The engineering in beaver dams

G. Müller & J. Watling
University of Southampton, Southampton, UK

ABSTRACT: Before their near extinction, beavers populated the smaller rivers in Eurasia and North America. Beavers are called '*ecosystem engineers'*, since their dam building activities dramatically change the character of river (flow characteristics, groundwater and morphology), river habitats and ecosystems. The largest dam currently in existence has a length of 850 m, raising the question of the engineering required for such large structures. A research programme was initiated at Southampton University to assess the engineering importance, and characteristics of beaver dams. It was found that the dams are built in rivers of up to 45 m width. They modify the flow duration curves, increasing ground water retention, reducing the gradient and sediment transport, trapping sediment and improving ecosystems. Model tests were conducted to investigate the strength and permeability of beaver dams. It was found that beavers employ interesting construction techniques, creating semi-permeable dams able to withstand flow volumes of up to 1.34 m^3/s per meter width for a 1.4 m high dam. Beaver dam technology may allow to create novel, nature based solutions for ecosystem redevelopment and river renaturalisation.

1 INTRODUCTION

1.1 *General characteristics of beaver dams*

With a length of up to 1.2 m, and weights from 22 to 30 kg the beaver is the second largest rodent in the world. Only the South American Capybara (*Hydrochoerus hydrochaeris*), with weights of 35 to 66 kg, is larger. There are two subspecies, the Eurasian Beaver (*Castor fiber*) and the American beaver (*Castor canadensis*) which are however very similar in appearance. Beavers lead a semi-aquatic lifestyle, and build dams in creeks and smaller rivers in order to create a habitat for themselves. These dams can be impressive structures. Fig. 1 shows a 2.5 m high dam in Kanton Zurich, Switzerland.

The Eurasian beavers inhabited rivers from Portugal to Kamchatka, and from Norway to Syria and Northern Iran. They were however hunted to near extinction already in the 16th century, and only small, local populations survived in a few remote areas. In Europe, there is little or no collective memory of what beaver engineered riverscapes look like. Reintroduction programmes in several European Countries were initiated in the 1920s, and by now there are growing populations in Sweden, Germany, Austria etc. In North America, beavers were also near extinct in the 1930s. Again, protection measures helped to redevelop populations

Fig. 1: Beaver dam in Switzerland (with permission)

The construction activities of beavers modify river valleys and their ecosystems to an extent that completely new habitats are created. Beavers are therefore termed '*ecosystem engineers'*. They are also considered a '*keystone species*', since their existence has a disproportionately large influence on the ecosystem they inhabit. Beavers have lived in our river systems for 24 million years, so that the river environments, ecosystems and species evolved and developed within their engineered landscape, Rybczynski (2007).

The scientific literature about beaver dams comprises several hundred articles and books see e.g. the overview in Burchstedt (2013). It is however practically exclusively written by biologists and geo-ecologists. Despite the apparent technical aspects, such as the dam's strength, the importance of beaver dams e.g. in the context of river hydraulics, morphodynamics and management, or the question of what a natural river actually looks like, only one paper has to the authors' knowledge so far been published on their engineering aspects, Müller (2014). Details of engineering relevance are only sporadically mentioned in the literature. A research programme was therefore initiated at the University of Southampton to assess the engineering aspects of beaver dams and their effects on river hydraulics. The first step was a literature review to find quantifiable information such as the main dimensions and boundary conditions. From the literature, they could be determined as follows:

1. Length: 1 to 850 m, Geostrategies (2007)
2. Head difference or height: 0.3 to 5 m; most dams are however below 1.5 m high.
3. Width of river: up to 46 m, Pollock et al. (2003), the majority of dams is however located in 4th order streams with widths of 10 m or less, Naiman et al. (1988).
4. Gradient: most dams are built in streams with gradients of 0.06 or less. Dams are also reported in steeper streams with gradients of up to up to 0.12, e.g. Retzer et al. (1956).

Information about the flow volume of the rivers with beaver dams is unfortunately usually not mentioned. From the descriptions, it can be estimated that beaver dams are built in streams even with very low average flow volumes of 0.01 m^3/s. There is no information available about the upper limit of average flows. A width of 45 m suggests flow volumes of 10 to 15 m^3/s. Here it should however be noted, that the presence of beavers and beaver ponds has a strong influence on average and minimum flows due to their effect on ground water recharge and water retention. In particular low flow volumes increase when beaver dams are present.

In North America it is estimated that before the settlement by humans, approximately 25 million beaver dams existed, i.e. 1.5 dams per square kilometer, Pollock et al. (2003). In Europe, a similar density could be expected. The number of dams per km river length is a function of the gradient and estimated as 2.5 to 10 per km. It appears that in a natural river landscape, beaver dams exist in virtually all smaller rivers.

1.2 *Hydraulic effects*

Beaver dams modify the hydraulics and hydromorphology of rivers:

1. Pond formation: the rivers are changed into a succession of river channels, beaver ponds and wetlands. The pond area here can range from several dozen square meters to several hectares.
2. Ground water level: The rise in water level caused by the beaver dam generates a local increase of the ground water level. The increased wetted area leads to an increase in ground water recharge. This again causes changes of the vegetation, as well as a retention of water and a dampening of seasonal flow variations.
3. Flow: in particular in arid zones, it was observed that after the introduction of beavers, streams which were seasonal and ran dry during the summer became perennial, e.g. Naiman et al. (1988).
4. Retention: beaver ponds and wetlands retain water, and can therefore reduce the peak flow during flood events.
5. Erosion and incision: the dams reduce the effective gradient of rivers, and thereby their dynamics and erosive tendencies. In rivers where beaver dams were removed, incision began, leading to a lowering of the river bed and ground water level, e.g. Pollock et al. (2014).

1.3 *Morphological effects*

Beaver dams slow down flow velocities in rivers and thereby lead to the deposition in particular of fine sediment. The low depths of the beaver ponds combined with the removal of trees by the beavers lead to the production of significant amounts of biomass, which again is also deposited in the ponds. Dams are subsequently increased in height to maintain water depth in the ponds, so that the length of dams increases with time. Geologists have argued that beaver dams permanently formed river valleys, Ruedemann and Schoonmaker (1938). Studies showed that depth erosion and incision of small streams in North America only began after settlement of the land by Europeans, and after the disappearance of beavers, Mackie (1997).

1.4 *Ecological effects*

As ecosystem engineers, beavers modify the environment substantially. Habitats within the areas of the ponds, in the wetlands created by the increasing ground water level and further away are changed. The habitats around beaver ponds and wetlands differ substantially from those near rivers without beaver dams, Collen and Gibson (2001). The number of species and individuals in beaver engineered rivers is significantly larger than in those without beaver activities. In particular amphibious species find habitats which would otherwise not exist on fast flowing rivers, Dalbeck and Weinberg (2009).

1.5 *Longevity and dam failure*

The longevity of beaver dams ranges from several months to several decades. Recent comparison of historic records, and the present situation in the Great Lakes Region (USA) showed that some dams can last 150 years, Johnston (2015). There appear however to be intermediate periods of abandonment and decay of the dams, probably caused by the deterioration of the food supply. The temporal dynamics of beaver dams and their effects on river hydraulics and ecosystem seem to be another interesting topic in the assessment of natural rivers. Although failures of beaver dams occur frequently, more detailed information about the conditions leading to failure are rare. Westbrook e al. (2006) report the failure (breaching) of an 8 m long, 0.8 m high dam ("upper dam") made of alder and willow stems during a flow of 8 m^3/s. Levine and Meyers (2014) described the failure of a 9.7 m wide wooden a dam in Odell Creek, Montana under a flow of 7 m^3/s. This failure was however initiated by bank erosion rather than breaching of the dam itself. The reported failures indicate a failure flow of 0.7 to 1 m^3/s and meter dam width. Older dams appear to have a higher failure flow than new dams.

2 DAM STRUCTURE AND PERFORMANCE

2.1 *Wooden dams*

Most beaver dams are built from wooden sticks, with stones at the base. The cross section is triangular, with an average width-to-height ratio of 2.9, Watling (2015). The dams have a shallow upstream, and a steep downstream slope with a sealing layer made of mud and leaves on the upstream side. A gap is usually left in the sealing layer to allow the water to flow through the dam.

2.2 *Stone dams*

When wood is not in sufficient supply, beaver dams are also built from stones with diameters of up to 300 mm, combined with some wood, e.g. Jung and Staniforth (2010). The beavers employ a construction technique where stones and branches are stacked in layers. The addition of wooden branches in the rubble dam provides tensile strength, and thereby increases the stability of these structures considerably. The beaver's construction method is very similar to a widespread civil engineering construction technique called 'reinforced earth' or 'mechanically stabilized earth'. This technique is employed to create very steep embankments e.g. for roads or bridge abutments, with angles of up to 80 degrees, using alternating layers of sand and mesh reinforcement.

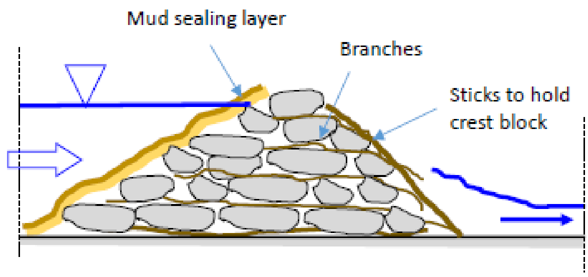


Fig. 2: Stone dam with wooden reinforcement and props

In stone beaver dams, additional branches are added on the downstream side to keep the crown layer of stones in position when the dam is overflown, Fig. 3.

2.3 *Conclusions*

The construction techniques of beaver dams are interesting in their own right. They do also open up the possibility of thinking about nature-based solutions for small dam structures e.g. to create sustainable water supplies in seasonal streams in arid regions, to reduce flood peaks, erosion and incision and to provide the basis for ecosystem recovery. These solutions would be cheap, since they are non-permanent structures the planning permission effort would be reduced, and public acceptance increased. In addition, these solutions would gradually merge into the natural environment, eventually becoming part of it. A better knowledge of construction techniques and performance seems therefore interesting.

3 EXPERIMENTAL WORK

3.1 *Overview*

Very little is known about the engineering aspects of beaver dams. For the assessment of the dams it would however be useful to have an idea about e.g. the permeability of a dam, or its stability as a function of the flow volume. Two series of experiments were conducted at Southampton University.

3.2 *Wood dams*

The aim of the first set of tests was, to determine the permeability of typical wooden dam structures. Tests took place in a trapezoidal channel of 2.5 m width, 0.5 m depth and 50 m length, Fig. 3. The dam had a height of 0.45 m. the water depths upstream varied from 0.29 to 0.42 m, with head differences between 0.12 and 0.19m. A sealing layer made from clay was attached to the upstream side, leaving only a small gap to let the flow of 0.031 to 0.129 m^3/s pass through.

Fig 3: 0.45 m high wooden dam

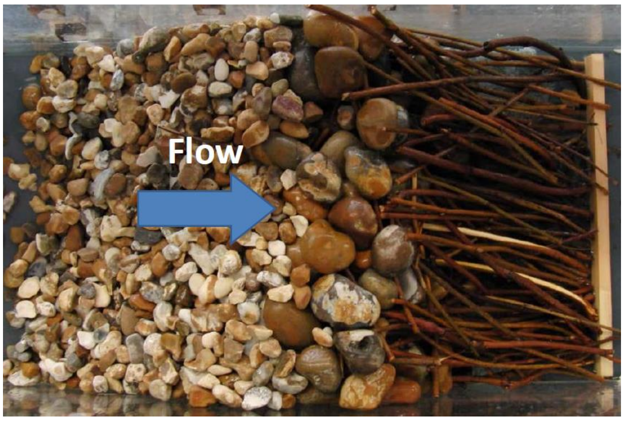
The flow volume was measured as a function of the head difference. It was found that the dam can best be described as a linear or *Darcy* filter, with a filter coefficient of k_f = 0.67 m/s, Duckett (2013). The filter coefficient allows to estimate the flow velocities inside of a beaver dam. Assuming a typical head difference of 1 m, and a width of 3 m, the flow velocity inside the dam becomes 0.2 m/s. These low velocities may allow small aquatic organisms or juvenile fish to pass upstream through the dam.

3.3 *Stone and stick dams*

A second series of tests was conducted in the University of Southampton's Hydraulics Laboratory using a smaller flume of 0.30 m width, 0.40 m depth and 12 m length. The aim of this set of tests was to assess the stability of rock-and-branches dams, Fig. 4. The dams had a height of 200 mm

With a scale of approximately 1:7, this corresponds to a typical dam height of 1.44 m. As construction material, pebbles with a diameter of D_{50} = 30 mm were chosen to model the rounded stones available in rivers. The dams had an upstream sealing layer made from plastic foil so simulate the characteristics of a beaver dam. A benchmark test was conducted with a dam built from stones only. It failed for flow rates of 0.06 m^3/s and meter width (full scale).

a. Dam with internal reinforcement and crown support



b. Plan view with sediment deposition upstream

Fig. 3: Rock-and-branches dam

The insertion of branches as internal reinforcement increased the failure flow to 0.53 $m^3/s \cdot m$, whilst the addition of props gave a further increase to 0.88 $m^3/s \cdot m$.

In real dams, sediment is deposited upstream. The inclusion of a sediment wedge resulted in an even higher failure flow of 1.34 $m^3/s \cdot m$. This is quite an impressive performance for a very simple structure, and implies that beaver dams could have been constructed in a large number of rivers..

Observations showed that the props kept the uppermost stone layer in position when the dam was overflown. The rock dam's design was very interesting, and may actually be useful for the ecologically compatible construction of small retention dams.

4 DISCUSSION

4.1 *Beaver dams in natural rivers*

Before human intervention, most smaller rivers in Eurasia and North America with widths of up to 45 m, and gradients below 0.06, were modified by beavers. This had a profound effect on hydraulics, the morphology and the ecosystems of rivers. The ecosystems evolved round the river-and-pond system created by beavers. Sediment accumulation in the ponds formed the river valleys. The dynamics of beaver dams, with dams being destroyed or abandoned means that the riverscape was subject to continuous change. The erosion and incision observed on many small streams in particular in arid environments, where steams are seasonal, was prevented by the dam building activities. It appears that a natural river system includes, and is transformed by, the effects of beaver construction. This also means that larger beaver dams form barriers for fish migration. Natural rivers were therefore probably not continuous for all aquatic animals.

4.2 *Upstream fish passage*

Beaver dams with heights of 1 m or more effectively block the upstream passage of fish during average flow conditions. Upstream passage is only possible during high flow situations, where the dam is over-flown or after failure of the dam. Mitchell and Cunjak (2007) considered a 2.5 m high, 30 m long beaver dam in Alaska as the end point of salmon migration. Bryant (1983) reported that juvenile salmon were found upstream of a 2.1 m high beaver dam, indicating that Salmon can pass over beaver dams in certain flow conditions. Recent work on beaver dams in Scotland indicates that beaver dams and ponds actually benefit the fish population, Kemp et al. (2012). It must be considered that beavers and their dams have existed in rivers for more than 15 Million years, and that the river ecosystems and species evolved around them.

4.3 *River renaturalisation*

In the context of river re-naturalization, these aspects are now being recognized in the US, see. e.g. Burchstedt (2013). It is often suggested to use beavers as agents for the re-naturalisation of rivers. Near human settlements or infrastructure, beaver activities and their consequences can however have detrimental effects such as dam construction in irrigation or drainage canals, flooding of fields and roads and the potential danger created by dam failures. In addition, beavers cannot settle if e.g. the ecosystem is degraded to an extent that not enough food and water is available. Artificial beaver dams (AFDs) were therefore tested by Oregon State University in order to restore a deeply incised seasonal stream, where the ecosystem was continuously degrading, Nash (2015). The dams employed here were simple stone and earth barrages. Nevertheless, the effects of small dams were profound. The stream changed from ephemeral to perennial flow, water retention increased, erosion reduced and the vegetation cover re-established itself and increased. The study demonstrated the potential value of nature-based solutions in river management.

4.4 *Evolution of river and ecosystems*

The role of beaver dams in the evolution of river valleys and ecosystems has been discussed in the scientific community since Ruedemann and Schoonmaker's 1938 paper. The most recent consensus appears to be, that the role of beavers in the formation of river valleys is significant and stronger than assumed as yet. This debate, and the extent of beaver populations and their effects on natural river systems not affected by human intervention has however not yet found a mirror in the river engineering community. On the contrary, it has been ignored and the "natural state" of a river as defined e.g. in the European Water Framework Directive does not even mention beaver dams. This has very significant consequences, since the actual development strategies and implementation measures as discussed in the following section.

4.5 *The European Water Framework Directive*

The European Water Framework Directive (WFD) is a guidance document for the assessment and development of all water bodies (rivers, lakes, groundwater, coastal waters). The ideal development aim hereby is a 'good ecological status', which is defined as the state of the water body without human intervention. In rivers, one of the main demands is that for continuity: "*The best approximation to ecological continuum therefore requires consideration of all hydromorphological mitigation measures that could reduce any obstacles to migration and improve the quality, quantity and range of habitats affected by the physical alterations. This could include connectivity to groundwater and to riparian, shore and intertidal zones. However, the WFD emphasises migration in particular. Priority should therefore be given to reducing any obstacles that significantly inhibit longitudinal and lateral migration of biota*.", CISWFD (2003). Unfortunately, beaver dams as integral components of a natural river systems within the constraints mentioned in section 2, are not even mentioned in the WFD. The possibility of biologically created alterations of the river, which affect continuity for organisms and sediment profoundly, is therefore not part of the perceived 'natural state' of a river. Beaver dams also affect water retention, morphodynamics and river valley formation. This opens up an important question, namely does the WFD's demand for complete longitudinal continuity and its consequences, such as removal of weirs, really lead to more natural rivers? Or is a new definition of the 'natural state' of rivers required?

4.6 *Nature based solutions for stream restoration and hydro-meteorological risk reduction*

The construction methods employed by beavers may allow to develop simple, nature based solutions for small dams in the upper reaches of small streams. In many semi-arid regions such as the Mediterranean regions, the ecosystems around such streams are degraded to such an extent that they cannot recover even if left alone. This is mainly caused by the lack of water supply. Rain water runs off directly, eroding the streams in the process. Flood peaks tend to be very high since there is only little retention. The construction of dams based on beaver technology would mean that a nature based solution could be developed. The experiments conducted so far have given the initial information regarding construction technique, and failure loads. Small dams would be cheap and easy to construct. The materials used are local. The ponds serve to recharge the groundwater, provide a sustainable water supply, and to provide retention zones to reduce flood peaks.

4.7 *Outlook*

The knowledge about the beaver dam's engineering characteristics is still very limited. Their effects on sediment transport and river valley formation requires further work. The stability and construction methods employed, and the ecological characteristics such as the passability for aquatic organisms need to be investigated. In order to create a development framework for small rivers, a new definition of what constitutes a natural river, including beaver dams, has to be found. It has already been discussed that the interests of beavers and humans are not necessarily compatible. Technical solutions – i.e. artificial beaver dams with characteristics similar to actual dams (height, length, permeability) - need to be developed. River renaturalisation concepts which include the effects of beaver dams, and possibly even taking their temporal dynamics into account could be envisaged. Finally, the possibilities and potential of nature based solutions for ecosystem redevelopment could be explored.

5 CONCLUSIONS

The engineering characteristics of beaver dams were investigated using a literature study, and hydraulic model tests. The following conclusions were drawn:

- With lengths of up to 850 m, beaver dams resemble engineered structures.
- Dam heights can reach 5.3 m, although heights of up to 1.5 m are typical.
- Their effect on river hydraulics, sediment transport, ground water retention and flood peak reduction is profound.
- Stone dams employ a reinforced earth construction technology which results in significantly enhanced strength.
- Failure flows were determined as 0.8 m^3/s per meter width for a 1.4 m high dam without sediment deposition (i.e. just after construction).
- Failure flows for dams with upstream sediment deposition reached 1.34 m^3/s and meter width.
- The construction methods employed by beavers may provide a basis for nature-based solutions for river restoration, water retention and flood peak reduction.
- The role of beaver dams as integral components of natural rivers needs further discussion.

REFERENCES

Bryant, M. D. 1983. The role of beaver dams as coho salmon habitat in southeast Alaska streams. Pages 183–192 in J. M. Walton and D. B. Houston, editors. *Proceedings of the Olympic Wild Fish Conference*. Olympic Wild Fish Conference, Port Angeles, Washington.

Burchsted, D. 2013. The Geomorphic and Hydrologic Impact of Beaver Dams on Headwater Streams in Northeastern Connecticut and Implications for River Restoration.

CISWFD. 2003: COMMON IMPLEMENTATION STRAT EGY FOR THE WATER FRAMEWORK DIRECTIVE (2000/60/EC) Guidance Document No 4. Identification and Designation of Heavily Modified and Artificial Water Bodies Produced by Working Group 2.2 – HMWB (https://circabc.europa.eu/sd/a/f9b057f4-4a91-46a3-b69a-e23b4cada8ef/Guidance%20No%204%20-%20heavily%20modified%20water%20bodies%20-%20HMWB%20(WG%202.2).pdf, accessed 03.12.2015)

Collen, P., & Gibson, R. J. 2000. The general ecology of beavers (Castor spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish–a review. *Reviews in fish biology and fisheries*, *10*(4), 439-461.

Dalbeck, L., & Weinberg, K. 2009. Artificial ponds: a substitute for natural Beaver ponds in a Central European Highland (Eifel, Germany)?. *Hydrobiologia*, *630* (1), 49-62.

Duckett M. (2013.) *Engineering aspects of beaver dams*. Individual project report. University of Southampton. Faculty of Engineering and the Environment.

Geostrategies.2007. http://www.geostrategis.com/p_beavers-longestdam.htm (accessed 31.08.2015)

Johnston, C. A., & Windels, S. K. 2015. Using beaver works to estimate colony activity in boreal landscapes. *The Journal of Wildlife Management*, 79 (7), 1072-1080.

Jung, T. S., & Staniforth, J. A. 2010. Unusual Beaver, Castor canadensis, Dams in Central Yukon. *The Canadian Field-Naturalist*, *124* (3), 274-275.

Kemp, P. S., Worthington, T. A., Langford, T. E., Tree, A. R., & Gaywood, M. J. 2012. Qualitative and quantitative effects of reintroduced beavers on stream fish. *Fish and Fisheries*, 13(2), 158-181.

Levine, R., & Meyer, G. A. 2014. Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA. *Geomorphology*,*205*, 51-64.

Mackie, R. S. (2011). *Trading Beyond the Mountains: the British fur trade on the Pacific, 1793-1843*. UBC Press.

Mitchell S.C. und Cunjak R.A., 2007: Stream flow, salmon and beaver dams: roles in the structuring of stream fish communities within an anadromous salmon dominated stream. Journ. Animmal Ecology, Vol. 76, p 1062-1074.

Müller G. Ingenieurtechnische Aspekte der Biberdaemme (Engineering aspects of beaver dams, in German). KW Korrespondenz Wasserwirtschaft. 7, Nr.3, 2014,158-163.

Naiman, R. J., Johnston, C. A., & Kelley, J. C. (1988). Alteration of North American streams by beaver. BioScience, 753-762.

Nash, C. (2015, August). Impacts of Artificial Beaver Dams (ABDs) on Degraded Wet Meadow Habitat, Silvies Basin, Oregon. In *145th Annual Meeting of the American Fisheries Society*. Afs.

Pollock M.M., Heim M. und Werner D. 2003, Hydrological and geomorphic effects of beaver dams and their influence on fishes. Pages 213- 233 in S.V. Gregory, K. Boyer, and A. Gurnell, editors. *The ecology and management of wood in world rivers*. American Fisheries Society Symposium 37. Bethesda, Maryland, 2003.

Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., & Volk, C. 2014. Using beaver dams to restore incised stream ecosystems. *BioScience*, 64 (4), 279-290.

Retzer J. L., H. Swope M., Remington J. D., and Rutherford W. H.: *Suitability of physical factors for beaver management in* *the Rocky Mountains of Colorado*. *State of Colorado, Department of Game and Fish Technical Bulletin No. 2*, Denver, 1956.

Ruedemann, R., & Schoonmaker, W. J. 1938. Beaver-dams as geologic agents. *Science*, 88 (2292), 523-525.

Rybczynski, N. 2007. Castorid phylogenetics: implications for the evolution of swimming and tree-exploitation in beavers. *Journal of Mammalian Evolution*,*14* (1), 1-35.

Watling J. 2014. *The structural and strength characteristics of beaver dams and their potential application as bio-dams for river restoration projects*. Individual project report. University of Southampton. Faculty of Engineering and the Environment.

Westbrook, C. J., Cooper, D. J., & Baker, B. W. 2006. Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area. *Water Resources Research*, *42*(6).