CHAPTER 3:
Ecosystem Services

Flooding in the lower River Otter Valley

Photo: David White

→ Where the river flows across the lower floodplain, the sandy nature of the soils and floodplain deposits makes the planform very mobile, with channel meanders, oxbow lakes and channel cut offs, where the river is allowed to flow overbank.

Character of the River Otter hydrology

The Blackdown Hills are the highest elevation in the River Otter catchment and its principal source. Numerous headwater springs feed into the River Otter and associated tributaries including the Gissage, River Wolf, Vine Water and the River Tale. The lower half of the Otter catchment is underlain by a major sandstone aquifer comprising the Otter Sandstone and the underlying Budleigh Salterton Pebble Beds. Both of these strata yield significant quantities of groundwater, which provide the strategic fresh water supply for local communities and are the major component of the flow regime of the River Otter and associated tributaries during dry periods. Hydrological and hydrogeological processes in the catchment are known to be complex.

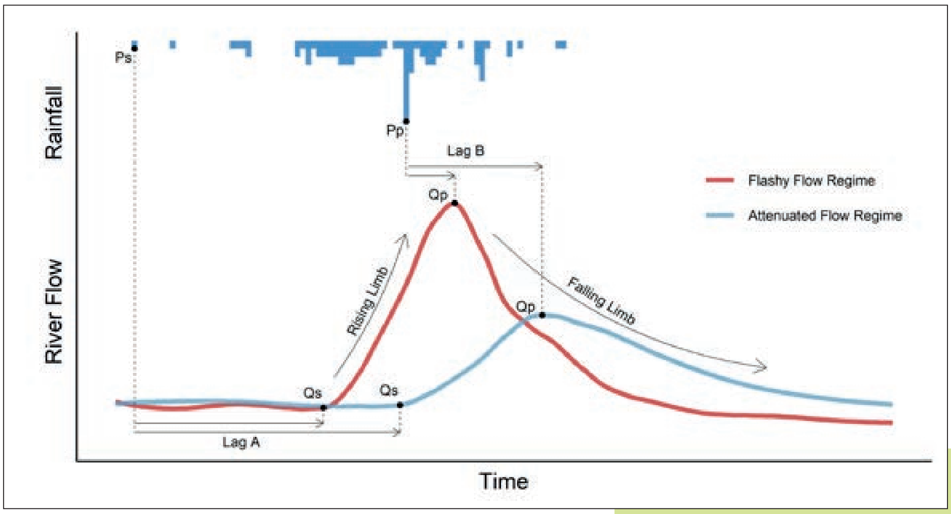
↓ The geology of the River Otter provides important baseflows from groundwater and also makes it a very spatey or flashy catchment, which reacts quickly to heavy rainfall in the Blackdown hills.

There is a large difference between the maximum daily mean flow recorded at Dotton, and the maximum instantaneous flow. The flow record at Dotton gauging station on the River Otter for the period 1963 – 2018 shows a mean daily flow of 3.22 m^3s^{-1} and a measured Q95 (the flow exceeded for 95% of the time, on average) of 0.97 m^3s^{-1}. The Q95 represents 30% of the mean daily flow. This is a relatively high percentage and reflects the strong groundwater influence of this river system. Surface water runoff in the Otter catchment is also significant with floods in the catchment characterised by a very rapid rise and fall of water levels, with high flood peaks.

Understanding how beavers can influence flood risk

Natural Flood Management (NFM) interventions are gaining momentum, as more sustainable catchment-based approaches to flood risk management are implemented nationwide[1]. In parallel with the ROBT, a variety of approaches to 'Working with Natural Processes (WWNP)' have emerged[1] and it is argued that beaver reintroduction is the epitome of such an approach, delivering multiple benefits. Understanding the role that beaver dams could contribute in reducing flood risk by storing water in headwaters/floodplains has formed a central part of the investigation into hydrological change presented below. The monitoring experiments described provide data to test whether changes to high (flood) flows in the River Otter might be attributed to beaver activity.

Figure 3.1 describes the difference between a 'flashy' or fast response hydrograph (in red), that is typical of intensively-managed landscapes, where the emphasis on water resource management is to move the water from the land to the watercourse as fast as possible, and a more natural, or attenuated, hydrograph (in blue). Of note, the flashy hydrograph rises fast, peaks high and falls fast, with a short duration before water levels return to baseflow. Such hydrographs respond very quickly after heavy rainfall especially when the soil is saturated or has poor infiltration characteristics or is impermeable due to compaction or urbanisation. In contrast, the attenuated hydrograph rises slowly, with a delayed response to rainfall, peaks at a lower level, with a longer duration and often a post-storm baseflow that is elevated, even during dry periods. As such, flashy, or fast response flow regimes pose a greater risk to communities downstream and attenuated flow regimes will reduce flood risk.



↑ **Figure 3.1** The key hypothesis that the hydrological research tests is whether beaver dams deliver the attenuated hydrograph response (in blue) when compared with pre-beaver flows (in red) or whether flows into beaver dam complexes (in red) might be attenuated as they pass through beaver dams (in blue). 'Lag A' illustrates the time lag between the start of a rainfall event (Ps) to the start of a flow event (Qs); 'Lag B' describes the lag time between peak rainfall (Pp) and peak flow (Qp).

In order to understand the role that beavers might have on flooding, analysis is required to understand flow regimes before beaver reintroduction or upstream of beaver-impacted landscapes. Such work permits comparison with flood regimes after beaver dams have been built, or downstream of beaver dams to draw conclusions as to the potential for downstream flood attenuation. Ideally this work is undertaken at a number of different scales and locations.

Implications of changes to the observed flood regimes in terms of flood risk to communities downstream can theoretically be quantified using the above data. However, such extrapolation is highly complex, requiring site-specific data in terms of both how beaver dams impact floods and socioeconomic analysis of flood risk changes for society in flood-prone locations.

In order to deliver this understanding, research is being undertaken by the team at the University of Exeter on a number of other beaver sites around the country. These include (as well as the ROBT sites): Pickering, the Forest of Dean and Cornwall beaver projects.

The team have also been monitoring flows on a first order stream where it passes through the Enclosed Beaver Project site in West Devon since 2013. The findings of this work have been published in peer reviewed journals[2,3]. Between 2011 and 2016, 13 dams were created by beavers along 183 m of first order stream increasing the surface area of ponded water from 90 m^2 to 1800 m^2. Within the ponds ca. 1,000,000 litres of water are stored at any one time.

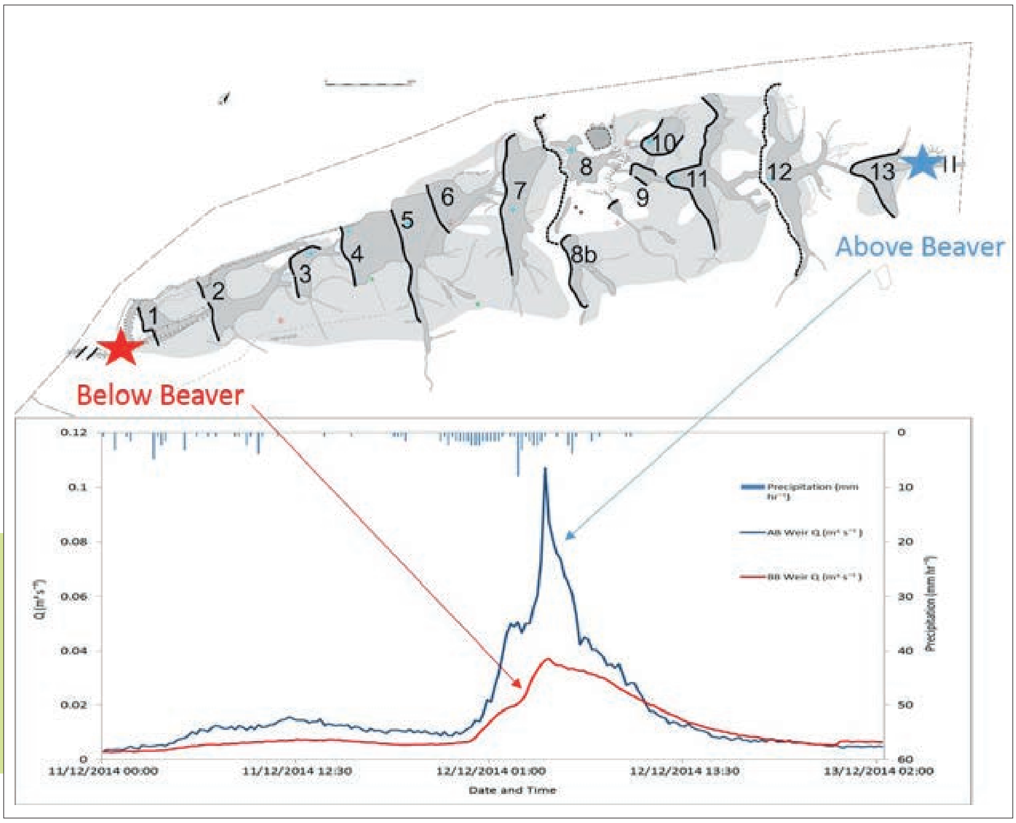
▶ BBC Springwatch piece about Enclosed Beaver Project

The beaver dams slow the flow of water. During storms, on average, peak flows were 30% lower leaving the site than entering. The lag time between peak flow entering the site and peak flow leaving the site was on average one hour, over a distance of only 183 m. Even in saturated conditions and for the largest monitored flood events, similar effects are observed due to the hydraulic roughness of the dams and felled trees and the leaky nature of the dams.

This research provides strong evidence for the role that beavers could play in reducing flood risk at a catchment scale, even during prolonged wet periods. The water storage and gentle release effect also results in elevated baseflows from the site, maintained even when periods of drought led to no flow into the site. Such baseflow maintenance is critical for aquatic ecology and water supply downstream, especially during times of drought, when many species suffer due to the lack of water[4] or high temperature of water[5].

▶ Beaver dam on River Otter after heavy rain

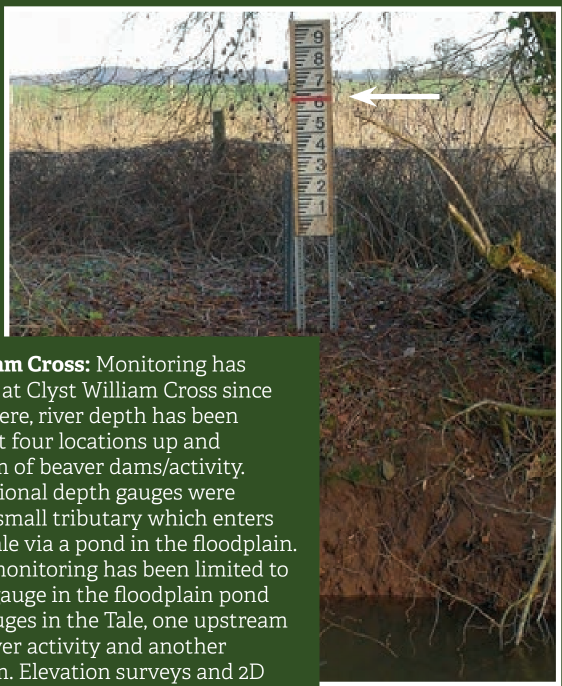
▶ BBC 2 Politics Live piece about beavers and flooding



→ **Figure 3.2** Map showing sequence of 13 beaver dams along 183 m of watercourse at Enclosed Beaver Site, with graph showing an example of flow data measured upstream (blue) and downstream (red) during a single high flow event.

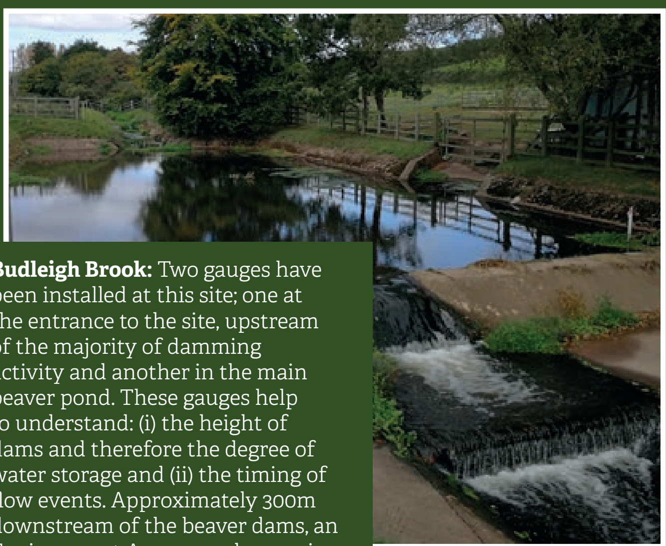
Overview of hydrology monitoring work undertaken on River Otter

With the objective of detecting any significant impacts of beaver dams on flows, hydrological monitoring equipment was installed in four of the beaver territories where beaver dams were built. The installations were designed to complement the network of hydrometric monitoring stations managed by the Environment Agency.

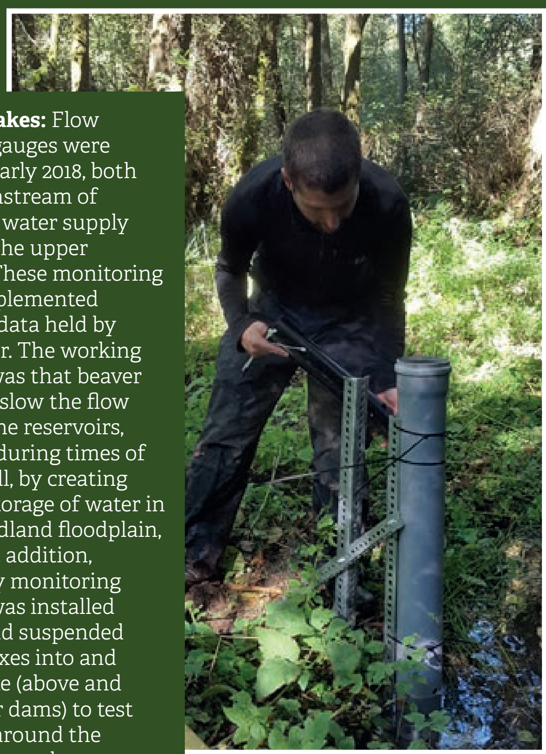


Clyst William Cross: Monitoring has taken place at Clyst William Cross since May 2016. Here, river depth has been measured at four locations up and downstream of beaver dams/activity. Three additional depth gauges were placed in a small tributary which enters the River Tale via a pond in the floodplain. From 2018 monitoring has been limited to one depth gauge in the floodplain pond and two gauges in the Tale, one upstream of core beaver activity and another downstream. Elevation surveys and 2D hydrological modelling of this site has enabled the installation of a stage board to demonstrate the height a beaver dam would need to reach to cause water to back up to the road bridge upstream.

Colaton Raleigh Stream: The main beaver site on this watercourse was instrumented in 2016 and data were collected showing how water levels responded to the construction of beaver dams. Four depth gauges were placed within the channel, one upstream, two within beaver ponds and one downstream of damming activity. However, due to upstream alterations to the channel (not relating to beaver activity), the majority of flow is no longer conveyed along this channel and consequently, in November 2018, all gauging equipment was removed from the site.



Budleigh Brook: Two gauges have been installed at this site; one at the entrance to the site, upstream of the majority of damming activity and another in the main beaver pond. These gauges help to understand: (i) the height of dams and therefore the degree of water storage and (ii) the timing of flow events. Approximately 300m downstream of the beaver dams, an Environment Agency early warning gauging station records water depth at 15 minute intervals (picture). With records dating back to July 2009, this gauge provides vital pre-beaver flow data to compare with post-beaver flows over the last 2-3 years. This depth data has been used to estimate river flow using established weir rating equations[6].



Otterhead Lakes: Flow monitoring gauges were installed in early 2018, both up and downstream of the drinking water supply reservoir in the upper catchment. These monitoring stations supplemented longer-term data held by Wessex Water. The working hypothesis was that beaver dams would slow the flow of water to the reservoirs, particularly during times of heavy rainfall, by creating significant storage of water in the wet-woodland floodplain, upstream. In addition, water quality monitoring equipment was installed to understand suspended sediment fluxes into and out of the site (above and below beaver dams) to test hypotheses around the impact of beaver dams on reservoir siltation[3].

Preliminary findings from work undertaken on the River Otter

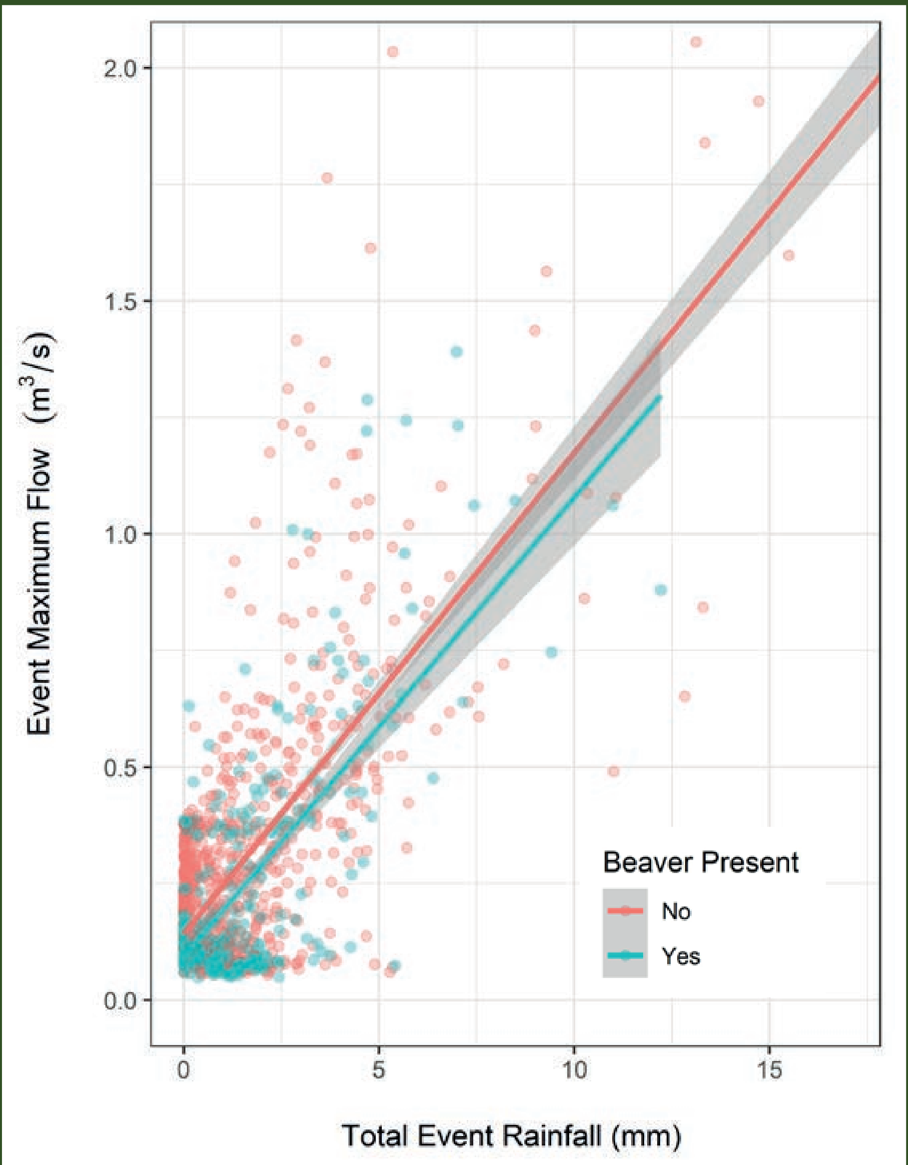
Using automated identification of when rainfall and flow events occur, we have begun preliminary analysis of these data. This investigation indicates that there are detectable and significant differences in the hydrological response to rain events pre- and post-beaver, i.e. beaver dams attenuate floods, as we have recorded elsewhere[2].

The accompanying **Case Study 2** illustrates change in the hydrological regime upstream of a flood-prone village in the Lower Otter catchment. As the case study details, the pre-beaver hydrology (recorded at the EA gauging station 300 m downstream of the beaver dams since 2009) is markedly different to that observed since beaver damming began in 2017. For the same amount of rainfall on the catchment, peak flow is reduced (post-beaver), demonstrating downstream flood attenuation. The mechanism of this attenuation is, at least in part, attributable to the observed increase in the duration of the falling limb of the storm hydrograph – evidence of the slowing effect of the beaver dams (see Figure 3.1 for explanation and Figure 3.3 for changed relationship between total rainfall and maximum flow due to beaver damming).

At the other hydrological monitoring sites, Clyst William Cross, Colaton Raleigh Stream and Otterhead Lakes, no measurable change to flow volumes have yet been observed, though significant changes to the patterns of water storage have been recorded, with additional water being stored in the floodplain. At Clyst William Cross there is now 6,880 m^2 of standing surface water on the floodplain, compared with 1,400 m^2 before beavers were reintroduced. Colaton Raleigh stream **(Case Study 1)** showed an increase in surface water out of channel, prior to reduction of effective dam height at the request of landowners, whereas the area of new standing water at Otterhead lakes is now 5200 m^2.

Already at Otterhead, the data collected show that water arrives upstream of the beaver dams rapidly (and also loaded with sediment – see water quality section) and is slowed through a series of up to seven dams, before entering the reservoir – i.e. increased lag times. Water levels in the reservoir have also increased due to beaver damming of the outlet, but have reduced after removal of these dams to protect the reservoir spillway at the request of the water company.

↓ **Figure 6.4** Relationship between total rainfall and maximum flow for hydrological events before (red) and after (blue) beaver dams were constructed. After beavers constructed dams, downstream flows were more likely to be lower for a given amount of rainfall.



Risk associated with dam failure

Concerns have been expressed regarding the risks associated with sudden failures of beaver dams. Dam failures, particularly in high energy environments, may cause infrequent and significant pulses of water and sediment[7].

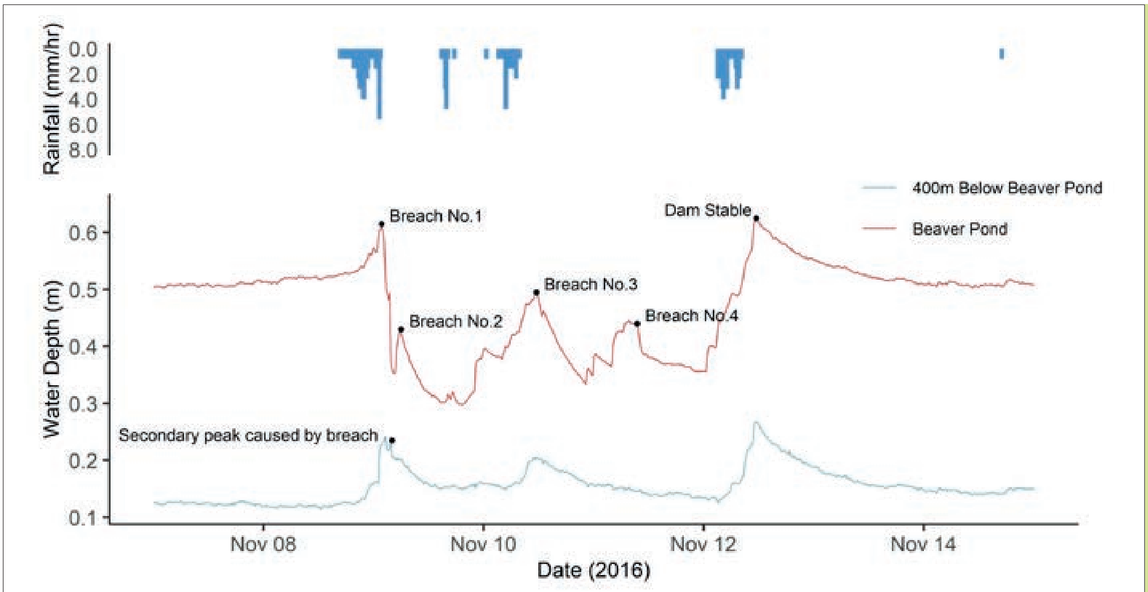
Beaver dam collapses typically coincide with significant discharge events[8] and are more common in alpine environments where seasonal meltwater can dramatically increase river flows[9]. Hydrological monitoring across beaver sites in 1st to 4th order channels throughout Britain since 2014 has been undertaken, and complete failure of established dams has rarely been observed. On 1st to 3rd order channels, dams are commonly stabilised by vegetation, over time becoming an integral component of the landscape.

On larger, 4th order channel reaches where dams are less frequently built, small temporary dams built during low flow conditions are eroded when normal or high flow conditions resume. When such dams do break down it is often gradual, and they store comparatively less water. They often erode slowly from the top or, following a partial 'blow out', the material is gradually washed away.

Damage to dams of varying magnitudes has been observed during high energy winter storm events (Figure 3.3). This damage is typically more severe on larger streams which experience higher stream power. In dam sequences, the impact on downstream flow regimes is mitigated/negated by the overall combined impact of the dam sequence (often associated with dense riparian vegetation) rarely producing discernible downstream flood pulses. Damage typically manifests itself as partial breaches in dams. These breaches are commonly repaired by beavers overnight.

The most significant collapses observed have not been to dams themselves but to adjacent stream-banks. This has occurred in two locations. One was on a 4th order reach in the River Tale and another on a 2nd order reach outside of the River Otter catchment. In both of these cases, the erosion led to increased channel complexity, providing new habitat types, and beavers subsequently rebuilt dams in or adjacent to the site of the collapse.

Only one case of damming has been observed on a stream of 5th order. This was however in the River Inny (Tamar catchment). The dam was built during very low flow summer conditions and would have been expected to have been breached during high flow conditions. However, it was removed by fishermen before this could be confirmed.



← **Figure 3.3** Watercourse hydrograph immediately upstream of beaver dam (red) and 400m downstream (blue) during a partial breach of the dam during a high flow event in November 2016. During the high flow event that caused the breach, there is a lower secondary peak observed downstream which is likely to be the result of the dam failure. It is also possible to see how the beaver dam collapsed and was rebuilt several times before it re-stabilised.

▶ **High flows leading to bank collapse**

Overview of water quality monitoring work undertaken and equipment installed

The approach to understand beaver impacts on water quality has employed two different techniques: (1) water chemistry monitoring and (2) monitoring change in macro-invertebrate species as an indicator of ecological status.

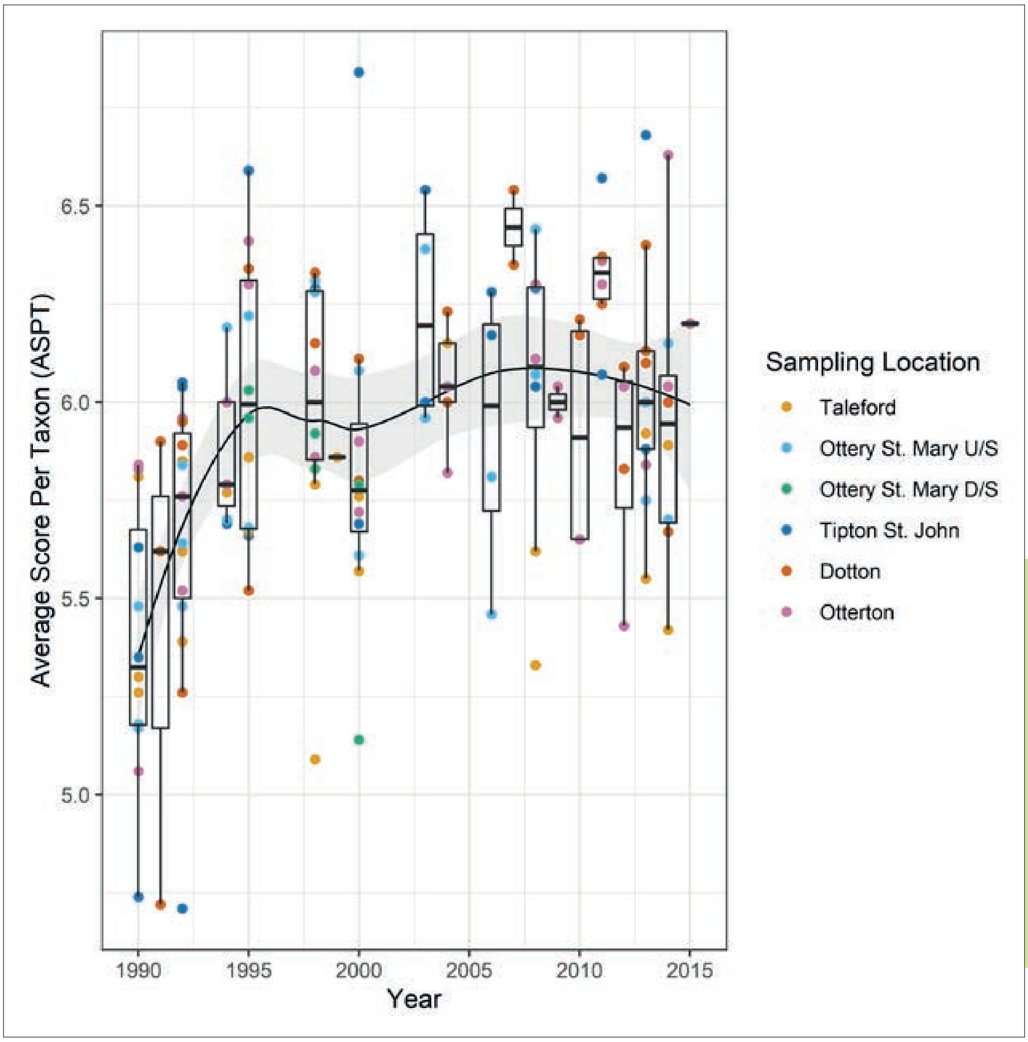
Both of these approaches are in line with EA methods to monitor freshwater health in the River Otter catchment as part of the drive to improve freshwater ecological status under the Water Framework Directive (WFD). The ROBT water quality research has focussed on the Otterhead Lakes site **(Case Study 4)**, wherein suspended sediment has been the key variable of interest. The macro-invertebrate survey work has been undertaken at a number of sites where beaver dams are present, to quantify ecological status both up and downstream of beaver dams and within beaver ponds (the processing of these data is ongoing). Routine EA invertebrate monitoring data has been used to understand the current ecological status of the River Otter.

↓ To complement the aquatic invertebrate sampling carried out by the EA, additional samples have been collected from routine EA monitoring sites, using comparable techniques. This information will contribute to current understanding of the impacts of beaver dams on macro-invertebrate communities as they evolve.

Use of aquatic macro-invertebrates to monitor water quality

Through analysis of the EA macro-invertebrate data obtained during the 1990s (see Figure 3.6 for details) there was a clear increase in the invertebrate biomonitoring metrics (Biological Monitoring Working Party (BMWP) and Average Score Per Taxon (ASPT)) at most sampling sites. This can be attributed to improved farming practices, catchment management and wastewater treatment, thus reducing both diffuse and point source pollution. In general, recent surveys suggest that the river is therefore in moderate condition. The pattern of water quality status in the river mirrors that of lowland rivers in agricultural systems across the UK. The headwaters tend to be in the best condition and as the river progresses downstream it is subject to increased pollutant loading, with the worst condition in the lower reaches. Isolated low-scoring surveys confirm there are still significant nutrient loading pressures on the river. There is no clear change in the data set to suggest that beavers have, as yet, had any impact (either positive or negative) on water quality at EA monitoring sites in the River Otter catchment.

→ **Figure 3.5** Locations and description of EA invertebrate sampling locations.



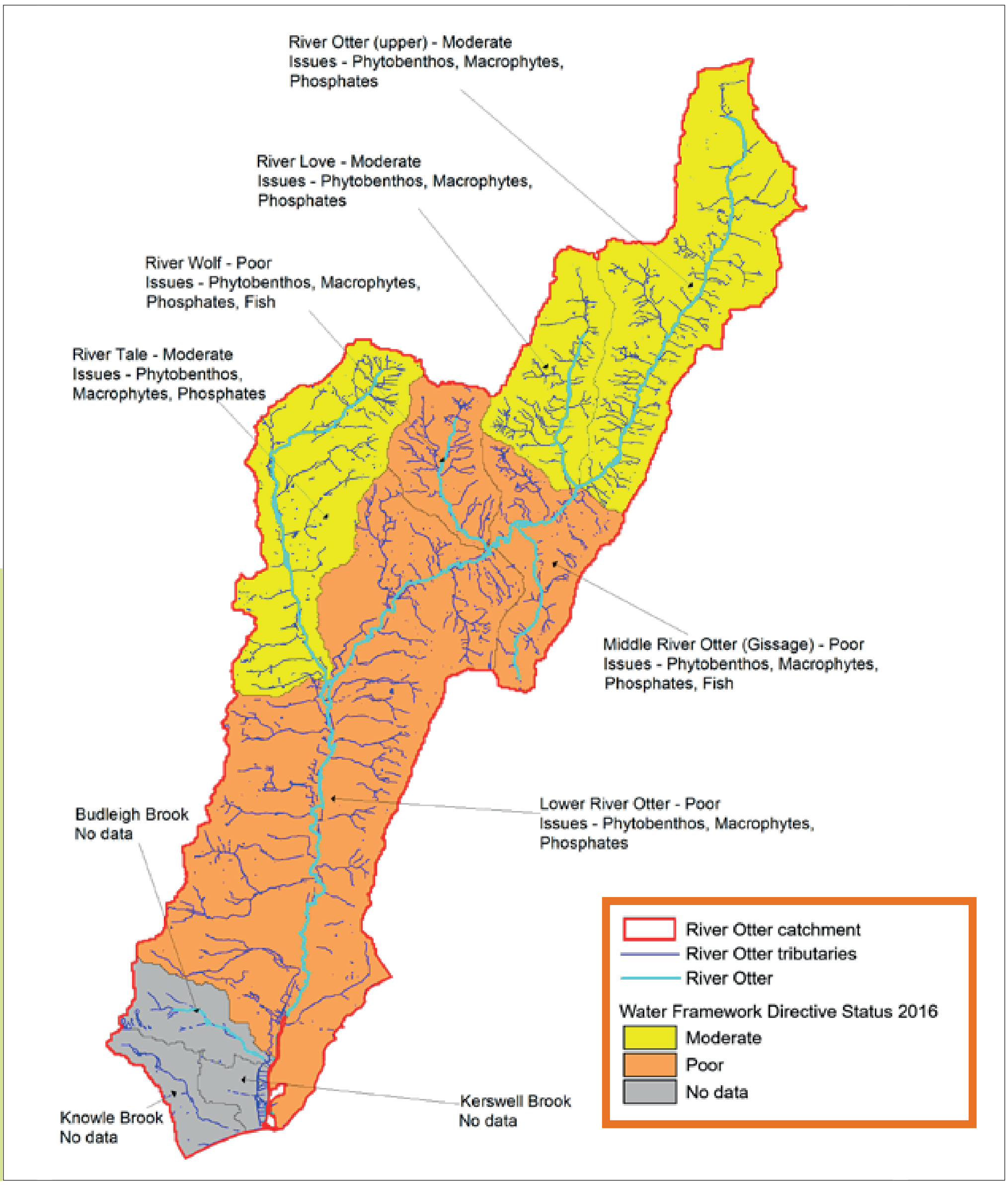
← **Figure 3.6** Plot indicating the change in the average (BMWP) score per taxon (ASPT) (i.e. per macro-invertebrate species) for all ASPT (EA monitoring sites) between 1990 and 2015. The trend line indicates the change in ASPT across all sites combined. These data provide a valuable baseline for understanding future impacts of beavers on water quality and the macro-invertebrate community in the River Otter.

Macro-invertebrate samples from dam sites (Clyst Williams Cross and Budleigh Brook) have been collected by the University of Exeter. The processing of these samples is ongoing and will provide a valuable understanding of the early-stage response of the macroinvertebrate community to beaver dam construction in the River Otter catchment.

Changes in macro-invertebrate communities associated with beaver activity

Beavers are known to alter the structure and function of habitats, positively impacting benthic riverine invertebrate communities in the reaches they inhabit. Principally, by turning rapidly moving (lotic) reaches into slow moving (lentic) habitats, the community composition alters accordingly. Therefore, it is typical to see a greater number of lentic species within ponds. These ponds, especially where they are watercourse fed or connected to floodplains, also collect a considerable volume of fine sediment which would otherwise be transported downstream, improving downstream habitat condition. In addition to the formation of ponds, beavers also provide numerous other habitats (e.g. canals and accumulation sites for woody debris), all of which will contribute increased macro-invertebrate biodiversity. For a review of the impacts of beaver on macro-invertebrate communities see Stringer and Gaywood (2016)[10].

Impact on Ecological Status of Waterbodies



→ **Figure 3.4** The most recent Water Framework Directive classification shows the ecological status in 2016. The impact of beavers on this is unlikely to be significant in the short term, although their presence over time is likely to be responsible for significant improvements in water quality as dams in the headwaters reduce sediment and nutrient impacts downstream.

Water quality work being undertaken at the Enclosed Beaver Project, West Devon

In addition to the results presented above, water quality is being monitored at the Enclosed Beaver Project in the Tamar catchment by the University of Exeter in partnership with Devon Wildlife Trust[2,3,11].

As well as impacting the storage and flow of water, impoundment behind dams can affect the quality of water leaving beaver impacted sites and the amount of diffuse pollutants transported downstream. By slowing and filtering the water, beaver dams cause sediment and nutrients to be deposited in ponded waters. In this case, the source of the material is intensively managed grassland, which elevates levels of sediment (from soil erosion), and also nitrogen and phosphorus, from manures, slurries and fertilisers that are added to the land (and are bound to the sediments). By the time the water has flowed through the sequence of 13 beaver dams, a high proportion of these diffuse pollutants has been removed from the water, settling out in the ponds.

Each instrumented weir above and below the site was equipped with an automated water sampler. These ‘pump samplers’ allowed researchers to collect one litre of water every time water depth changed by 2 cm, during high rainfall events. Sampling storms is important as this is when the water has most energy and most erosive capacity resulting in diffuse pollution. Samples were analysed in University of Exeter laboratories for suspended sediment, nitrogen, phosphate, and dissolved organic carbon content.

Additionally, ground-based surveying was undertaken of all ponds within the site to quantify sediment (and associated nutrient) storage and gain an increased understanding of the mechanisms by which the site was influencing downstream water quality.

Full water quality results are published in Puttock et al., (2017)[2], whilst sediment and nutrient storage results are published in Puttock et al., (2018)[3]. Both these papers are included in Appendix 3 with summary results provided below.

Implications for mitigating diffuse pollution from agriculture

Loss of sediment and nutrients from agricultural landscapes is a serious and chronic problem, which is widespread globally. It results in unsustainable soil loss, with the land also becoming less fertile, becoming depleted of nutrients, and requiring greater fertiliser use and causing downstream water quality problems such as eutrophication. Pollutants such as sediment, nitrate and phosphate, negatively impact on ecological status and water quality downstream[12]. The presence of beavers at the Enclosed Beaver Project has been shown to play a significant role in filtering these pollutants from water[2].

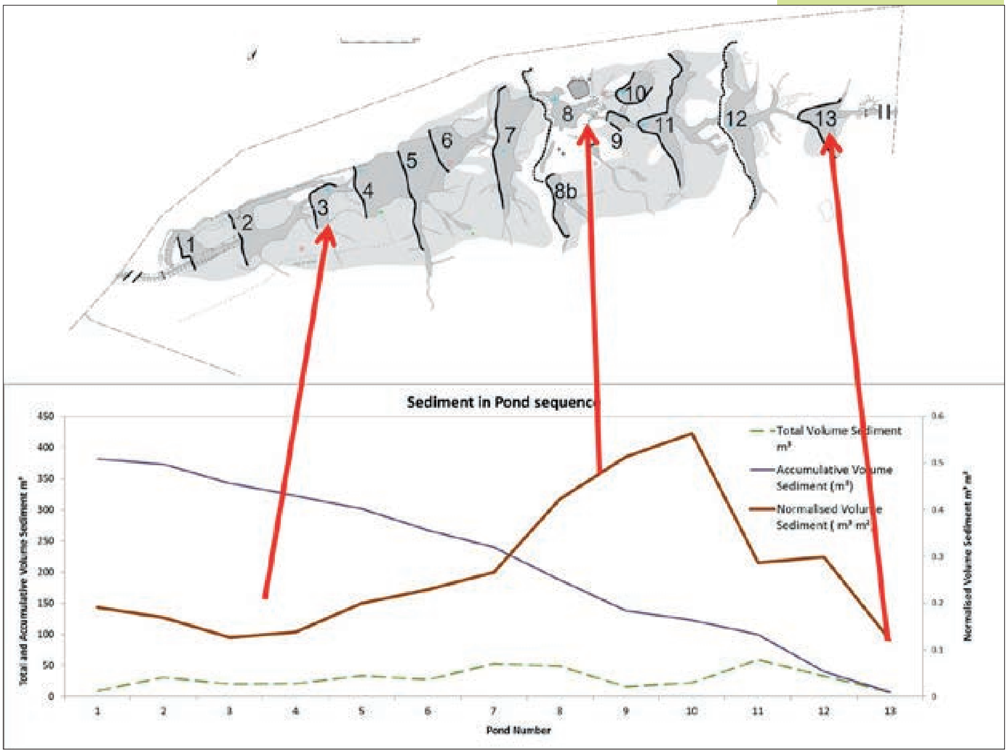
Impacts on Sediment

During storm events, each litre of surface water leaving the beaver-modified site has 3 times less sediment than the water entering the site. On average 112 mg l^{-1} of sediment enters the site and under 40 mg l^{-1} of sediment leaves the site during stormflow[2].

Site surveying showed that 13 ponds held over 100 t of sediment (normalised average of 70 kg m^2 ponded extent). Associated with this sediment was 15 t of carbon and 1 t of nitrogen[3].

It is clear that pond size has the greatest control over storage; larger ponds hold more sediment per unit area, although position in dam sequence may play a role too. It was estimated that over 70 % of sediment within the ponds was sourced from the farmland upstream. Thus, beaver ponds may have a role to play in mitigating negative impacts of soil erosion and diffuse pollution from agriculture. At the time of sampling, it is estimated that ponds would have over 50% remaining storage capacity, even without continued modification by beavers of the site over time to maintain/increase capacity[3].

↓ **Figure 3.7** Sediment storage within beaver ponds.



Key documents in Appendix 3

- Flooding, Beavers and a Community in the River Otter catchment – UoE November 2019
- Structure from Motion Photogrammetry poster – UoE April 2018
- Summary Paper on Beaver Dam failure – UoE November 2019

The appendices are available to view at www.exeter.ac.uk/creww/research/beavertrial/appendix3/

NB. These appendices will be updated with other relevant supporting documents, not necessarily listed here.

References

1. Burgess-Gamble, L. *et al. Working with Natural Processes – Evidence Directory.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/681411/Working_with_natural_processes_evidence_directory.pdf (2018).
2. Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M. & Brazier, R. E. Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. *Science of The Total Environment* 576, 430–443 (2017).
3. Puttock, A., Graham, H. A., Carless, D. & Brazier, R. E. Sediment and nutrient storage in a beaver engineered wetland. *Earth Surface Processes and Landforms* 43, 2358–2370 (2018).
4. Wood, P. J. & Petts, G. E. The influence of drought on chalk stream macroinvertebrates. *Hydrological Processes* 13, 387–399 (1999).
5. Weber, N. *et al.* Alteration of stream temperature by natural and artificial beaver dams. *PLOS ONE* 12, e0176313 (2017).
6. Rantz, S. E. *Measurement and computation of streamflow: Volume 2, Computation of Discharge*. https://pubs.er.usgs.gov/publication/wsp2175 (1982) doi:10.3133/wsp2175.
7. Butler, D. R. & Malanson, G. P. The geomorphic influences of beaver dams and failures of beaver dams. *Geomorphology* 71, 48–60 (2005).
8. Butler, D. R. The failure of beaver dams and resulting outburst flooding: a geomorphic hazard of the southeastern Piedmont. *The Geographical Bulletin* 31, 29–38 (1989).
9. Butler, D. R. Beavers as Agents of Biogeomorphic Change: A Review and Suggestions for Teaching Exercises. *Journal of Geography* 90, 210–217 (1991).
10. Stringer, A. P. & Gaywood, M. J. The impacts of beavers Castor spp. on biodiversity and the ecological basis for their reintroduction to Scotland, UK. *Mam Rev* 46, 270–283 (2016).
11. Puttock, A. K., Cunliffe, A. M., Anderson, K. & Brazier, R. E. Aerial photography collected with a multirotor drone reveals impact of Eurasian beaver reintroduction on ecosystem structure. *J. Unmanned Veh. Sys.* 3, 123–130 (2015).
12. Bilotta, G. S. et al. Assessing catchment-scale erosion and yields of suspended solids from improved temperate grassland. *Journal of Environmental Monitoring* 12, 731 (2010).