MONITORING THE IMPACT OF LEAKY BARRIERS USED FOR NATURAL FLOOD MANAGEMENT ON THREE RIVER REACHES IN THE STROUD FROME AND TWYVER CATCHMENTS, GLOUCESTERSHIRE, UK

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Key points

- Three sites in the Stroud Frome and Twyver catchments in Gloucestershire, UK were monitored for hydrology, sediment and water quality variables in five different flow conditions; these included two featuring leaky barriers installed in different years and a natural control site.
- The results indicated that that leaky barriers were effective at reducing channel velocity and storing water up to a 1 in 9-year flow event (no higher magnitude flow events were captured), but did not impact on low flow velocities.
- The time a leaky barrier had been in place was important; there were improvements in water quality and a reduction in the suspended sediment content when leaky barriers were present and these were more pronounced the longer a leaky barrier had been present. However, associated with this there was an increase in silt content in the bedload sediment upstream of leaky barriers which was increased through time since installation.

Natural Flood Management

Natural Flood Management (NFM) aims to work with natural processes to reduce flood risk and improve the ecological status of a river; this can include the enhancement, restoration and alteration of natural features and excludes hard-engineering defences which interfere with natural processes (Forbes *et al.,* 2015). NFM is a multi-beneficial strategy, reducing flood risk and positively affecting connectivity, sediment cycles, ecology and water quality (Environment Agency, 2017). There are a number of NFM strategies that can be implemented (these are outlined in full in EA, 2017), this research focused on leaky barriers (Figure 1).

Leaky barriers are purposely placed pieces of wood that form an obstruction on the water course, these allow low water flow to pass underneath the obstruction but when water flow increases the barrier slows the downstream flow and acts as a temporary water storage area (Cabaneros *et al.,* 2018; Grabowski *et al.,* 2019). Pre-existing leaky barrier research has outlined that leaky barriers do not interfere with a river natural cycle and are successful at attenuating water in high frequency flood events (Burgess-Gamble *et al.,* 2018). In addition to reducing flood risk, leaky barriers have been shown to also improve the water quality, river ecology and store in-channel sediment. However, there are still aspects of the long-term impact of these features on the in-channel longitudinal connectivity and wider river reach that are poorly understood.

Figure 1: A leaky barrier at the Workman’s Wood NFM site in the Stroud Frome catchment in Gloucestershire, UK.

Project aim

The Stroud Frome and Twyver catchments (Figure 2) flow through the urban areas of Stroud and Gloucester respectively, which were both severely impacted by the 2007 summer floods (Environment Agency, 2007). Following on from this NFM strategies have been implemented in both catchments to reduce the flood risk.

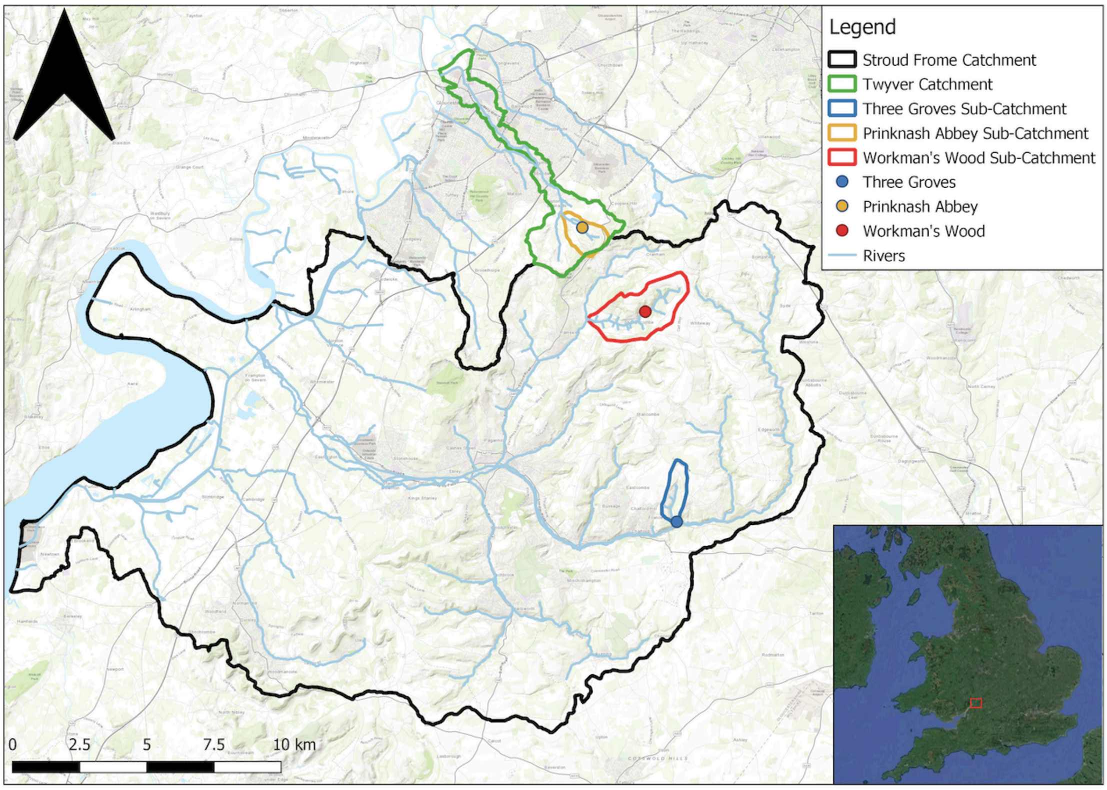

Figure 2: Catchment, sub-catchment and site location map of the three sites (Three Groves - control; Prinknash Abbey - recently installed leaky barriers; Workman’s Wood – leaky barriers installed 2015).

This project focused on evaluation of the leaky barriers across three sites within these two catchments, investigating the impact of these interventions on the connectivity, hydrology and geomorphology of a river system. There were two aspects to the research: (1) to monitor the effects that different flow events have on leaky barriers with regards to the hydrology, suspended sediment and water quality, and (2) to analyse the effect that leaky barrier age has on the hydrology, sediment dynamics, habitat diversity, and water quality of the surrounding river channel.

Three sites were selected that had similar catchment characteristics, but which had been installed with leaky barriers at different times or did not have leaky barriers at all to be used as a comparison (Table 1 and Figure 2).

Table 1: Information on the three selected study sites

Site	Catchment	Year NFM installed	Sub-Catchment Area (km²)	Elevation (m)	Land Use (%)	Aspect
Three Groves	Stroud Frome	N/A (No leaky barriers)	1.45	99	Grassland (52.3) Woodland (29.8) Agriculture (12.1) Urban (5.8)	W-facing on east bank
Prinknash Abbey	Twyver	2019	1.65	101	Woodland (48.6) Grassland (42.9) Urban (8.2) Agriculture (0.2) Water (0.1)	Mainly S- and W-facing. Part of true left bank faces N
Workman's Wood	Stroud Frome	2015	5.27	164	Grassland (44.8) Woodland (44.6) Agriculture (6.5) Urban (4.1)	Northern segment is E-facing; remainder SW- and NE-facing

Fieldwork was conducted between January to August 2020 to collect data under five different flow magnitudes; this resulted in recording during two low flow events, an average flow, a high flow (1 in 4-year flow event) and, what was classified for this research as, a very high flow (1 in 9-year flow event). During each field visit data was collected on flow velocity, channel dimensions (including active water width and depth), water quality variables (Ammonia, Phosphate, pH, Electrical Conductivity, Total Dissolved Solids and water temperature), suspended and bedload sediment, silt depth, and photo monitoring was conducted to observe the build-up of natural foliage. Channel habitat and riparian diversity was determined using the Modular River Survey (MoRPh) in both winter and summer conditions.

On the control site (Three Groves) variables were collected every 20m across five monitoring points. The leaky barrier sites had eight monitoring points so that either side of a leaky barrier could be monitored as well as upstream and downstream of the intervention sequence; monitoring points were 10m before and after the leaky barrier sequence, with monitoring on either side of the upstream, middle and downstream leaky barriers.

Key findings

The impact of different flow events

During low magnitude events, all three sites acted similarly in terms of hydrological variables, demonstrating that leaky barriers are behaving as expected (Environment Agency, 2017; Metcalfe *et al.,* 2017; Burgess-Gamble *et al.,* 2018; Leakey *et al.,* 2020; Hankin *et al.,* 2020) and not interfering with river dynamics during low flow conditions (Figure 3). Hydrology changed significantly in higher magnitude flow events; velocity (Figure 3a) and active water depth (Figure 3b) increased at all sites, but when comparing leaky barrier sites to the control there was a reduced velocity and increase in water depth, demonstrating that the leaky barriers were slowing the flow and attenuating water.

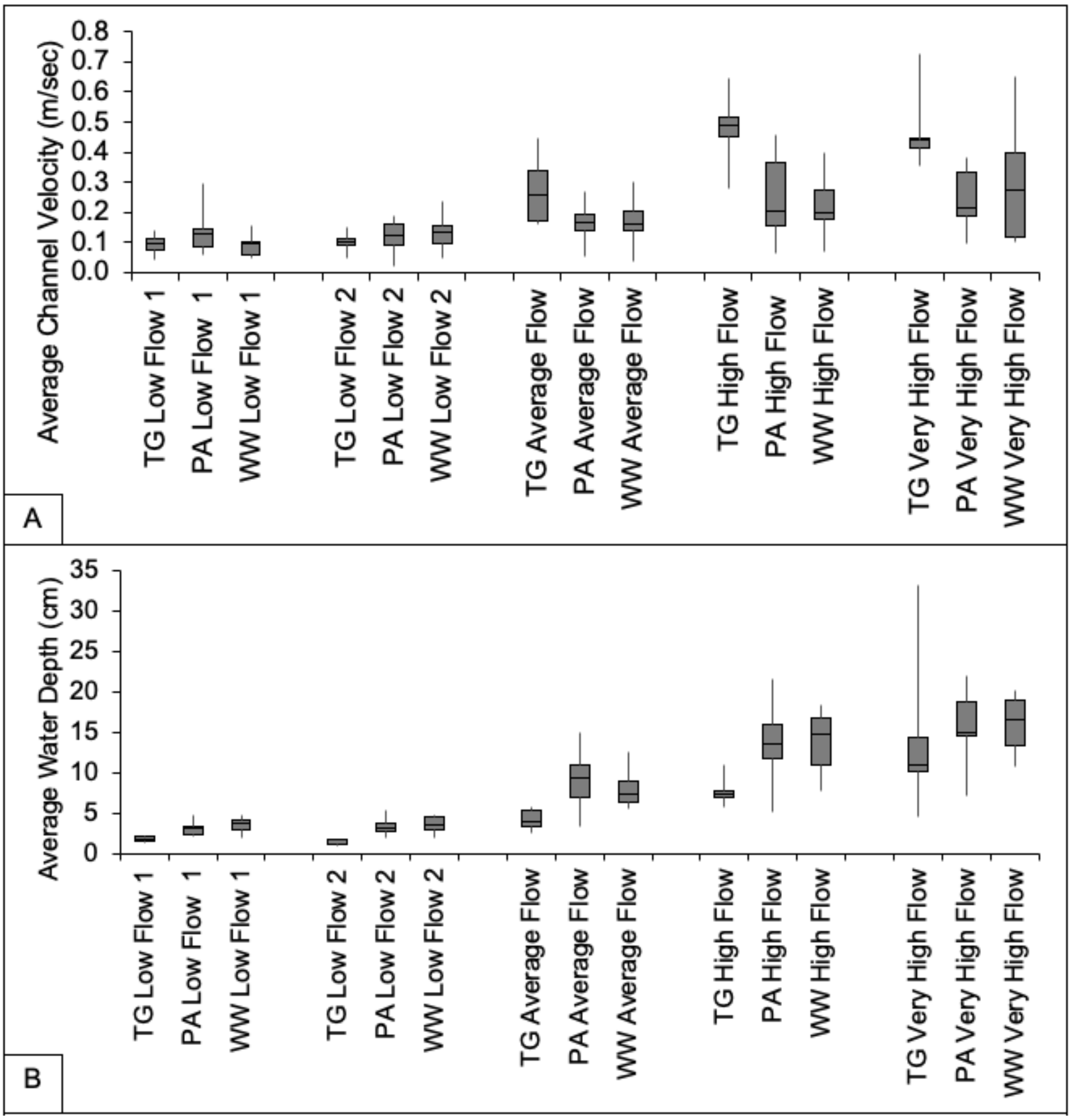

Figure 3: Hydrological variables related to flow for average a) channel velocity and b) water depth. Boxplots were formulated by averaging the three recordings taken at each monitoring point and using that data from each flow event. Percentage changes in text formulated using median values and range from 25th to 75th quartiles.

Analysis on the upstream and downstream areas of leaky barrier interventions displayed an insight as to why leaky barrier sites had a reduced channel velocity and increase in water depth in higher flow events compared with the control site. Leaky barrier upstream and downstream areas were hydrologically very similar for low flow events (Figure 4 and 5). In higher flow events, active water width (Figure 4) and active water depth (Figure 5) was greater in upstream barrier areas as water ponded behind the leaky barrier. There was an increase in velocity in the area immediately downstream of a leaky barrier (Figure 4), but the depth of this water is lower and due to the presence of another leaky barrier a short distance downstream this is not causing any additional transportation of water out of the reach and demonstrates the importance of multiple small interventions in reducing flow out of the reach.

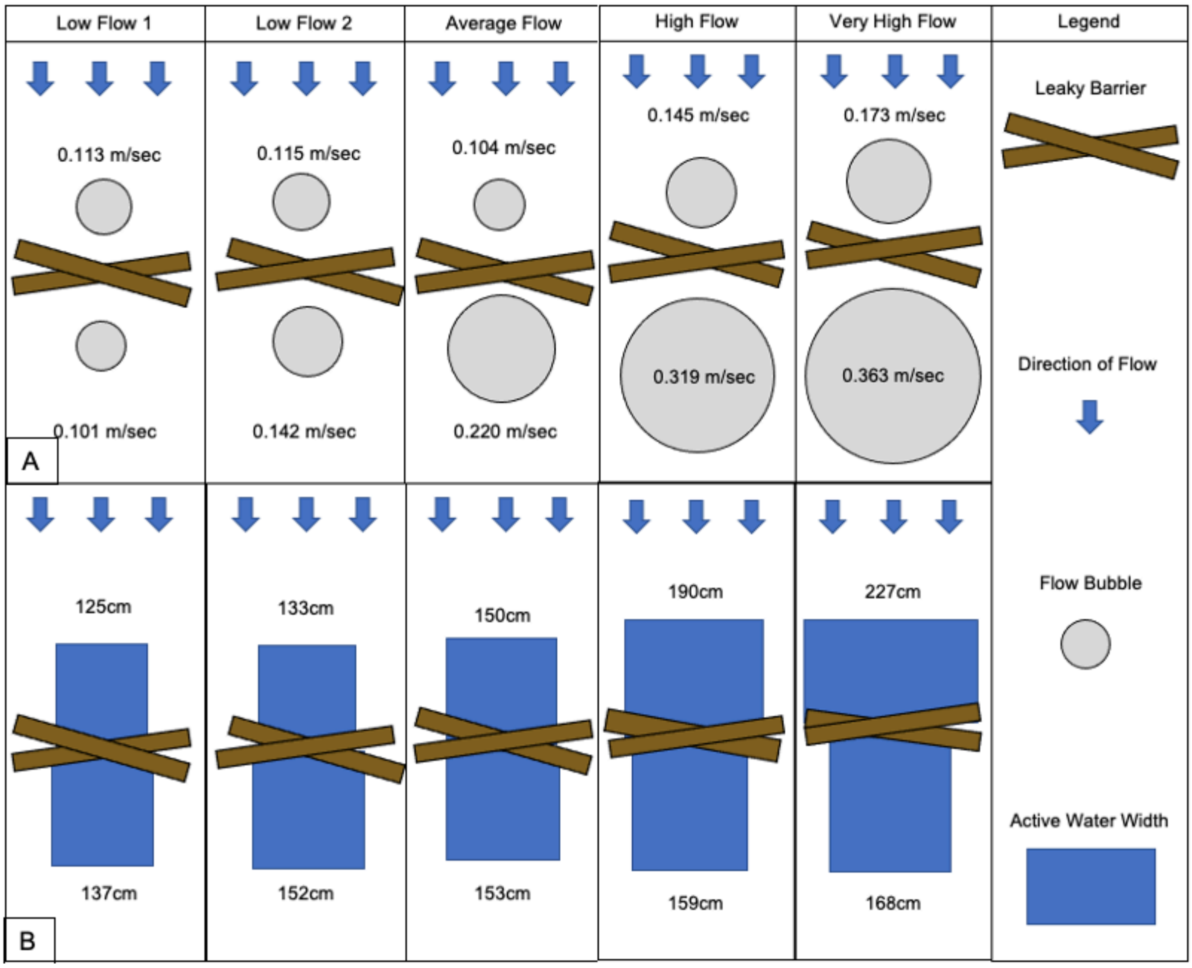

Figure 4: Hydrological variables for upstream and downstream intervention analysis for a) velocity and b) active water width. Variables are proportional to raw data with averages formulated by combining all monitoring points from both leaky barrier sites. Note: the leaky barrier size symbol and flow direction arrows are not proportional.

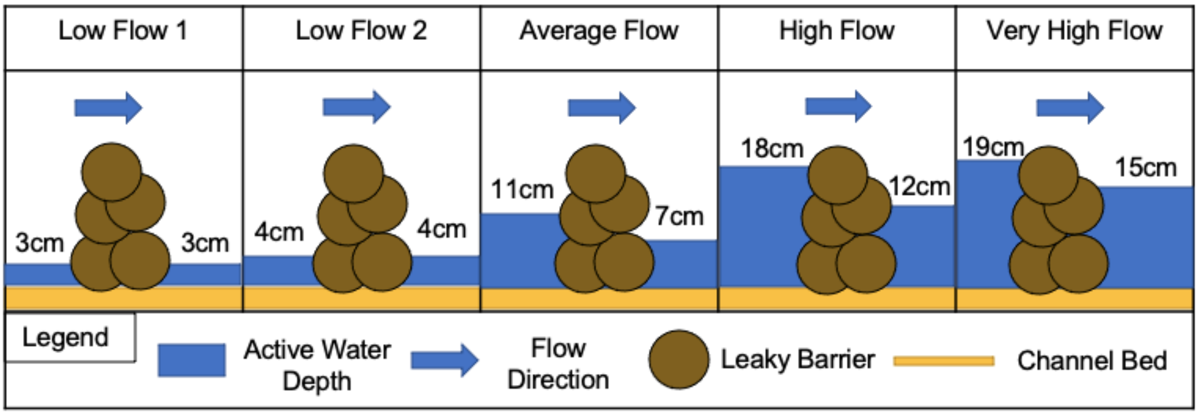

Figure 5: Water depth for upstream and downstream intervention analysis. Variables are proportional to raw data with averages formulated by combining all monitoring points from both leaky barrier sites. Note: the leaky barrier size, flow direction arrow and the channel bed depth symbols are not proportional.

There was no significant relationship between water quality variables and flow magnitude. However, there was some evidence that during high magnitude events nutrients such as Ammonia were diluted. There was no significant difference in any water quality variables between upstream and downstream areas during any flow event, demonstrating that the leaky barriers were not impacting on the water quality.

With regards to sediment, the leaky barrier sites displayed a slight increase in the amount of suspended sediment during high magnitude flow events compared to during the low flow events, but this was considerably higher at the control site during the highest flow magnitude event (Figure 6). Leaky barriers were therefore reducing the amount of suspended sediment transportation in high flow events, despite the higher volume of silt available in the bedload material upstream of the leaky barrier (described in more detail later).

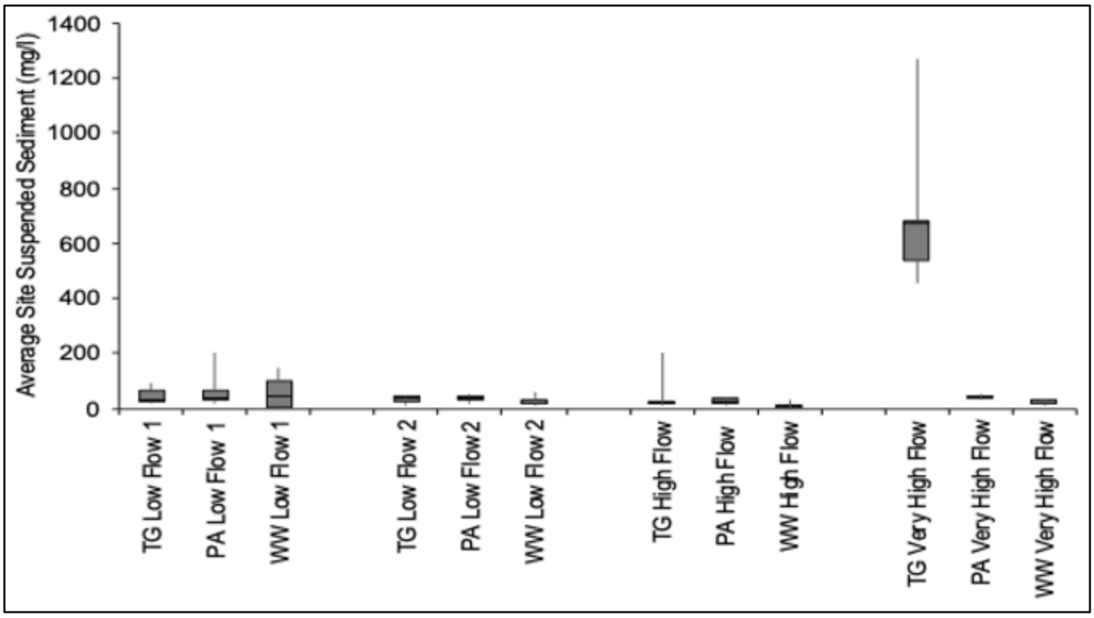

Figure 6: Sediment variables related to flow event for suspended sediment – TG = Three Groves (control), PA = Prinknash Abbey (recently installed leaky barriers), WW = Workman's Wood (leaky barriers installed in 2015). Boxplots were created using average readings from each monitoring point for each flow event.

All leaky barriers were monitored for natural foliage build up. Upon completion of the data collection, it was clear that for this variable the most interesting trends appeared when the data was presented in chronological order by flow event (Table 2). All leaky barriers displayed a build-up of natural foliage around the original interventions, especially in the upstream barrier areas and with the first upstream leaky barrier in the sequence having the largest increases in foliage build up over the study period. Evaluating the patterns of foliage build up during different flow events (Table 2) there appears to be a build up following large events, where the high flows will mobilise material that then becomes trapped behind the leaky barriers and then is either incorporated into the structure and remains (i.e. Workman's Wood) or remobilised during subsequent flows (i.e. Prinknash Abbey).

Table 2: Chronological changes to the areal extent of natural foliage (displayed in m^2) in upstream areas at Prinknash Abbey and Workman's Wood. Data collected using photo monitoring and extraction through ImageJ, averages calculated from all leaky barriers during each flow event are presented for each site.

Site	Extent of natural foliage upstream of leaky barriers (m^2)				
	Flow event 1: Ave flow	**Flow event 2: V high flow**	**Flow event 3: High flow**	**Flow event 4: Low flow**	**Flow event 5: Low flow**
Prinknash Abbey	0.83	0.87	1.06	1.03	0.88
Workman's Wood	0.90	0.91	1.13	1.01	1.15

The impact of leaky barrier age

With regards to the impact of leaky barriers and time since installation, this research found that hydrological variables changed quickly following installation, with reduced velocity (Figure 7) and increased active water depth; Prinknash Abbey displayed a 37% decrease in velocity compared with the control site (Three Groves). Both leaky barrier sites were similar in terms of average water depth and average velocity, indicating there is continuing effectiveness the time of installation for at least five years.

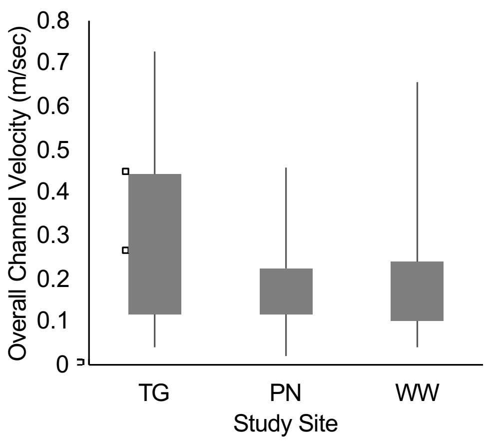

Figure 7: channel velocity for the three sites – TG = Three Groves (control), PA = Prinknash Abbey (recently installed leaky barriers), WW = Workman's Wood (leaky barriers installed in 2015). Boxplots were formulated by taking the average from each monitoring point for every flow event recorded.

Leaky barriers act as a natural filter for pollutants in the water (Nicholson *et al.,* 2012; Puttock *et al.,* 2020; Brazier *et al.*, 2020), and this was demonstrated in these results with a reduction in Phosphate and Ammonia levels the longer a leaky barrier had been installed (Figure 8). This does, however, appear to take time before any significant difference could be noted, as the control site (Three Groves) and the leaky barriers that had recently been installed at Prinknash Abbey had similar average values, although the maximum value was lower. There were differences in Total Dissolved Solids and Electrical Conductivity across the sites, but there was no obvious trend to suggest that this was because of the leaky barriers and more likely a result of geological differences. pH remained similar across all sites.

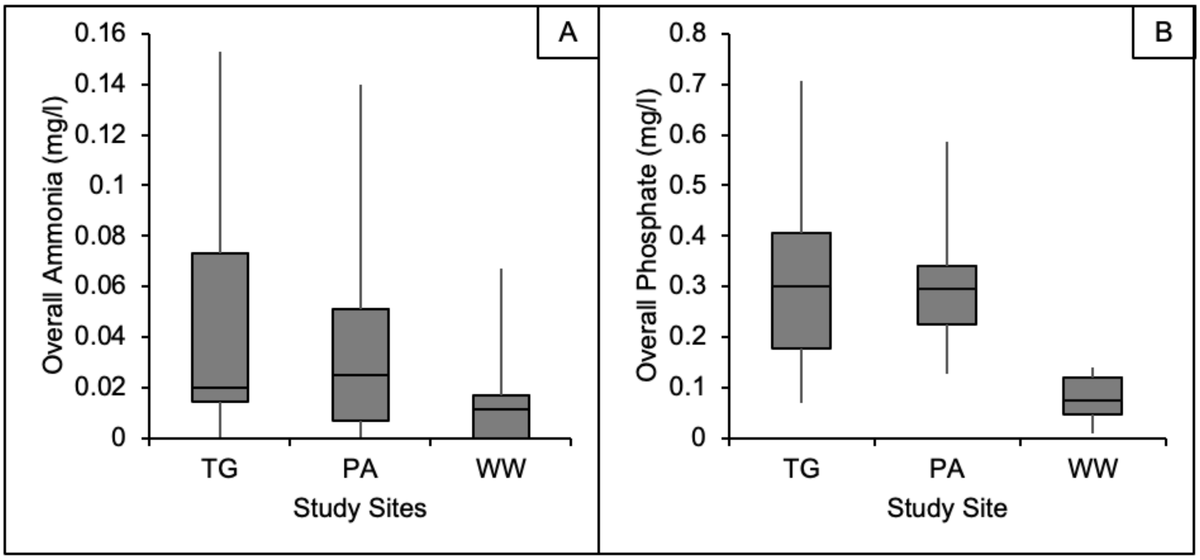

Figure 8: Water quality variables for a) Ammonia and b) Phosphate for the three sites – TG = Three Groves (control), PA = Prinknash Abbey (recently installed leaky barriers), WW = Workman's Wood (leaky barriers installed in 2015). Boxplots were formulated by taking the average from each monitoring point for every flow event recorded.

The suspended sediment amounts showed a gradual change the longer barriers had been installed; suspended sediment reduced slightly at Prinknash Abbey compared with the control (Three Groves), but Workman's Wood (that has had leaky barriers installed for the longest) had minimal suspended sediment (Figure 6). Bedload sediment was much siltier at leaky barrier sites, but Prinknash Abbey was still coarser than Workman's Wood (Figure 9), demonstrating that bedload fining and silt accumulation around leaky barriers occurs over time. Silt build-up was much more prominent in leaky barrier streams, with the silt depth greatest in upstream barrier areas. This is an important finding, as if silt is allowed to build up then the leaky barrier will begin to lose effectiveness and will eventually no longer mitigate flood risk.

The MoRPh surveys found only partial evidence leaky barriers improve habitat variables. Scores out of 10 (with 0 being poor and 10 being the good) were provided for riparian vegetation structural complexity, channel physical habitat survey and riparian physical habitat complexity (Figure 10). Leaky barriers improved riparian vegetational complexity scores but results on channel physical habitat survey displayed no trend, and riparian physical habitat complexity reduced. The latter could be because Three Groves has a range of habitat features including large areas of tufa and natural vegetation within the channel, which is likely to have improved the final habitat metrics.

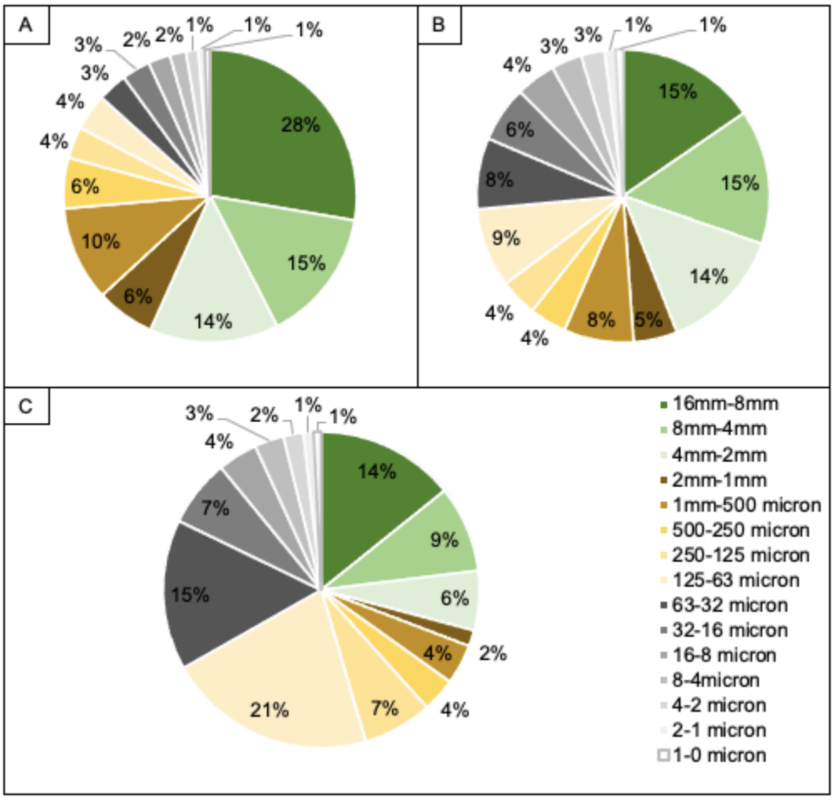

Figure 9: Bedload sediment distribution for a) Three Groves – the control site with no interventions, b) Prinknash Abbey – leaky barriers installed recently, and c) Workman's Wood – leaky barriers installed in 2015. Distribution calculated by averaging both bedload sediment collections. Colours give an indication of the size faction: green being the coarsest reducing through brown and into grey/white.

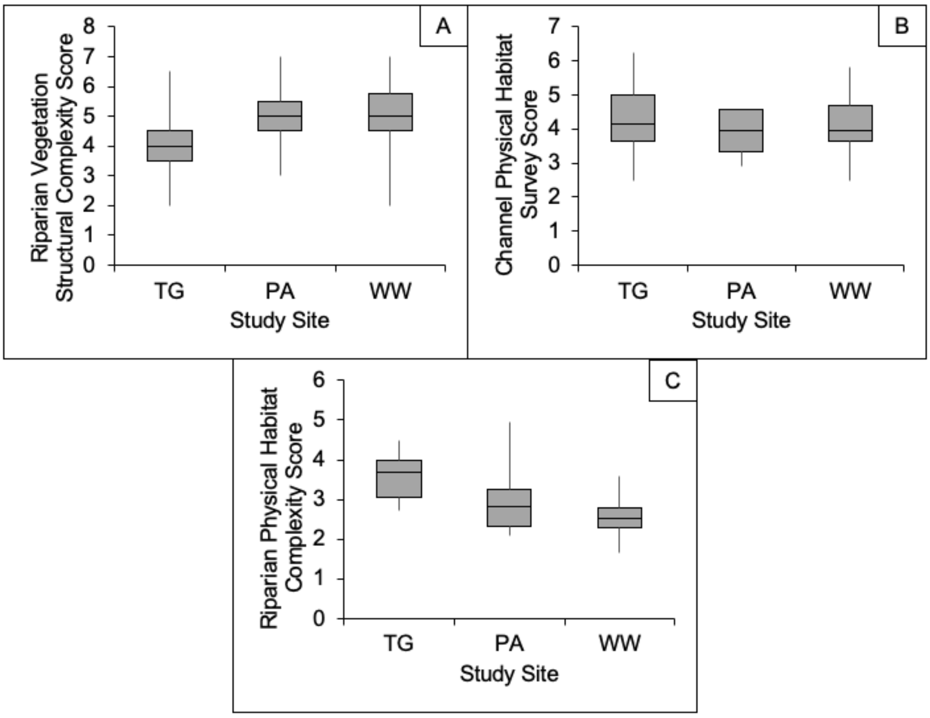

Figure 10: Habitat diversity indices for a) riparian vegetation structural complexity score, b) channel physical habitat survey score, and c) riparian physical habitat complexity score. Boxplots formulated by averaging the scores from the winter and summer MoRPh10 surveys. Metrics are scored from 0 (poor) to 10 (good).

Project summary

Over the river reach as a whole, leaky barriers positively impacted lateral connectivity to the floodplain and reduced longitudinal connectivity during high magnitude events, reducing the amount of water and sediment travelling downstream. Therefore, if enough of these interventions were installed they would be beneficial flood mitigation for the high-risk downstream areas such as Gloucester and Stroud. As leaky barriers age they are still effective, with Workman's Wood displaying similar results to Prinknash Abbey. The multi-benefits of leaky barriers improved over time since installation of the leaky barriers (i.e. water quality and sediment retention), however overall downstream flow velocity is reduced immediately.

The main project findings were as follows:

Impact of flow magnitude: During low flow events there was no noticeable impact on flow velocity between the sites with leaky barriers and the control site. During high flow magnitude events the longitudinal connectivity was reduced which interrupted the flow velocity and reduced the amount of suspended sediment being transported downstream. Lateral connectivity increased as more water was stored across the channel width during these high flow events and the leaky barriers provided effective barriers to with downstream movement of water causing it to exceed bankfull upstream of the leaky barriers. No significant changes occurred for any water quality variables related to the implementation of leaky barriers. Therefore leaky barriers are effective flood mitigation measures as the disrupt the flow velocity (overall slowing the flow) and encourage floodplain attenuation, if enough of these features are installed.

Impact of leaky barrier age: Following installation of leaky barriers the changes to the hydrology occurred instantaneously and remained similar the longer a barrier had been in the river system. However, the longer a leaky barrier had been in place the greater the reduction in suspended sediment downstream of the barriers and the higher the silt content of the bedload material, this was also linked with large areas of silt build up, especially in upstream barrier areas. Gradual improvements were made to water quality variables such as Phosphate and Ammonia, but it is likely to be number of years before significant improvements are seen after implementation.

Recommendations:

The project offered three core recommendations:

- Further research on leaky barriers during high magnitude flow events. This project successfully showed that barriers are effective in flow velocities up to a 1 in-9-year flow events, however more examples are needed of higher magnitude flow events to assess at what point a leaky barrier will become overwhelmed.
- Continued monitoring on the impact of silt build up. The build-up of silt could reduce the effectiveness of leaky barriers and therefore further monitoring is required to assist with future management plans to prevent this.

- On a local scale, monitoring on the three study sites should continue. At the leaky barrier sites (Prinknash Abbey and Workman's Wood) continued monitoring would provide long-term evidence of the impact of leaky barriers, as well as analysing issues associated with decay and breakdown of the interventions. This research provides the foundation for baseline data at Three Groves should leaky barriers be implemented in the future to provide BACI evidence of impact.

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