream depth (A), stream width (B), stream velocity (C), distance from dam or burrow until vegetation (D) and bank height (E) were found to be significant, difference for bank slope (F) and for percentage of woody vegetation (G) was not significant .

A Principal Component Analysis (PCA) was conducted with all environmental conditions which differed significantly between dam and no-dam areas (figure 10). The first component explains 64% of the total variation and includes the highly correlated stream width, bank height, stream depth and stream velocity (table 3). The second component explains an additional 17% of the total variation and mainly includes the distance from the dam or burrow/lodge until vegetation.

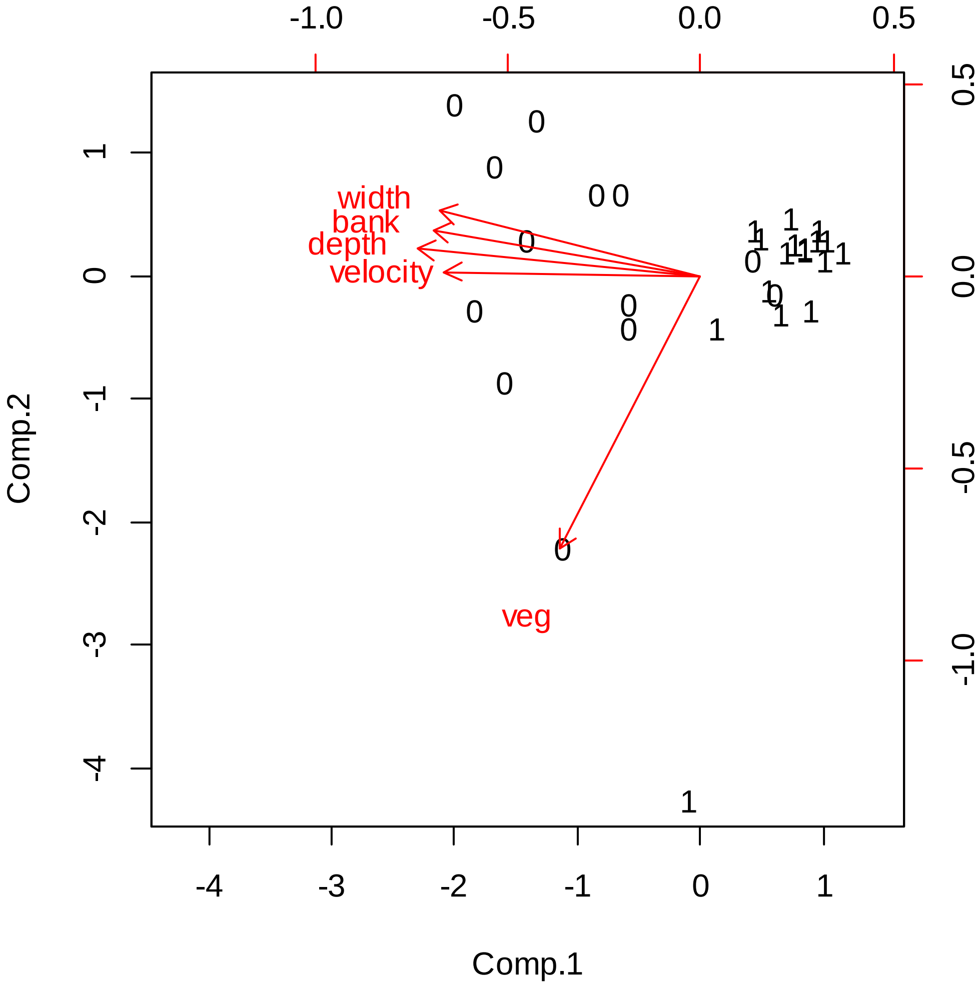


Figure 10: A Principal Component Analysis (PCA) was conducted with the factors stream width, stream depth, bank height, stream velocity and distance from dam or burrow to vegetation in relation to the presence of dams (1) or the presence of a control area (0). Stream width, bank height, stream depth and stream velocity are highly correlated in the first component which contains 64% of the total variation. Distance from dam or burrow to vegetation is mainly explained by the variation in the second component which explains an additional 17% of the total variation. All factors are negatively correlated to the presence of dams which means that with increasing values of these factors, the chance on the construction of a dam will decrease.

Table 3: Loadings of each factor per component and the importance of the components.

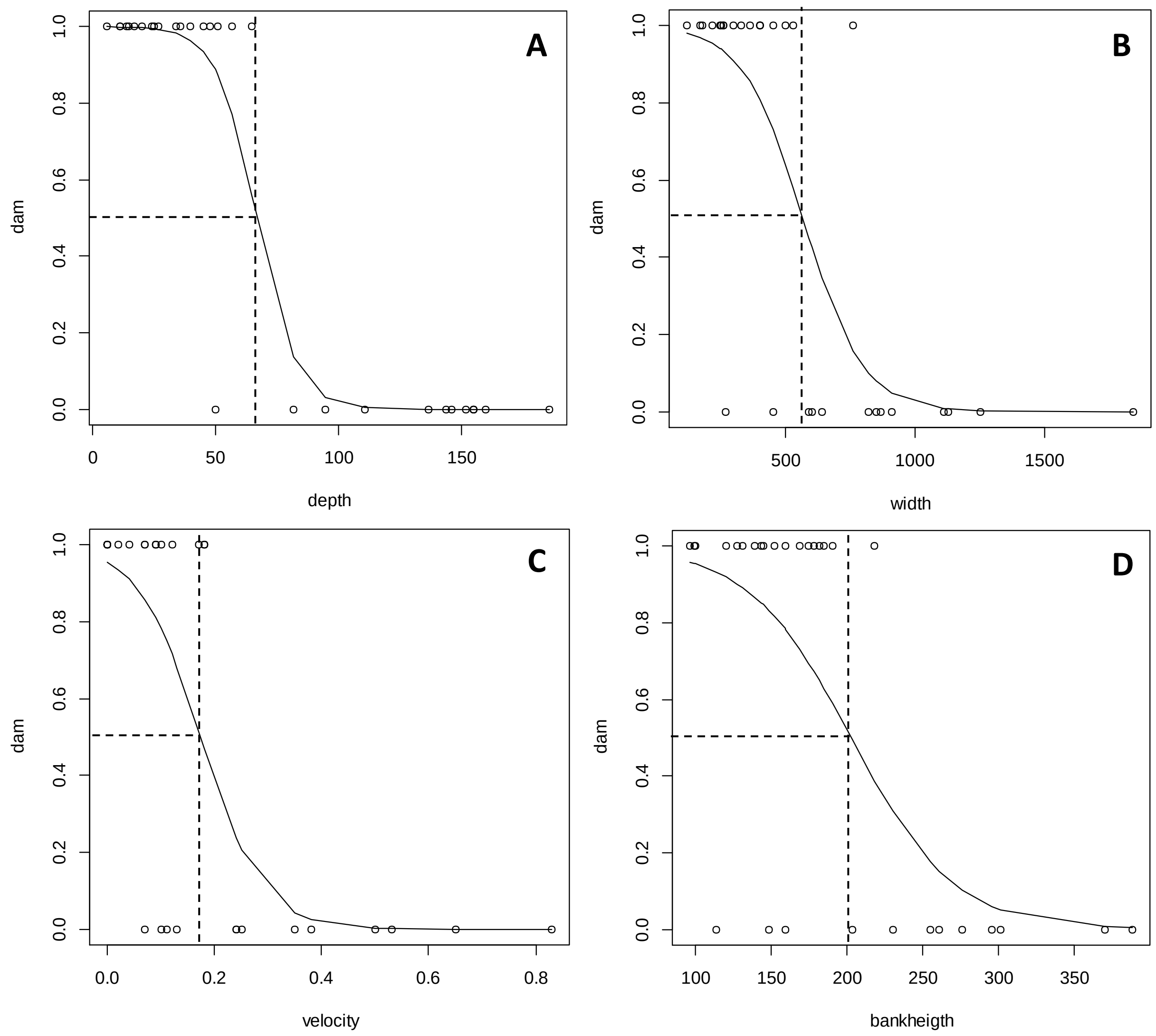
	Component 1	Component 2	Component 3
Loadings			
Width	-0.472	0.229	0.390
Depth	-0.513		
Velocity	-0.463		-0.850
Bank	-0.485	0.062	0.325
Vegetation	-0.254	-0.955	0.138
Importance of components			
Standard deviation	1.79	0.93	0.64
Proportion of variance	0.64	0.17	0.08

When analysing these components with a generalised linear model, the first component loadings, including the highly correlated stream width, stream depth, stream velocity and bank height in in lower importance the distance to vegetation, the model could make a significant distinction ($p < 0.05$) between dam- and no-dam areas. Other components were found not to have a significant contribution to the model ($p > 0.05$).

The threshold values of the five environmental conditions could be calculated (table 4) based on the binomial distribution graphs (figure 11).

Table 4: Threshold values for each environmental condition based on the binomial distribution graphs in figure 10. Threshold values are determined by the value of each environmental factors when there is a 50% chance of dam building and are calculated by the help of the logistic regression equitation.

Environmental condition	Threshold value	Unit
Depth	68,2	cm
Width	563,2	cm
Velocity	0.17	$cm.s^{-1}$
Bank height	202,8	cm
Distance to vegetation	528,3	cm



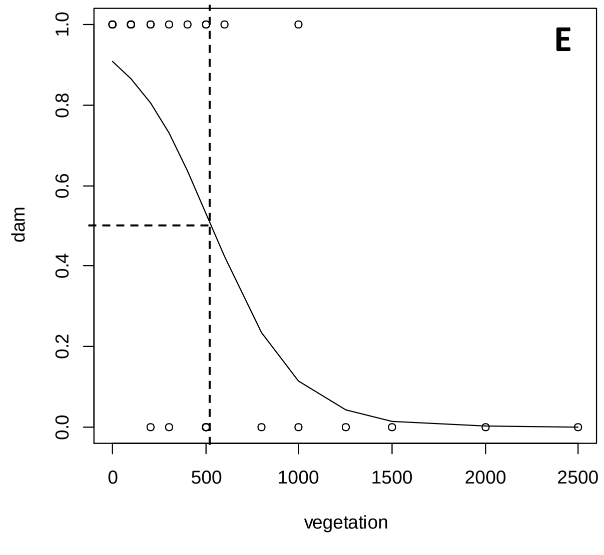


Figure 11: binomial distribution graphs of the 5 environmental conditions which are determinant for a waterway to be suitable for dam building. Environmental conditions water width (cm) at 10 m downstream of the dam or at the burrow/lodge of a control area (A), water depth (cm) at 10 m downstream of the dam or at the burrow/lodge of a control area (B), stream velocity (cm.s^{-1}) (C), average bank height (cm) from 50 m downstream to 50 m upstream of the dam or burrow/lodge (D) and distance from dam or burrow/lodge to nearest woody vegetation (E) in relation to the presence of a dam (1) or the absence of a dam (0). Threshold values are shown by the dashed lines.

These threshold values can now be used to determine if a certain area in a waterway would be suitable for dam building or not.

In order to combine the 5 environmental conditions and make a complete analysis of the conditions, a classification tree (ctree) was set up (figure 12). This classification analysis (nonparametric regression tree) revealed that based only on stream depth, a distinction can be made between dam and no dam areas with 97% certainty. When the water level in a waterway is less than 65 cm, a dam will be built; when water depth is more than 65 cm, no dam is built. Further inclusion of other parameters did not result in an improved model, resulting in this simple tree with just one branching point.

The threshold values on the classification tree deviated slightly from the values in table 4. This can be explained because these thresholds are based on recursive partitioning needed to develop the classification tree in which the environmental conditions are connected to each other to make a distinction between dam and no-dam areas. Based on this recursive partitioning, the split is chosen at that specific value (65 cm) where there is a maximal distinction between dam and no-dam areas.

All 18 dam areas were correctly classified as dam area (1) by the classification tree, 12 of the 13 control areas were correctly classified as control areas (1). One control area was falsely classified as a dam area. But it later turned out that, after the fieldwork for this study was finalised, a dam was built in this area anyhow.

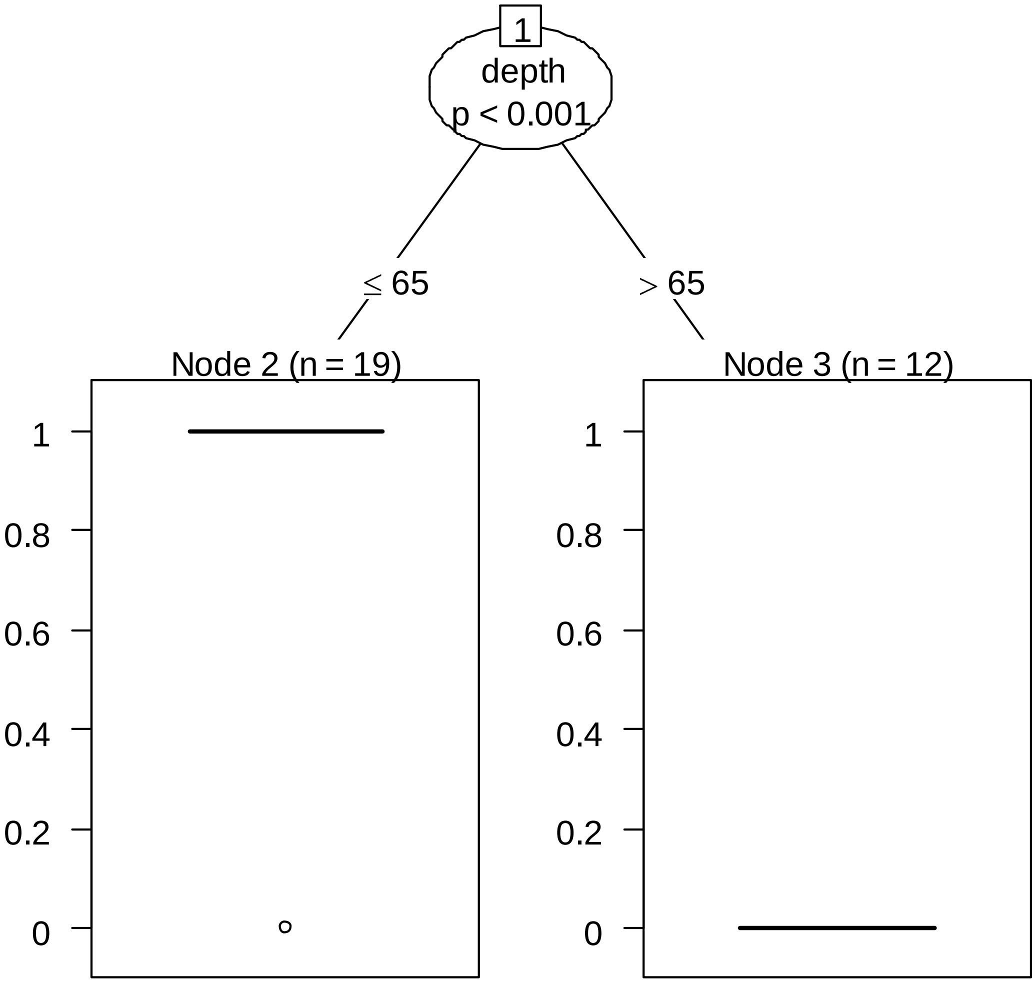


Figure 12: Classification tree (ctree) based on the combination of the five environmental conditions. With stream depth only, a distinction can be made between dam (1) and no-dam (0) areas with 97% certainty. When water depth is lower than 65 cm a dam will be built, when water depth is higher than 65 no dam is constructed. One location with a dam was falsely classified as a dam area. However, after fieldwork was finished, a dam was constructed at this very location

Dam localisation

A confluence was situated at average on 37.5 m (SD = 25.5 m) upstream of the dam. A confluence downstream of the dam was found to be on average 510 m (SD = 170 m) downstream of the dam (table A4). This difference in confluence is significantly different ($p < 0.01$, Wilcoxon test) so dams are preferably build downstream and in the surroundings of a confluence if there is a confluence.

The analysis of the bank height and bank slope (table A5) revealed that there were no differences over the transect so there is no specific localisation of the dam defined by differences in bank height and bank slope.

Effects of a dam

Water depth

The difference between upstream and downstream water depth (averages over 5 m to 100 m upstream or downstream) was found to be significant ($p < 0.01$, Wilcoxon test) (table A6).

The average profile of water depth at a dam territory in figure 13 shows that there was an increase upstream of the dam in comparison to 100 m downstream of the dam. The effect of the water rising was shown to extend beyond 100 m upstream of the dam. Large errors were explained by the high variability of the waterways themselves.

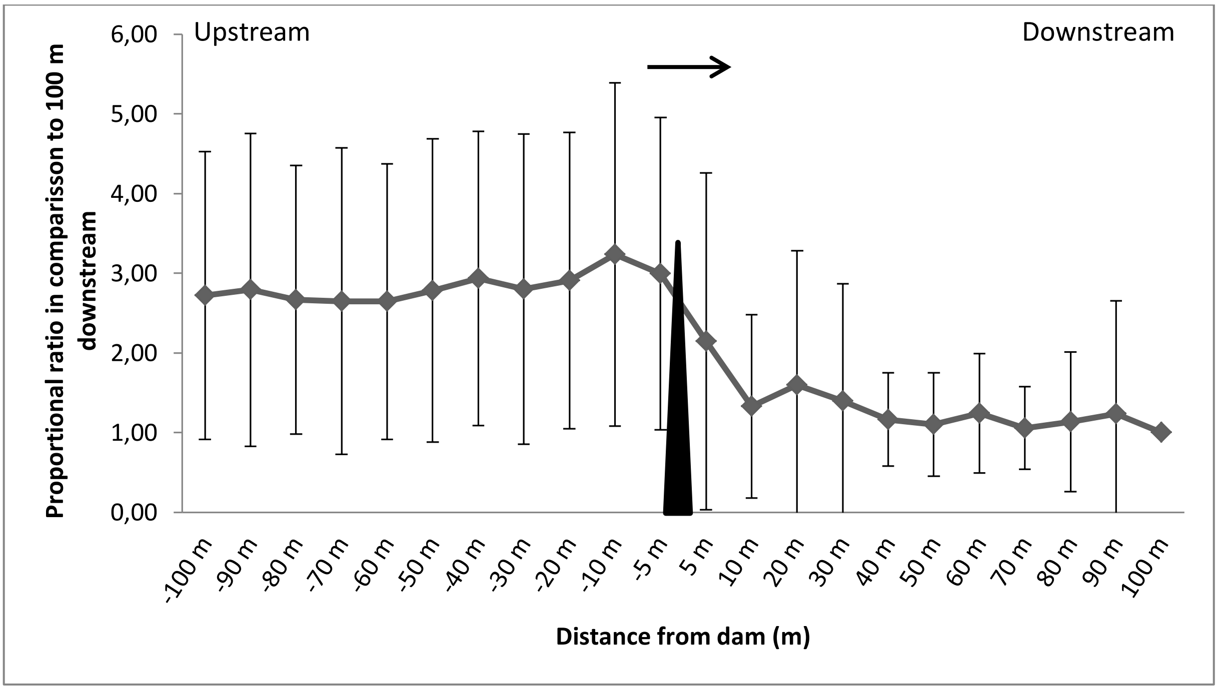


Figure 13: The average profile of water depth at a dam area. 100m downstream the dam was considered to be the original water depth before a dam was constructed. The rest of the measurements were calculated as the proportional ratio in comparison to the water depth at 100 m downstream so measurements over all dams were relative and comparison was possible. Large error bars were due to a high variability of waterways. Upstream of the dam, a large increase compared to downstream of the dam was found. The effect of the water level rising as a consequence of the dam building goes further than 100 m upstream of the dam.

The profile of water depth at a control area was found to be uniform (figure 14) (table A6). A weak tendency for a deeper water level at the entrance of the burrow/lodge could be seen but this was found not to be significant ($p > 0.05$).

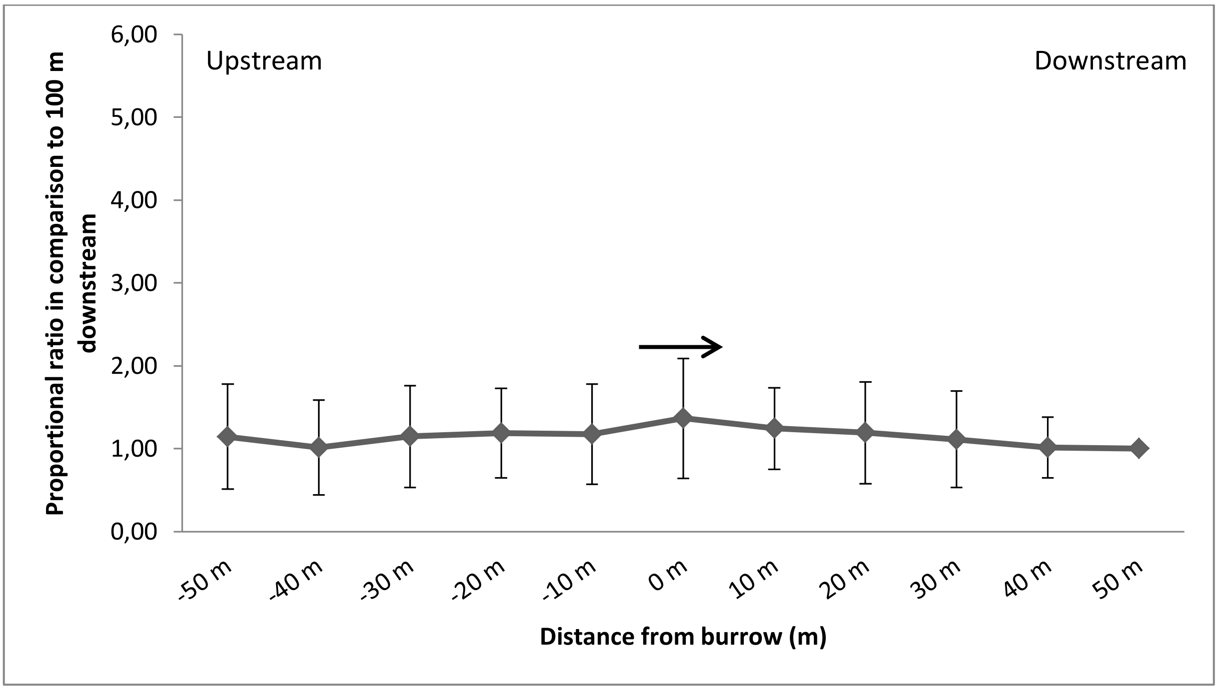


Figure 14: The average profile of water depth at a beaver territory without the influence of a dam. At point 0, the entrance of the lodge or burrow was situated.

The average water depth was compared upstream and downstream of a dam with the control area (table 5).

Table 5: the average water depth at 10m upstream compared to the average water depth at 10m downstream.

Stream depth	10 m downstream of dam	10 m upstream of dam	Control area
Average (cm)	30	93	133
Standard deviation (cm)	17	30	38

Water width

The difference between upstream and downstream water width (averages over 5 m to 100 m upstream or downstream) was found to be significant ($p < 0.001$, t-test) (table A7).

The average profile of water width at a dam territory in figure 15 shows that there an increase of the water width was found upstream of the dam in comparison to the water width downstream of the dam. The effect of the increase of water width was shown to extend beyond 100m upstream of the dam. Large errors are explained by the variability of waterways.

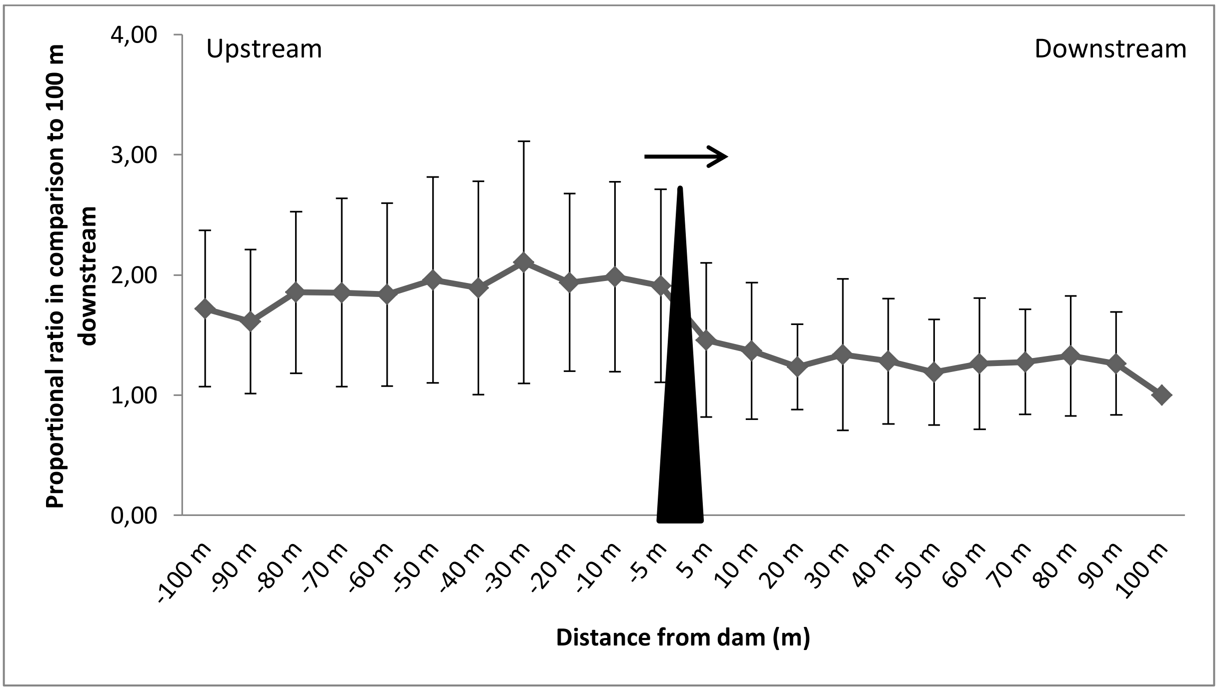


Figure 15: The average profile of water width at a dam territory. The water width at each point was calculated as the proportional ratio in comparison to the water width at 100 m downstream so measurements were relative and dams could be compared. Large error bars were due to a high variability of waterways. Upstream of the dam, an increase of water width compared to downstream of the dam was found. The effect of the waterway widening as a consequence of the dam building goes further than 100 m upstream of the dam.

The profile of water width at a control area was found to be constant (figure 16) (table A7).

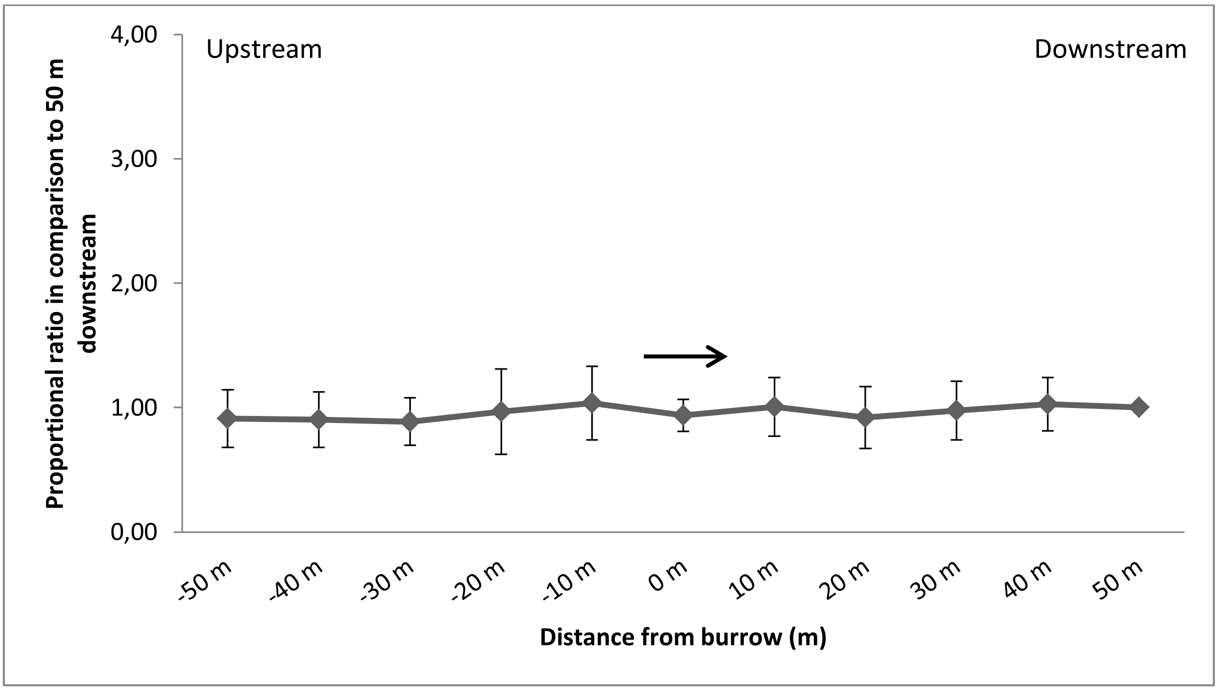


Figure 16: the average profile of water width at a control area without the influence of a dam. At point 0, the entrance of the lodge or burrow can be found.

The average water width was compared upstream and downstream of a dam with a control area (table 6).

Table 6: the average water width at 10m upstream compared to the average water width at 10m downstream at a dam territory and the comparison with the water width at a control area.

Stream width	10m downstream of dam	10m upstream of dam	Control area
Average (cm)	339	502	871
Standard deviation (cm)	165	142	403

Flooding risk

An average increase of the water level (table A8) as a consequence of a dam was found to be 47 cm (SD = 21 cm).

The average of the lowest bank height over all dams (table A9) was found to be 25.3 cm (SD = 29.5 cm). The large standard error indicates that because of the high variability between the areas, flooding is likely to happen in some places and very unlikely in other places.

Sedimentation profile

The difference between upstream and downstream sediment depth (table A10) was found to be significant ($p < 0.001$, t-test). The average profile of sedimentation is shown in figure 17, apart from an average larger sedimentation upstream, no clear profile was observed.

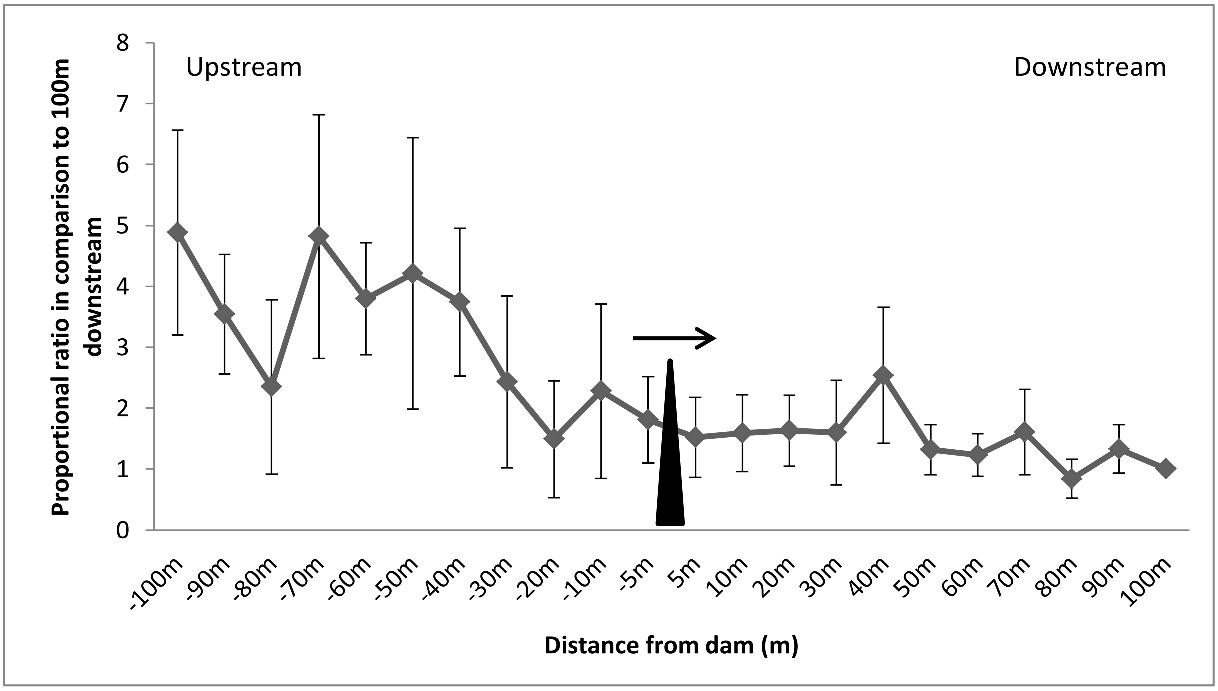


Figure 17: average profile of sedimentation from 100 m upstream to 100 m downstream of a dam. Values were the proportional ratio of sediment depth in comparison to the sediment depth at 100 m downstream of the dam; these relative values made comparison between dams possible. Large error bars were due to variable waterways with variable sediment loadings and variable ages of dams.

Discussion

Characteristics of dam occurrence

In 2004, in the beginning of the return of the beaver in Flanders, a rapport about the chances, bottlenecks and measures needed, connected to the unexpected return as a consequence of unofficial reintroductions, was published (Niewold, 2004). In this report, the conclusion was that a vision should be developed about the policy towards the beavers in which adequate reaction was essential at delicate sites where conflicts could arise. Important for this policy development regarding beaver conflicts in Flanders is to be able to predict whether a dam will be constructed at a specific location or if the location is suitable without dam construction. Until now, this was not yet done for Flanders and therefore the goal of this thesis.

So, which environmental conditions determine the suitability of a waterway to construct a dam? For this, seven environmental conditions were analysed. While significant differences were found between dam areas and control areas for the following five environmental conditions: water depth, water width, stream velocity, distance from dam or burrow/lodge to nearest woody vegetation and bank height, no differences were found for bank slope and percentage of woody vegetation around the dam or burrow/lodge. This led to five environmental conditions which poses predictive information in order to determine if a waterway is suitable for beavers with or without dam building. The highly correlated factors water depth, stream width, bank height and velocity were able to make a good distinction between areas with and without dams based on the first component in the Principal Component Analysis. The generalised linear model based on these five environmental factors by using the loadings of the first component of the PCA analysis so correlations were included, can make a significant distinction between dam and control areas ($p < 0.05$). So based on stream depth, stream width, bank height, stream velocity and of minor importance the distance to vegetation, it is possible to make a distinction for an area if it is suitable or not, based on the measurements of these five environmental conditions.

When threshold values are calculated for these five each environmental condition, some environmental conditions have a higher chance on false negative predictions then others. For this reason, the five environmental conditions were combined in a classification tree. This tree can make a distinction between dam an no-dam areas based on water depth only with 97% certainty. A depth of 65 cm is the critical value to predict if a dam will be built or not. Other environmental conditions were found less important than water depth. Obviously, because of the small dataset, it is probable that some variability occurs in reality which was not recorded. More data would include more variation which probably results in more extensive partitioning including more conditions however the dataset contains all dams present in Flanders at the time of the measurements. At the control area which was falsely predicted to be a dam area, a dam is built in meantime after the fieldwork was done. This observation indicates that perhaps a higher precaution is needed in cases where water level varies around 65 cm and it would be more optimal to incorporate other environmental conditions in the analysis to decide if the area is suitable with or without dam building. Moreover, precaution is needed when using this classification tree in practice throughout different seasons. This tree is based on data which were collected in the summer, the driest period of the year. This approach was chosen since dams will be the most necessary and will be constructed during this driest period. When using this tree to predict whether a site is suitable for dam construction, water depth needs to be measured when water level is lowest, mostly in summer. In periods with heavy rainfall, the accuracy of the classification tree is not ensured.

The percentage of woody vegetation did not seem to differ between dam areas and control areas measured over 100 m (50 m upstream to 50 m downstream of the dam or burrow/lodge). In both dam and control areas, an average of about 50 to 55% of woody vegetation in the direct surroundings of the dam or burrow/lodge was found. This confirms the need of woody vegetation as the most important part of the beavers' diet (Jenkins, 1975; Nolet et al., 1995). But the findings in this research are in contrast to the research of McComb et al. (1990) and Curtis and Jensen (2004) since they did find a significant difference between dam and no-dam areas for the percentage of woody vegetation. Possibly, this difference can be explained by the fact that the research of McComb et al. (1990) in Canada made a distinction between dam- and no-dam areas based on the fact that they defined no-dam areas as random areas so there was no certainty that beavers were present in these random areas without dam building or that beavers were not present at all. While in the research of this thesis, a distinction was made between dam areas and control areas where beavers were certainly present without dam building. The research of Curtis and Jensen (2004) in New York, U.S., made a distinction between occupied and unoccupied streams where they did not make clear a distinction between occupied streams with or without dams (i.e. a control area like in the research of this thesis). So the difference in defining what is occupied or not and the choice to work with random areas can lead to different conclusions and can be important for policy development. Although no clear differences have been shown in dam construction behaviour, in this research, the Eurasian beaver is examined while the previous studies focused on *Castor canadensis*.

Some environmental conditions have not been examined in this research but was found to be important for dam construction in other researches. Possibly, the stem diameter of the woody vegetation could be another important condition in the determination if a beaver will build a dam or not as was found in the research of Barnes an Mallik (1996). This has not been examined in this thesis because it was not feasible during this research and we there was opted to focus on more hydrological and geographical environmental conditions. The topographic gradient at dam and control areas has not been examined in this thesis in contrast to the research of McComb et. al (1990), Barnes and Mallik (1996) and Suzuki and McComb (1998) in Canada where they found that this factor can play a determinant role for dam building. The topographic gradient is important for dam construction because on too steep gradients, dam building can become impossible because of limited ability of creating a sufficient beaver pond area and a limitation in stability when a dam needs to be build higher to create a sufficient pond area on a steep hill and because a too high stream velocity. That is why these researchers found that dams were constructed in areas where the topographic gradient is lower. This gradient along the stream bank was not measured in this thesis because Flanders is fairly flat and no difference were believed to be found between control and dam areas for this region.

The research of Barnes and Mallik (1996) was conducted to distinguish dam and no dam sites in Northern Ontario, Canada. For this they focussed on physical features like watershed area, water depth and gradient. The topography in the region was considered hilly. Next to their own findings, they also analysed the accuracy of McCombs model (McComb et al., 1990) who constructed a model based on their findings in Oregon, Canada where the topography is more variable than in Northern Ontario. Barnes and Mallik (1996) found that McCombs model was not accurate because of regional differences. Here they already pointed out the importance of regional differences on the accuracy of a model which is also applicable for this thesis as the topography in Flanders is not comparable to other dam studies where models were constructed. Also Suzuki and McComb (1998) constructed a regional model for Oregon, Canada because they found that general models were not sensitive enough for local conditions.

The model together with the classification tree developed in this thesis can now be an important tool in managing the further expansion of the beaver in Flanders. Several studies showed that beavers first occupy the most optimal sites and prefer sites where dam building is not required (Hartman & Tornlov, 2006) and when such primary habitat is not available anymore, they will colonize secondary habitat where dam building will occur more frequently (Hartman & Tornlov, 2006). But as colonisation in Flanders is still going on towards the Scheldt estuary (Niewold, 2004) and a lot of primary habitat where dam building is not required is still available there, it is believed that beavers will first occupy optimal sites when it is available in their direct surroundings but they will not keep on dispersing until they find optimal habitat were dam building is not required, when the optimal environmental conditions are met they will colonize the area with dam building. That is why dam building is Flanders is already frequent while primary habitat is still available. Beavers primarily move through water and, because of this, movement between watersheds and basins is highly restricted (Halley and Rosell, 2002). This also influences dam building behaviour while primary habitat is still available but not easy to reach. However, with ongoing dispersal more and more secondary habitat will also be colonised so conflicts will increase. With this model and classification tree it is now possible to be one step ahead of these conflicts. When a certain waterway is believed to be problematic for dam construction if a beaver would settle there, with this model and classification tree it can be determined if that particular waterway is in fact also suitable for dam building. In case dam building is expected, pre-emptive measures can be determined so a beaver would not settle at this problematic place. What these particular measures could be is not always straightforward. As woody vegetation is an essential part of the beavers’ diet (Jenkins, 1975; Nolet et al., 1995) and beavers only forage within a 20 m range next to a river (Barnes & Dibble, 1988; Parker et al., 2012) a measure could be to remove all suitable riparian vegetation for dam building in conflict areas within a 20 m range next to the water way. But as this riparian vegetation is also an important area for other animals this is not always a realistic solution. Another possibility is to cover the bank of the river with an iron net or with rocks so beavers are unable to dig a burrow or the entrance to their lodge (Niewold, 2008) but more research is needed for the feasibility of this method for conflicting areas. The model can now also be used to analyse areas where beavers can settle without dam construction. This can be very important for beavers who need to be translocated because they are causing conflict in their current territory.

Dam localisation

When looking at the analysis of the specific localisation of dams on a scale of tens of meters some factors give an additive value to the specific location of a dam while other factors do not seem to contribute to the localisation of a dam when general environmental conditions were favourable for dam construction like discussed in the part above.

The clear difference found in distance to the confluence upstream and downstream leads to the conclusion, that if local environmental conditions are in favour of dam building, the specific location of the dam will probably be influenced by a upstream confluence if this is located in the surroundings of these favourable conditions and the dam will be built downstream in the vicinity of this confluence. Next to that, analysis of the bank height and bank slope showed that there are no specific differences over the transect in favour of dam building so these factors are not found to be determinant for optimal flooding as a consequence of dam construction.

In addition to this, a human induced factor, namely the effect of the construction of a flow device through a dam can have an effect on the location of a dam. At 5 sites, a dam was situated with a flow device. These flow devices are constructed when the rising water level as a consequence of a dam causes conflicts with the surrounding land use. The flow devices are meant to find a compromise in the water level that is sufficient for the beavers' needs and a water level were the conflicts with the surroundings are solved or minimalized (Agency of Nature and Forestry (ANB), 2013). In two of the sites were a flow device is installed, the flow device did not yet cause the construction of additional dams to counteract the working of the flow device. In three other sites, a flow device trough the dam led to the construction of multiple dams upstream and downstream of the dam with the flow device in order to counteract the working of the flow device. So when a dam is situated in a conflict area and an optimal solution would be to lower the water level upstream of the dam, it should be carefully considered for the water level to remain sufficient for the beaver. In the three sites where multiple dams were constructed after a flow device was installed, the water level was probably not sufficient anymore and beavers tried (and succeeded) to counteract the effect of the flow device by the construction of extra dams which caused additional conflicts by extra water level risings in the surroundings. Monitoring and analysis of different flow techniques in Flanders (ANB, 2013) showed that flow devices technically work but that they are not always efficient and the new water level is not always sufficient for beavers. This leads to the consequence that multiple dams are constructed and the effort put in the construction and monitoring of flow devices and the accompanied price of these flow devices are therefore not always efficient.

Dams in Flanders are often situated in very urbanised areas where there is a lot of human activity. The research of McComb et al. (1990) in Canada concluded that the distance to human feature did not influence dam building. In Flanders it was also found that beavers live in close proximity to humans and man-made structures if all habitat requirements are met. Thus, this effect will be likely not the have an important influence on the specific location of a dam.

Effects of a dam

The original water depth at a dam area and at a control area found in Flanders are comparable to the research of Hartman and Törnlöv (2006). Comparable large standard deviations in their research reflect that the high variability of waterways was also found in this research. A dam increases the water level on average 2.8 times the original water level to an average depth of 93 cm (63-123 cm) at 10 m upstream of the dam. Taking into account the large standard error, the conclusion can be drawn that a depth of at least 63 to 123 cm is required at for a beaver to be suitable habitat which is comparable to the depth found by Hartman and Törnlöv of 70 to 100 cm which is sufficient without dam construction. These values are comparable to the threshold value of 65 cm defined by the classification tree. The average profile of water depth at a dam area (figure 2), shows a clear profile despite the large standard errors. The water depth both upstream and downstream of the dam is fairly constant and it is clear that the effect of dam building on the water depth goes further than 100 m upstream of the dam.

Analysing at the stream width made comparison with the research of Hartman and Törnlöv (2006) possible, the findings of Flanders are included in the ranges of the research in Sweden although the range in Sweden is more variable. This is probably due to a more hilly topography in Sweden compared to Flanders which is fairly flat. The average profile of water width at a dam territory (figure 5) shows an significant increase upstream of the dam but less pronounced compared to water depth. This, together with the finding that there is an overlap in the range of stream width between the average at 10 m downstream of dam areas and at control areas in comparison to the water depth and the preference for water depth in the classification tree leads to the conclusion that water width is not as important as water depth for the suitability of an area without dam construction. The research of Hartman and Törnlöv (2006) resulted in the same conclusion.

Measurements have been done during three summer months July, August and October in 2013. The spreading of measurements possibly can have an effect on water levels because of precipitation variation. Therefore it was chosen to do measurements in the driest period of the year and to do the measurements in a period as short as possible to keep this water level variation minimal. Because of this, it is believed that water level variation as a consequence of precipitation will be minimal and has no major influences the results. Large standard deviations in the analysis of water depth and water width are mainly because of variable waterways. Because of a limited number dams in Flanders, there was no possibility in the analysis to divide the water ways in which dams are built in categories according to general water depth and water width which would lower the standard deviation.

The analysis of the flooding risk associated with dam building showed that 2 aspects were important: the average water level rising at the dam and the lowest bank height upstream of the dam because this will be the place where flooding occurs first. Like McComb et al (2006) found that dam height are highly variable, that was also found in the research of this thesis. With an average rising of 47 cm (26 – 68 cm) of the water level it is clear that the dam is only build until a height that the water level is sufficient for the beaver’s needs and is highly dependent on the original water depth of the water way. This average raising of the water level can also be seen as a limitation of dam stability when increasing the water level although dams are known in the Walloon area until 2 m height (personal observation). With an average lowest bank height over all dams of 25 cm (-4 – 54 cm) the high variability shows that in some waterways a dam will flood the surrounding area and that in other waterways the bank height is sufficient high to create a sufficient water depth for the beavers’ needs without the flooding of the environment. This is what was also seen during the measurements. At some locations a part of the upstream area was flooded as a consequence of the dam which was also frequently the cause of conflicts and therefore the reason for the destruction of the dams or the installation of a flow device. In Holsbeek, flow devices are installed in two dams, the other situated dams (3 at the time of the measurements) are frequently removed as they flood a valuable orchid meadow (ANB, 2013). In Zandhoven, a flow device is installed in one dam, the other situated dams (five at the time of the measurements) are removed in the meantime because they caused the flooding of a valuable reed meadows. The dam in Kinrooi has also been removed after measurements because it flooded the footpath of a nature area. In Venray, also a large upstream area was flooded but no measures have been taken until now as it is not yet causing conflicts. In Lummen, the flooding as a consequence of the dam is the cause of conflicts with landowners and dams have been removed at this place. In Bocholt, a flow device was installed after measurements because of the flooding of surrounding agricultural fields.

The analysis of the sedimentation measurements did not show the expected results. As dams reduce stream velocity upstream of the dam, a higher sedimentation rate would be expected to occur just before the dam (Rosell et al., 2005; Butler and Malanson, 1995) while downstream of the dam, an increase erosion is expected because of the fast flowing water coming from the dam so a depression would be expected just behind the dam (Rosell et al., 2005). A significant higher sedimentation was found upstream of the dam, but no clear profile can be seen from the analysis (figure 7). This is probably due to the fact that all dams in Flanders are relatively young which result in a time span which is yet to short for a noticeable change of the sedimentation profile and to build up the expected profile. Next to this, the current situation in Flanders is that a lot of dams are frequently removed as they are the cause of conflicts. Because the places where dams are destructed were clearly suitable habitat, beavers will try to rebuild the dams which does not always occur on exactly the same place so sedimentation profiles can get mixed up and no general profile can be found.

Conclusion

Based on stream depth, stream width, stream velocity, bank height and the distance from the dam or burrow/lodge to woody vegetation, the linear model made a good distinction between dam areas and control areas ($p < 0.05$). By the help of the classification tree which can make significant distinction between dam and no-dam areas based only on a water depth threshold value of 65 cm with 97% certainty, this analysis can now be used as a base to predict whether an specific location, which is likely to be colonised by beavers in the future, would be suitable with dam building or not. Being able to predict the occurrence of a beaver dam allows us to be on step ahead of conflicts with beavers and their dam because they frequently cause flooding's of valuable land. This will be an important factor in the policy development with the increasing beaver population in Flanders. The detailed analysis of the effects of a dam showed what the consequences of a dam can be for the surrounding area. With an average increase of 47 cm of the water level, it can now be assessed if suitable dam areas which are not yet colonised would be possible conflict areas if bank heights would be too low so flooding will occur of the surroundings.

These findings can now be used to assess available waterways for beaver colonisation, asses the possible conflicts which can arise and evaluate what sort of measures can be taken before conflicts arise. Being one step ahead of these conflicts is essential in the management of the beaver as a protected species. This allows us to find a balance between the re-establishment of the beaver in the highly urbanised Flanders and the acceptance of the Flemish population of this remarkable and valuable species for nature.

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Annex

Annex 1: Measurements schedule

Place						
Date						
Territory type						
Coordinates						
Stream velocity	Distance					
	time	1.	2.	3.		
Description of woody vegetation						
Distance to woody vegetation						
DAM MEASUREMENTS						
Dam length						
Vegetation of dam						
Height difference water level	Height upstream	1.	2.			
	Height downstream					
Distance to confluence upstream						
Flow device						
Type dam						
Remarks						
TRANSECT MEASUREMENTS						
			Upstream		Downstream	
5m (dam) or 0m (control area)	Water depth	1m left				
		Middle				
		1m right				
	Water + sediment depth	1m left				
		Middle				
		1m right				
	River width					
	Bank profile		Left	Right	Left	Right
	BT					
	BB					
	HBT					
10m	….					

Annex 2: Analysed data

Table A1: Water depth measurements of all measuring point at all dams In the middle of the waterway (WM). 1 m at the left of the middle (WL) and 1 m at the right of the middle (WR). At each row WL. WM and WR are connected to each other and are therefore pairwise tested.

PLACE	DISTANCE	WL	WM	WR	PLACE	DISTANCE	WL	WM	WR
Bree	-100m	0.95	0.90	0.71	Kinrooi	-100m	0.06	0.09	0.07
Bree	-90m	0.31	0.34	0.28	Kinrooi	-90m	0.15	0.16	0.18
Bree	-80m	0.13	0.13	0.15	Kinrooi	-80m	0.24	0.23	0.21
Bree	-70m	0.09	0.07	0.05	Kinrooi	-70m	0.41	0.36	0.25
Bree	-60m	0.12	0.13	0.11	Kinrooi	-60m	0.17	0.16	0.23
Bree	-50m	0.10	0.10	0.09	Kinrooi	-50m	0.22	0.24	0.21
Bree	-40m	0.07	0.07	0.07	Kinrooi	-40m	0.24	0.21	0.23
Bree	-30m	0.12	0.13	0.10	Kinrooi	-30m	0.29	0.32	0.23
Bree	-20m	0.11	0.10	0.07	Kinrooi	-20m	0.28	0.29	0.36
Bree	-10m	0.12	0.10	0.07	Kinrooi	-10m	0.33	0.53	0.78
Bree	-5m	0.13	0.15	0.14	Kinrooi	-5m	0.10	0.12	0.10
Bree	5m	0.26	0.22	0.28	Kinrooi	5m	0.22	0.20	0.14
Bree	10m	0.18	0.16	0.14	Kinrooi	10m	0.24	0.22	0.25
Bree	20m	0.24	0.32	0.38	Kinrooi	20m	0.10	0.22	0.14
Bree	30m	0.51	0.41	0.33	Kinrooi	30m	0.10	0.14	0.08
Bree	40m	0.43	0.47	0.42	Kinrooi	40m	0.12	0.16	0.14
Bree	50m	0.50	0.42	0.43	Kinrooi	50m	0.14	0.22	0.16
Bree	60m	0.45	0.49	0.45	Kinrooi	60m	0.16	0.20	0.22
Bree	70m	0.58	0.62	0.53	Kinrooi	70m	0.25	0.24	0.14
Bree	80m	0.53	0.57	0.53	Kinrooi	80m	0.28	0.35	0.30
Bree	90m	0.39	0.42	0.36	Kinrooi	90m	0.28	0.27	0.23
Bree	100m	0.49	0.49	0.50	Kinrooi	100m	0.30	0.35	0.40
Bocholt	-100m	0.25	0.46	0.48	Lienne	-100m	0.65	0.77	0.83
Bocholt	-90m	0.12	0.10	0.06	Lienne	-90m	0.08	0.10	0.08
Bocholt	-80m	0.38	0.35	0.27	Lienne	-80m	0.18	0.17	0.12
Bocholt	-70m	0.37	0.29	0.25	Lienne	-70m	0.20	0.18	0.22
Bocholt	-60m	0.38	0.42	0.58	Lienne	-60m	0.08	0.18	0.12
Bocholt	-50m	0.31	0.37	0.35	Lienne	-50m	0.08	0.12	0.07
Bocholt	-40m	0.25	0.19	0.13	Lienne	-40m	0.10	0.13	0.12
Bocholt	-30m	0.23	0.27	0.25	Lienne	-30m	0.47	0.38	0.37
Bocholt	-20m	0.17	0.37	0.31	Lienne	-20m	0.53	0.45	0.53
Bocholt	-10m	0.13	0.23	0.17	Lienne	-10m	0.50	0.49	0.48
Bocholt	-5m	0.15	0.19	0.17	Lienne	-5m	0.53	0.75	0.43
Bocholt	5m	0.37	0.37	0.29	Lienne	5m	0.51	0.54	0.46
Bocholt	10m	0.61	0.62	0.45	Lienne	10m	0.77	0.81	0.70
Bocholt	20m	0.98	0.98	0.59	Lienne	20m	0.47	0.43	0.38
Bocholt	30m	0.15	0.12	0.17	Lienne	30m	0.48	0.54	0.47
Bocholt	40m	0.00	0.00	0.00	Lienne	40m	0.14	0.14	0.12

Bocholt	50m	0.00	0.00	0.00	Lienne	50m	0.15	0.18	0.20
Bocholt	60m	0.00	0.01	0.00	Lienne	60m	0.33	0.39	0.42
Bocholt	70m	0.00	0.00	0.00	Lienne	70m	0.56	0.77	0.68
Bocholt	80m	0.00	0.00	0.00	Lienne	80m	0.29	0.28	0.26
Bocholt	90m	0.00	0.00	0.00	Lienne	90m	0.21	0.26	0.21
Bocholt	100m	0.73	0.87	0.68	Lienne	100m	0.21	0.26	0.21
Dilsen	-100m	0.14	0.12	0.16	Lummen	-100m	0.30	0.28	0.22
Dilsen	-90m	0.00	0.00	0.00	Lummen	-90m	0.24	0.30	0.23
Dilsen	-80m	0.00	0.00	0.00	Lummen	-80m	0.27	0.26	0.23
Dilsen	-70m	0.00	0.01	0.00	Lummen	-70m	0.17	0.21	0.19
Dilsen	-60m	0.00	0.00	0.00	Lummen	-60m	0.22	0.23	0.21
Dilsen	-50m	0.00	0.00	0.00	Lummen	-50m	0.15	0.10	0.09
Dilsen	-40m	0.00	0.00	0.00	Lummen	-40m	0.23	0.22	0.16
Dilsen	-30m	0.00	0.00	0.00	Lummen	-30m	0.22	0.27	0.22
Dilsen	-20m	0.00	0.00	0.00	Lummen	-20m	0.22	0.27	0.23
Dilsen	-10m	0.00	0.00	0.00	Lummen	-10m	0.32	0.30	0.24
Dilsen	-5m	0.43	0.48	0.40	Lummen	-5m	0.25	0.32	0.25
Dilsen	5m	0.36	0.32	0.26	Lummen	5m	0.29	0.27	0.25
Dilsen	10m	0.42	0.39	0.33	Lummen	10m	0.18	0.22	0.20
Dilsen	20m	0.43	0.40	0.40	Lummen	20m	0.24	0.25	0.22
Dilsen	30m	0.44	0.46	0.40	Lummen	30m	0.16	0.11	0.10
Dilsen	40m	0.43	0.42	0.39	Lummen	40m	0.11	0.17	0.15
Dilsen	50m	0.38	0.46	0.48	Lummen	50m	0.25	0.25	0.18
Dilsen	60m	0.49	0.47	0.30	Lummen	60m	0.55	0.52	0.39
Dilsen	70m	0.50	0.50	0.48	Lummen	70m	0.39	0.35	0.27
Dilsen	80m	0.42	0.46	0.38	Lummen	80m	0.55	0.63	0.61
Dilsen	90m	0.38	0.46	0.39	Lummen	90m	0.61	0.71	0.52
Dilsen	100m	0.09	0.09	0.09	Lummen	100m	0.68	0.65	0.73
Dendermonde	-100m	0.71	0.63	0.68	Pecrot	-100m	0.34	0.35	0.39
Dendermonde	-90m	0.85	0.89	0.90	Pecrot	-90m	0.29	0.33	0.34
Dendermonde	-80m	0.63	0.73	0.77	Pecrot	-80m	0.37	0.32	0.33
Dendermonde	-70m	0.66	0.81	0.81	Pecrot	-70m	0.37	0.35	0.35
Dendermonde	-60m	0.52	0.73	0.84	Pecrot	-60m	0.37	0.35	0.34
Dendermonde	-50m	0.95	0.97	0.98	Pecrot	-50m	0.40	0.39	0.40
Dendermonde	-40m	0.83	0.72	0.57	Pecrot	-40m	0.19	0.20	0.29
Dendermonde	-30m	0.30	0.43	0.43	Pecrot	-30m	0.20	0.24	0.19
Dendermonde	-20m	0.57	0.93	0.78	Pecrot	-20m	0.32	0.32	0.31
Dendermonde	-10m	0.30	0.46	0.50	Pecrot	-10m	0.13	0.15	0.14
Dendermonde	-5m	0.76	0.65	0.54	Pecrot	-5m	0.13	0.12	0.10
Dendermonde	5m	0.50	0.57	0.39	Pecrot	5m	0.13	0.14	0.14
Dendermonde	10m	0.41	0.57	0.54	Pecrot	10m	0.32	0.32	0.32
Dendermonde	20m	0.35	0.35	0.52	Pecrot	20m	0.19	0.19	0.19
Dendermonde	30m	0.87	0.98	1.00	Pecrot	30m	0.25	0.48	0.52
Dendermonde	40m	0.61	0.72	0.61	Pecrot	40m	0.83	0.80	0.62

Dendermonde	50m	0.83	0.87	0.78	Pecrot	50m	0.14	0.12	0.10
Dendermonde	60m	0.22	0.21	0.22	Pecrot	60m	0.30	0.50	0.33
Dendermonde	70m	0.29	0.32	0.28	Pecrot	70m	0.64	0.59	0.39
Dendermonde	80m	0.32	0.28	0.34	Pecrot	80m	0.39	0.44	0.28
Dendermonde	90m	0.38	0.37	0.40	Pecrot	90m	0.54	0.62	0.46
Dendermonde	100m	0.38	0.40	0.48	Pecrot	100m	0.54	0.44	0.32
Venray	-100m	0.41	0.42	0.37	Pecrot	-100m	0.75	0.80	0.50
Venray	-90m	0.38	0.39	0.39	Pecrot	-90m	0.77	0.93	0.97
Venray	-80m	0.35	0.35	0.35	Pecrot	-80m	0.42	0.49	0.37
Venray	-70m	0.43	0.36	0.44	Pecrot	-70m	0.29	0.36	0.39
Venray	-60m	0.37	0.39	0.37	Pecrot	-60m	0.31	0.33	0.35
Venray	-50m	0.37	0.40	0.42	Pecrot	-50m	0.41	0.41	0.41
Venray	-40m	0.32	0.38	0.52	Pecrot	-40m	0.13	0.09	0.15
Venray	-30m	0.37	0.40	0.53	Pecrot	-30m	0.20	0.13	0.13
Venray	-20m	0.43	0.36	0.56	Pecrot	-20m	0.20	0.22	0.38
Venray	-10m	0.45	0.52	0.62	Pecrot	-10m	0.29	0.40	0.38
Venray	-5m	0.47	0.42	0.54	Pecrot	-5m	0.29	0.36	0.33
Venray	5m	0.54	0.57	0.59	Pecrot	5m	0.35	0.36	0.35
Venray	10m	0.36	0.41	0.41	Pecrot	10m	0.42	0.44	0.36
Venray	20m	0.58	0.70	0.57	Pecrot	20m	0.33	0.36	0.38
Venray	30m	0.50	0.53	0.47	Pecrot	30m	0.36	0.36	0.40
Venray	40m	0.41	0.55	0.46	Pecrot	40m	0.65	0.49	0.44
Venray	50m	0.33	0.31	0.25	Pecrot	50m	0.40	0.40	0.42
Venray	60m	0.86	0.97	0.86	Pecrot	60m	0.03	0.06	0.02
Venray	70m	0.06	0.16	0.14	Pecrot	70m	0.08	0.07	0.06
Venray	80m	0.05	0.11	0.12	Pecrot	80m	0.08	0.05	0.05
Venray	90m	0.05	0.07	0.05	Pecrot	90m	0.08	0.08	0.12
Venray	100m	0.13	0.15	0.19	Pecrot	100m	0.12	0.13	0.10
Huldenberg	-100m	0.13	0.17	0.15	Zandhoven	-100m	0.04	0.04	0.04
Huldenberg	-90m	0.17	0.19	0.20	Zandhoven	-90m	0.01	0.01	0.01
Huldenberg	-80m	0.14	0.17	0.17	Zandhoven	-80m	0.05	0.05	0.05
Huldenberg	-70m	0.13	0.15	0.13	Zandhoven	-70m	0.03	0.02	0.02
Huldenberg	-60m	0.13	0.19	0.16	Zandhoven	-60m	0.07	0.06	0.06
Huldenberg	-50m	0.14	0.17	0.17	Zandhoven	-50m	0.20	0.13	0.12
Huldenberg	-40m	0.85	0.84	0.49	Zandhoven	-40m	0.30	0.46	0.52
Huldenberg	-30m	0.71	0.76	0.68	Zandhoven	-30m	0.27	0.31	0.43
Huldenberg	-20m	0.59	0.78	0.65	Zandhoven	-20m	0.41	0.45	0.45
Huldenberg	-10m	0.47	0.44	0.36	Zandhoven	-10m	0.24	0.19	0.20
Huldenberg	-5m	0.55	0.56	0.53	Zandhoven	-5m	0.26	0.30	0.34
Huldenberg	5m	0.79	0.83	0.74	Zandhoven	5m	0.39	0.36	0.36
Huldenberg	10m	0.79	0.83	0.74	Zandhoven	10m	0.36	0.34	0.21
Huldenberg	20m	0.85	0.75	0.71	Zandhoven	20m	0.34	0.36	0.36
Huldenberg	30m	0.49	0.46	0.40	Zandhoven	30m	0.45	0.38	0.34
Huldenberg	40m	0.76	0.87	0.75	Zandhoven	40m	0.42	0.63	0.66

Huldenberg	50m	0.66	0.51	0.51	Zandhoven	50m	0.22	0.34	0.41
Huldenberg	60m	0.48	0.53	0.60	Zandhoven	60m	0.42	0.43	0.40
Huldenberg	70m	0.57	0.60	0.58	Zandhoven	70m	0.42	0.43	0.40
Huldenberg	80m	0.27	0.29	0.35	Zandhoven	80m	0.32	0.29	0.31
Huldenberg	90m	0.39	0.39	0.39	Zandhoven	90m	0.40	0.34	0.34
Huldenberg	100m	0.42	0.45	0.42	Zandhoven	100m	0.30	0.34	0.33
Colonster	5m	0.46	0.47	0.41	Colonster	-100m	0.31	0.32	0.36
Colonster	10m	0.41	0.39	0.37	Colonster	-90m	0.51	0.36	0.38
Colonster	20m	0.54	0.75	0.58	Colonster	-80m	0.27	0.32	0.30
Colonster	30m	0.23	0.20	0.20	Colonster	-70m	0.31	0.33	0.34
Colonster	40m	0.26	0.32	0.32	Colonster	-60m	0.43	0.49	0.56
Colonster	50m	0.42	0.58	0.45	Colonster	-50m	0.17	0.20	0.28
Colonster	60m	0.18	0.16	0.15	Colonster	-40m	0.31	0.33	0.38
Colonster	70m	0.33	0.31	0.28	Colonster	-30m	0.31	0.33	0.38
Colonster	80m	0.30	0.25	0.29	Colonster	-20m	0.29	0.32	0.39
Colonster	90m	0.27	0.32	0.34	Colonster	-10m	0.40	0.36	0.29
Colonster	100m	0.17	0.28	0.29	Colonster	-5m	0.47	0.42	0.48

Table A2: Comparison of water depth and water width upstream between right stream, left stream and both streams together to analyse the difference between right en left stream at an upstream confluence. The measurements were converted to the proportional ratio in comparison to the water depth or water width at 100 m upstream so measurements over all dams were relative and comparison is possible.

Water depth												
		5m	**10m**	**20m**	**30m**	**40m**	**50m**	**60m**	**70m**	**80m**	**90m**	**100m**
Right stream	**Average**	1.50	1.31	1.17	1.01	1.18	1.08	1.11	1.09	1.11	1.11	1
	SD	0.86	0.63	0.44	0.24	0.57	0.19	0.52	0.35	0.31	0.38	0
Left stream	**Average**	1.52	1.32	1.20	1.02	1.16	1.08	1.10	1.06	1.09	1.10	1
	SD	0.88	0.64	0.54	0.32	0.59	0.21	0.53	0.38	0.27	0.38	0
Both streams	**Average**	1.51	1.30	1.23	1.06	1.16	1.06	1.08	1.03	1.10	1.10	1
	SD	0.79	0.58	0.49	0.32	0.54	0.20	0.47	0.34	0.29	0.34	0

Water width												
		5m	**10m**	**20m**	**30m**	**40m**	**50m**	**60m**	**70m**	**80m**	**90m**	**100m**
Right stream	**Average**	0.92	0.98	1.03	1.05	1.01	0.91	0.91	0.96	0.96	0.91	1
	SD	0.62	0.64	0.53	0.47	0.59	0.63	0.56	0.60	0.53	0.45	0
Left stream	**Average**	0.91	0.96	1.01	1.03	0.90	0.88	0.88	0.96	0.93	0.91	1
	SD	0.61	0.62	0.63	0.68	0.54	0.59	0.57	0.67	0.53	0.53	0
Both streams	**Average**	0.91	0.97	1.02	1.04	0.95	0.89	0.89	0.96	0.94	0.91	1
	SD	0.62	0.63	0.43	0.47	0.62	0.61	0.57	0.59	0.53	0.45	0

Table A3: Values of all environmental conditions at each dam site (first table) and each control site (second table). Water depth is the value at 10 m downstream of the dam or at the burrow at a control area. water width is the value at 10 m downstream of the dam or at the burrow. distance is from the dam or burrow until the nearest woody vegetation. stream velocity. average bank height is from 50 m upstream to 50 m downstream of the dam or burrow. average bank slope is from 50 m upstream to 50 m downstream of the dam or burrow. percentage of woody vegetation is calculated in a buffer of 15 m around the waterway from 50 m upstream to 50 m downstream of the dam.

Territory Dam area	Bank slope (rad)	Water width (cm)	Water depth (cm)	Stream velocity ($cm.s^{-1}$)	Distance (cm) to nearest vegetation	Bank height (cm)	Percentage of woody vegetation
Bocholt	0.69	260	6	0.18	100	143.54	51
Bree 1	0.67	400	14	0.18	500	169.21	79
Bree 2	0.63	400	20	0.18	200	190.58	35
Dilsen	0.75	530	24	0.17	200	178.21	40
Kinrooi	0.79	180	25	0.04	0	99.63	47
Liènne	0.56	450	36	0.00	0	96.88	NA
Lummen	1.06	360	40	0.07	0	152.50	68
Dendermonde	0.57	328	45	0.12	100	120.75	76
Venray	0.34	260	57	0.09	100	128.08	NA
Huldenberg 1	0.72	760	65	0.07	1000	159.38	41
Pecrot	0.74	120	15	0.00	500	185.08	69
Zandhoven	0.56	500	11	0.02	300	175.00	42
Holsbeek1	0.80	170	17	0.09	100	131.36	72
Holsbeek2	0.82	245	34	0.09	100	139.59	70
Colonster	0.54	250	51	0.00	0	100.14	NA
Huldenberg 2	0.77	215	27	0.10	600	182.00	30
Erps-Kwerps	0.67	400	11	0.00	100	144.77	44
Bonheiden	0.73	300	48	0.00	4000	218.46	22

Territory Control area	Bank slope (rad)	Water width (cm)	Water depth (cm)	Stream velocity ($cm.s^{-1}$)	Distance (cm) to nearest vegetation	Bank height (cm)	Percentage of woody vegetation
Bassenge 1	0.60	910	144	0.24	500	260.80	53
Huldenberg 1	0.66	1125	155	0.65	1500	295.57	58
Huldenberg 2	0.46	1250	160	0.35	2000	276.14	61
Oud-Heverlee	0.55	1840	155	0.50	500	301.25	44
Bassenge 2	0.52	850	146	0.38	200	370.27	48
Tongeren 1	0.58	600	137	0.25	1000	230.18	40
Tongeren 2	0.62	1110	82	0.24	500	254.95	65
Kinrooi	0.74	450	50	0.13	50000	114.00	72
Dendermonde	0.89	820	155	0.00	125000	203.45	66
Voeren	0.37	590	111	0.83	2500	159.23	18
Bassenge 3	0.71	640	186	0.53	500	388.18	57
Zemst	NA	866	152	0.70	800	NA	58
Bierbeek	0.81	270	95	0.11	30000	148.64	78

Table A4: Comparison of distance to upstream and downstream confluence (m).

Dam	Distance to upstream confluence (m)	Distance to downstream confluence (m)
Bocholt	40	345
Colonster 2	20	750
Holsbeek 1	80	315
Holsbeek 2	40	355
Holsbeek 3	80	435
Holsbeek 4	5	635
Holsbeek 5	30	640
Kinrooi	40	655
Bonheiden	30	640
Zanhoven 1	10	325

Table A5: Data for the analysis of bank height and slope effect on the distance from the dam (Distance A).

Location	Distance	Height	Slope	Location	Distance	Height	Slope
Bocholt	E	1.00	0.76	Dendermonde	E	1.00	0.60
Bocholt	D	0.94	0.74	Dendermonde	D	1.03	0.32
Bocholt	A	0.83	0.63	Dendermonde	A	0.86	0.44
Bocholt	C	0.40	0.70	Dendermonde	C	0.75	0.54
Bocholt	B	0.65	0.55	Dendermonde	B	1.32	0.64
Bree 1	E	1.00	0.74	Venray	E	1.00	0.49
Bree 1	D	1.02	0.68	Venray	D	1.03	0.47
Bree 1	A	0.87	0.67	Venray	A	0.95	0.46
Bree 1	C	0.90	0.69	Venray	C	0.71	0.67
Bree 1	B	0.98	0.67	Venray	B	0.77	0.62
Bree 2	E	1.00	0.61	Huldenberg 1	E	1.00	0.60
Bree 2	D	0.98	0.55	Huldenberg 1	D	0.89	0.55
Bree 2	A	0.88	0.63	Huldenberg 1	A	0.75	0.69
Bree 2	C	1.09	0.59	Huldenberg 1	C	0.54	NA
Bree 2	B	0.90	0.57	Huldenberg 1	B	0.38	NA
Dilsen	E	1.00	0.64	Colonster	E	1.00	0.54
Dilsen	D	1.01	0.64	Colonster	D	1.23	0.31
Dilsen	A	1.07	0.67	Colonster	A	0.93	0.47
Dilsen	C	1.19	0.68	Colonster	C	1.01	0.50
Dilsen	B	1.24	0.72	Colonster	B	1.53	0.64
ErpsKwerps	E	NA	NA	Pecrot	E	1.00	0.81
ErpsKwerps	D	1.00	0.69	Pecrot	D	1.04	0.82
ErpsKwerps	A	1.21	0.58	Pecrot	A	1.07	0.77
ErpsKwerps	C	1.10	0.53	Pecrot	C	1.07	0.90
ErpsKwerps	B	1.16	0.59	Pecrot	B	0.93	0.86
Kinrooi	E	1.00	0.55	Zandhoven	E	1.00	0.45
Kinrooi	D	0.74	0.36	Zandhoven	D	1.21	0.50
Kinrooi	A	0.91	0.46	Zandhoven	A	1.37	0.69
Kinrooi	C	0.91	0.46	Zandhoven	C	1.13	0.40
Kinrooi	B	1.06	0.40	Zandhoven	B	1.10	0.47
Lienne	E	1.00	0.25	Holsbeek 1	E	1.00	0.84
Lienne	D	0.91	0.18	Holbeek 1	D	1.09	0.81
Lienne	A	0.72	0.29	Holsbeek 1	A	0.99	0.72
Lienne	C	0.83	0.36	Holsbeek 1	C	1.01	0.64
Lienne	B	0.94	0.38	Holsbeek 1	B	1.29	0.66
Lummen	E	1.00	0.84	Holsbeek 2	E	1.00	0.84
Lummen	D	1.01	0.95	Holsbeek 2	D	1.09	0.81
Lummen	A	1.04	0.86	Holsbeek 2	A	1.04	0.75
Lummen	C	1.16	0.83	Holsbeek 2	C	1.07	0.62
Lummen	B	1.23	0.89	Holsbeek 2	B	1.04	0.64
Bonheiden	E	1.00	0.63	Huldenberg 2	E	1.00	0.70
Bonheiden	D	0.94	0.56	Huldenberg 2	D	1.01	0.75
Bonheiden	A	1.21	0.64	Huldenberg 2	A	0.96	0.75
Bonheiden	C	1.13	0.67	Huldenberg 2	C	0.86	0.57
Bonheiden	B	1.03	0.74	Huldenberg 2	B	0.91	0.62

Table A6: Average water depth over all dams at each distance to the dam or burrow/lodge. The measurements were converted to the proportional ratio in comparison to the water depth at 100 m downstream so measurements over all dams are relative and comparison is possible or at 50m downstream of the burrow/ lodge so measurements over all control areas are relative and comparison is possible.

Dam area

	-100 m	-90m	-80m	-70m	-60m	-50m	-40m	-30m	-20m	-10m	-5 m
Average	2.72	2.79	2.67	2.65	2.65	2.78	2.94	2.80	2.91	3.24	3.00
Standard Deviation	1.80	1.96	1.69	1.92	1.73	1.90	1.85	1.95	1.86	2.15	1.96

	5 m	10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m
Average	2.14	1.33	1.60	1.39	1.17	1.10	1.24	1.06	1.14	1.24	1.00
Standard Deviation	2.11	1.15	1.69	1.48	0.58	0.65	0.75	0.52	0.88	1.42	0.00

Control area

	-50m	-40m	-30m	-20m	-10m	0 m	10 m	20 m	30 m	40 m	50 m
Average	1.14	1.01	1.15	1.19	1.18	1.37	1.24	1.19	1.11	1.01	1.00
Standard deviation	0.64	0.57	0.62	0.54	0.60	0.72	0.49	0.62	0.58	0.37	0.00

Table A7: Average water width over all dams at each distance to the dam or burrow/lodge. The measurements were converted to the proportional ratio in comparison to the water width at 100 m downstream of the dam so measurements over all dams are relative and comparison is possible or at 50m downstream of the burrow/ lodge so measurements over all control areas are relative and comparison is possible.

Dam area

	-100 m	-90m	-80m	-70m	-60m	-50m	-40m	-30m	-20m	-10m	-5 m
Average	1.72	1.61	1.85	1.85	1.84	1.96	1.89	2.11	1.94	1.99	1.91
Standard deviation	0.65	0.60	0.67	0.78	0.76	0.86	0.89	1.01	0.74	0.79	0.80

	5 m	10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100m
Average	1.46	1.37	1.23	1.34	1.28	1.19	1.26	1.28	1.33	1.26	1.00
Standard deviation	0.64	0.57	0.35	0.63	0.52	0.44	0.54	0.44	0.50	0.43	0.00

Control area

	-50m	-40m	-30m	-20m	-10m	0 m	10 m	20 m	30 m	40 m	50 m
Average	0.91	0.90	0.89	0.97	1.04	0.94	1.01	0.92	0.97	1.03	1.00
Standard deviation	0.23	0.22	0.19	0.34	0.30	0.13	0.24	0.25	0.24	0.21	0.00

Table A8: Height difference of water level at each dam.

Dam	Height difference (cm)
Bocholt	79,50
Bree 1	36,50
Bree 2	36,00
Dilsen	15,00
Kinrooi	49,50
Liènne	31,00
Lummen	33,00
Dendermonde	57,50
Venray	86,67
Huldenberg	48,50
Average	47,32
Standard deviation	22,25

Table A9: Lowest bank height (cm) at each dam site.

Dam	Lowest bank height (cm)	Dam	Lowest bank height (cm)
Bocholt	5	Pécrot 2	46
Bree 1	38	Pécrot 3	24
Bree 2	49	Pécrot 4	71
Colonstèr 1	1	Bonheiden	16
Colonstèr 2	2	Dendermonde	0
Dilsen	71	Venray	26
Erps-Kwerps	5	Zandhoven 1	96
Holsbeek 1	42	Zandhoven 2	6
Holsbeek 2	28	Zandhoven 3	18
Holsbeek 3	5	Zandhoven 4	3
Holsbeek 4	15	Zandhoven 5	3
Holsbeek 5	15	Huldenberg 1	43
Kinrooi	-29	Huldenberg 2	67
Liènne	-21	Huldenberg 3	68
Lummen	21		
Average	25,31		
Standard deviation	29,48		

Table A10: Average sediment depths over all dams at each distance to the dam. The measurements were calculated as the proportional ratio in comparison to the water width at 100 m downstream of the dam so measurements over all dams are relative and comparison is possible.

	-100m	**-90m**	**-80m**	**-70m**	**-60m**	**-50m**	**-40m**	**-30m**	**-20m**	**-10m**	**-5m**
Average	4,88	3,54	2,35	4,82	3,8	4,21	3,74	2,43	1,49	2,28	1,81
Standard deviation	1,68	0,98	1,43	2	0,92	2,23	1,21	1,41	0,96	1,43	0,71

	5m	**10m**	**20m**	**30m**	**40m**	**50m**	**60m**	**70m**	**80m**	**90m**	**100m**
Average	1,52	1,59	1,63	1,6	2,54	1,32	1,23	1,61	0,84	1,33	1
Standard deviation	0,66	0,63	0,58	0,86	1,12	0,41	0,35	0,7	0,32	0,4	0