Effect of weir removal on the aquatic macroinvertebrate community of an urban river in the UK

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SUMMARY
Weirs are a globally abundant type of low-head dam that negatively alter river ecosystems. Their removal is an increasingly popular river restoration measure in many countries. However, it is unclear what benefits weir removal might provide for the typically depauperate macroinvertebrate communities of urban rivers, which are usually subject to a range of anthropogenic pressures. This Before-After Control-Impact Paired study tested whether the removal of a weir on an urban river in the UK resulted in a shift in the aquatic macroinvertebrate community towards a more natural state. Macroinvertebrates were sampled before and after removal, above and below the structure and at control sites over four years. Following weir removal, the proportion of macroinvertebrate families that were made up of mayfly, stonefly or caddisfly families (an indicator of stream health) underwent a statistically significant increase at the upstream impact sites. There was a concurrent statistically significant increase in two indices, the Lotic-invertebrate Index for Flow Evaluation and the Empirically-weighted Proportion of Sediment-sensitive Invertebrates index, suggesting weir removal had an ameliorating effect on flow and sediment stressors acting on the macroinvertebrate community upstream of the weir. 'Reference samples' for the study location were generated using the River Prediction and Classification System, which are predictions of what the macroinvertebrate community would likely be if the study site was in a near natural state. Non-metric multidimensional scaling ordination showed that the macroinvertebrate community upstream of the weir became more similar to the 'reference samples', suggesting that it had shifted towards a more natural composition.

BACKGROUND

Weirs are low-head run-of-the-river dams that impound numerous rivers worldwide, and are built for a variety of reasons, including to draw off river water for industrial uses or irrigation, and to help control erosion in river channels. These structures are generally considered to have a negative impact on river ecosystems for two main reasons. Firstly, they obstruct the movement of river animals such as fish through river networks, potentially inhibiting their ability to feed, shelter, reproduce and disperse effectively (Jungwirth *et al*. 2000). Secondly, the construction of a weir can radically alter the upstream river ecosystem, creating a long-ponded reach with low-energy, slow flowing, deeper, siltier (lentic) conditions, and a channel that is relatively uniform in terms of habitat (Fencl *et al*. 2015). This alteration of habitat has been found to adversely affect fish and macroinvertebrate communities (Santucci *et al*. 2005). Weirs and other river barriers are thought to be one of the leading causes of riverine biodiversity loss globally (He *et al*. 2021). For this reason, weir removal is growing in popularity in the UK and internationally as a river restoration measure thought to revert the river ecosystem back to a more natural state. While most weir removal studies lend support to this view, a wide range of ecological responses can result. These include both positive and negative outcomes, which are determined by the biological and physical contexts of each removal (Carlson *et al*. 2018; Bellmore *et al.* 2019).

Most rivers in the UK are heavily fragmented by weirs (Jones *et al*. 2019), and some of the highest concentrations of weirs occur in rivers in urban areas. Urban rivers are characterised by a high and often extreme level of human impact. Typically, they have a combination of elevated levels of pollution, a high degree of physical modification and habitat degradation, altered flow regimes, have lost sensitive taxa, and have become colonised by invasive non-native species (Booth *et al*. 2016; Francis *et al*. 2023). The low ecological quality of urban rivers can reduce the effectiveness of river restoration interventions (e.g. Walsh *et al*. 2023), and, as such, it cannot be assumed that the removal of a weir on an urban river will have a positive impact on that river ecosystem. For example, the mobilisation of contaminated sediments during weir removal, the presence of invasive species, or other pressures such as degraded habitat or a lack of colonist species could potentially lead to a neutral or negative outcome. Carlson *et al*. (2018) noted that, despite the popularity of weir removal, there have not been enough published studies on the ecological outcomes of this river restoration measure. At the time of writing the Conservation Evidence database holds only one 2-year study of the removal of a small dam from a North American river, which found that following removal macroinvertebrate density, algal biomass, and diatom species richness declined significantly downstream of the dam (Thomson *et al*. 2005). However, additional evidence on the effectiveness of weir removal in other contexts (e.g. on heavily impacted urban rivers) and over longer timeframes would better inform the priorities and decisions of river restoration practitioners.

The River Rother flows through an urbanised area of the Don catchment in northern England (Figure 1). It is

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impounded by 10 weirs that were built as infrastructure to support historic industrial activity. For much of the 20th century, the river was so polluted that it was considered ecologically dead. Water quality improvements resulting from better sewage management and the decline of heavy industry, particularly from the 1980s onwards, have led to many native and non-native aquatic species colonising the river (Firth, 1997).

In 2020 the Don Catchment Rivers Trust (DCRT), an environmental charity, demolished Slittingmill Weir on the River Rother with the intention of reestablishing longitudinal ecological connectivity, restoring natural processes and improving habitat. In this Before-After Control-Impact Paired (BACIP) study we aim to test whether the removal of a weir from this urban river results in a change to the composition of macroinvertebrate community. We postulate that removing the weir will improve river habitat which in turn will have a measurable positive effect on the aquatic macroinvertebrate community, manifested as changes in abundance, diversity or indices that reflect the alleviation of the pressure of habitat modification caused by the weir.

ACTION

Study location and weir removal

The study location (53°17'11" N, 1°21'06" W; see Figure 1) is a low-gradient reach of the River Rother in England, UK. Slittingmill Weir was built c. 1920 to divert water from the river to power a waterwheel. The weir was approximately 2 m high and 16 m wide and created an impoundment that extended 600 m upstream. It was dismantled using an excavator in autumn 2020 by a contractor appointed by DCRT. The cut stone blocks were salvaged, and the remaining debris (stone and concrete) redistributed in the channel in the immediate vicinity of the dismantled weir.

Sampling of aquatic invertebrates

Sampling and identification of the aquatic macroinvertebrate community was undertaken by a citizen science team composed of DCRT staff and trained volunteers. Six sites were sampled (Figure 1): one located downstream of the weir (D/S Impact), three located upstream of the weir within the impounded river reach (U/S Impact 1-3), and two located further upstream above the weir impoundment and beyond the hydraulic influence of the weir (Control 1-2). We prioritised having more site replicates upstream as we expected the removal of the weir to have a greater impact here than at the downstream reach.

Samples were collected on seven separate occasions in 2018-2022 (three before the weir was removed and four after). Sampling was carried out each autumn and spring, except autumn 2019 when a long period of heavy rain prevented sampling, and spring 2020 when COVID-19 travel restrictions delayed sampling until summer 2020.

Contextual data for each site was collected for each sampling event, including average river depth (cm), wetted channel width (m) and estimates were made of the percentage cover of five riverbed substrate classes: 'silt and clay', 'sand', 'pebbles and gravel', 'boulders and cobbles', and 'bedrock'.

All sampling was carried out using UK Environment Agency guidelines (BT001) (Murray-Bligh 1999). Using a standard 250 mm wide kick sampling net with a 1 mm mesh, three 1-minute kick samples were collected along a transect line across each of the six sites.

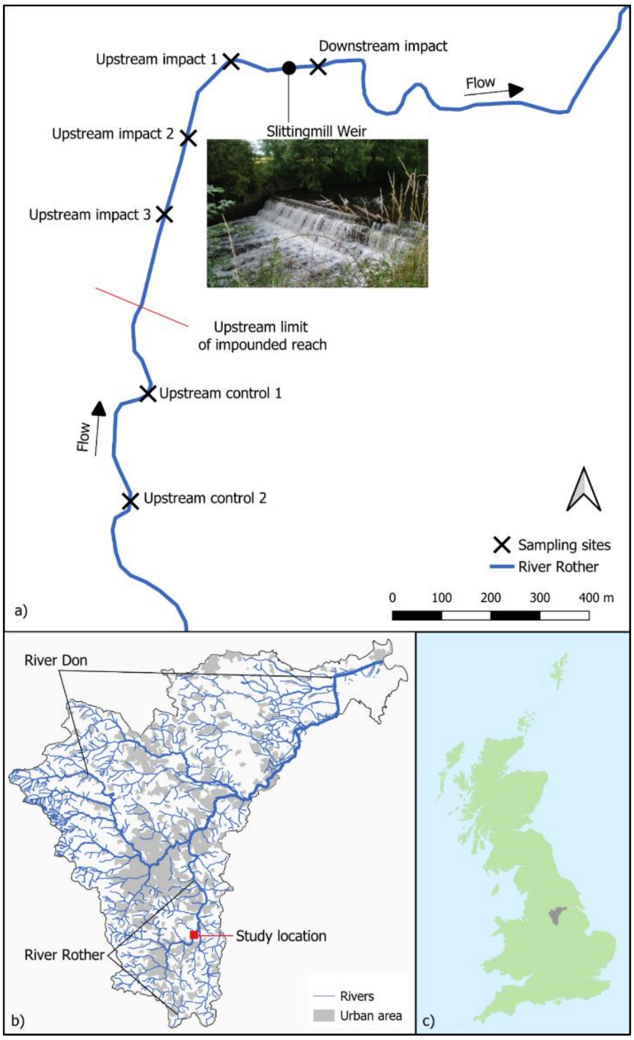

Figure 1. a) Position of the sampling sites relative to Slittingmill Weir, b) position of the study location on the River Rother in the Don Catchment, c) position of the Don Catchment in Great Britain.

The three samples were then combined to make a single sample per site. Afterwards, a 1-minute stone search was carried out, with macroinvertebrates scraped by hand into the combined site sample. For the site immediately upstream of the weir (U/S Impact 1), where the river was too deep to kick sample before weir removal, a sweep sample was collected using a net on an extended pole.

Samples were stored in 80% ethanol for later identification. All specimens were identified to at least family-level, and where possible to genus or species. Verification was provided by a lead volunteer with expertise in invertebrate identification and supported by tuition and written materials including the Guide to Freshwater Invertebrates (Dobson *et al*. 2013). The data has been published on the digital data repository Figshare (Hancock *et al*. 2025, DOI: https://doi.org/10.6084/m9.figshare.28840847.v1).

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Data analysis

Data were analysed using R Statistical Software (v4.4.2; R Core Team, 2024) using the ggplot2 package (v3.5.1; Wickham, 2016) for figures. Table 1 gives details of the different indices tested. In addition, counts of waterlice, broad-winged damselflies (Calopterygidae), net-spinning caddisflies, northern caddisflies and green sedge caddisflies were sufficiently abundant to enable statistical analysis to assess apparent changes in the abundance in these taxa following weir removal.

Generalised linear mixed-effect models (GLMM) of the following form were fitted to the macroinvertebrate indices and taxa counts (i.e. the response variables):

Response ~ BA * CI + (1|Site) + (1|Sampling event) + (1|Season)

Where BA (Before-After) and CI (Control-Impact) are fixed factors, and BA * CI represents their interaction. A statistically significant interaction indicates that the effect of weir removal differs between upstream impact and upstream control sites.

Sampling was carried out on three occasions before weir removal at three upstream sites (n = 9) and two control sites (n = 6), and four occasions after weir removal (upstream n = 12, control n = 8). Samples were treated as individual replicates in the analysis.

Site (n = 6), sampling event (n = 7), and season (n = 3) were tested as potential random effects and retained if they improved model fit (measured as a reduction in the Akaike Information Criterion). The inclusion of these possible random effects helped account for the potential effect of pseudoreplication from repeated sampling at the same sites. We did not use data from the downstream impact site as the absence of site replication downstream of the weir caused convergence issues with the GLMMs.

The models were created using the glmmTMB package (v1.1.10; Brookes *et al*. 2017). Model distributions were selected based on the statistical characteristics of the response variables: negative binomial for the counts; beta for the percentages; and normal for the LIFE and E-PSI indices. Pairwise comparisons of the before and after periods for the control and upstream site sites were conducted using estimated marginal means (EMM) using the emmeans package (v1.10.5; Lenth, 2024).

Table 1. Overview of the six macroinvertebrate community metrics and indices derived for each sample.

Metric / index	Description	Purpose
Macroinvertebrate count	The total count of individual macroinvertebrates.	To indicate potential changes to the macroinvertebrate community. For example, if populations declined at the impact sites due to disturbance caused by the weir removal.
Proportion of macroinvertebrate count EPT	The percentage of the total count of macroinvertebrates that are members of Ephemera, Plecoptera or Trichoptera (EPT).	EPT families are generally more sensitive than many other taxa to stressors such as pollution, flow regime and habitat degradation, and so this metric can be used as an indicator of stream health (Herman & Nejadhashemi 2005).
Taxon richness	The total number of macroinvertebrate families.	This metric is a coarse indicator of stream health, and assumes a positive association between the number of macroinvertebrate families present and stream health (Herman & Nejadhashemi 2005).
Proportion of taxa EPT	The percentage of the total number of macroinvertebrate families that are members of Ephemera, Plecoptera or Trichoptera.	EPT families are generally more sensitive than many other taxa to stressors such as pollution, flow regime and habitat degradation, and so this metric can be used as an indicator of stream health (Herman & Nejadhashemi 2005).
Lotic-invertebrate Index for Flow Evaluation (LIFE)	LIFE is a macroinvertebrate community-level index that is calculated using the known flow preferences of macroinvertebrate taxa (Extence *et al*. 1999). The present study uses a family-level application of the index (the index can also be applied at the species level). Life scores fall within the range of 0 to 12, where a higher score indicates faster prevailing flow conditions.	To indicate whether changes to the flow regime resulting from weir removal influenced the macroinvertebrate community.
Empirically-weighted Proportion of Sediment-sensitive Invertebrates (E-PSI) index.	E-PSI is a macroinvertebrate community-level index similar to LIFE in concept and operation, but has been designed to indicate fine-sediment related stress in streams based on the known sensitivities of taxa to fine sediment, generating a score between 0 (completely sedimented) and 100 (free from the impact of sediment) (Turley *et al*. 2016).	To indicate whether changes to the distribution of fine sediment resulting from weir removal influenced the macroinvertebrate community.

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To compare our macroinvertebrate data with a near natural state, we used the River InVertebrate Prediction and Classification System (RIVPACS) IV. This statistical tool predicts the likelihood of river macroinvertebrate families being present and their expected abundances in a kick-sample taken from a river in the UK based on a set of environmental attributes that includes altitude, latitude and longitude, and substrate (Davy-Bowker *et al*. 2008). As RIVPACS predicts the expected macroinvertebrate fauna that would be present at a site subject to minimal anthropogenic stressors, its predictions can serve as an ecological 'reference' state. We ran RIVPACS using the online River Invertebrate Classification Tool (RICT v3.1.8; Environment Agency *et al*. 2021). Predictions were obtained for the two control sites over each of the six sampling events, giving 12 reference predictions in total. The downstream and upstream impact sites were not included in this analysis as the weir had a large influence on some of the RIVPACS input variables such as average depth, average width and substrate composition, and so predictions generated for these sites would not be representative of the near natural state at the study location.

Non-metric multidimensional scaling (NMDS) was implemented using the vegan package (v2.6-8; Oksanen *et al*. 2024) to assess changes in the similarity of the macroinvertebrate community composition at the downstream impact, upstream impact and control sites. These were also compared to the reference predictions generated by applying RIVPACS to the control sites. RIVPACS does not make binary presence-absence predictions, but rather generates probabilities of occurrence and abundance estimates for a longlist of macroinvertebrate families. Therefore the 12 sets of reference predictions generated for this study were converted into simulated abundance data. Families were randomly assigned as present or absent in a simulated sample according to their probability of occurrence, resulting in the 'reference samples' used in the NMDS analysis. Dissimilarity between communities was calculated using Bray-Curtis distance. The NMDS solutions were determined in two dimensions using multiple random starts. Vector fitting was performed to test (Pearson's coefficient) whether the width, depth, and substrate related to the corresponding NMDS ordination. Statistical significance of these correlations was evaluated with 999 permutations of the data

CONSEQUENCES

Macroinvertebrate community

Table 2 presents the results of the GLMM analysis for the six macroinvertebrate indices and five macroinvertebrate family counts, while Figure 2 shows these indices and counts plotted over the seven sampling events for the downstream impact, upstream impact and control sites. There were statistically significant interactions between the control and impact sites for the proportion of taxa EPT, LIFE and E-PSI indices, with each undergoing a statistically significant increase at the upstream impact sites following weir removal, but not at the control sites. The proportion of the macroinvertebrate count composed of EPT taxa also underwent a statistically significant increase at the impact sites, but there was not a significant interaction with the control sites.

For the upstream impact sites, the counts of net-spinning caddisfly and green sedge caddisfly displayed statistically significant increases following weir removal (average sample counts before = 0.2, after = 66, and before = 0.3, after = 6 respectively) but there were no significant changes for the control sites. In contrast, waterlice, broad-winged damselflies, and northern caddisflies underwent statistically significant declines at the upstream impact sites (average sample counts before = 15, after = 0.3, before = 5, after = 0.08 and before = 1.2, after = 0.2 respectively). Again, there were no statistically significant changes in the counts from the control sites following weir removal.

Figure 2 shows that all the macroinvertebrate indices showed substantial variability within and across the sites, both before and after weir removal. Despite this variability, there was a discernible short sharp decline in the macroinvertebrate count and in taxon richness at the impact sites immediately following weir removal. For the impact site macroinvertebrate counts (both downstream and upstream combined), sampling event averages before weir removal ranged from 308 to 690. They then dropped to 141 immediately after weir removal, before rebounding to 726 (spring 2021), 657 (autumn 2021) and 221 (spring 2022). A similar short-term decline was apparent in taxon richness. Average upstream impact values before weir removal ranged from 14.7 to 18.3, compared to 11.7, 10.3, 19.6, and 11.7 afterwards. These short-term declines were not observed at the control sites. Although the GLMM did not detect a statistically significant difference between the before and after values, this may reflect the rapid rebound in values during the period following weir removal. Table 3 presents the 35 macroinvertebrate families predicted by RIVPACS to be more likely present than absent (>50%) at the study location under minimal anthropogenic stressors, with symbols representing their actual absence or abundance in each of the sampling categories. Seven families, non-biting midges, pea clams, gammarid freshwater shrimps, small squaregill mayflies, ramshorn snails, long-horned caddisflies and pond snails were found in all sampling categories before and after weir removal. Another seven, spiny-crawler and flat-bodied mayflies, rolled-winged stoneflies and springflies, little brown sedges, goerid caddisflies and bladder snails were absent from all sites before and after weir removal. Most of the change following weir removal occurred in the upstream impact sites. Predaceous diving beetles and lesser water boatmen disappeared, while small minnow mayflies and riffle beetles, two families predicted by RIVPACS to be almost certainly present under near natural conditions, appeared for the first time. There were no clear patterns in the changes in the downstream and control sites.

A two-dimensional solution was obtained for the NMDS ordination analysis of family-based macroinvertebrate community composition of the

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samples, with a final stress of 0.161, indicating a reasonable fit to the data. The upstream impact sites partially separated along the NMDS1 axis (see Figure 3), indicating these sites had community compositions that tended to differ. The NMDS1 axis was positively associated with trumpet-net caddisflies, small minnow mayflies, riffle beetles, blackflies and gammarid shrimps, and was negatively associated with broad-winged damselflies, and bushtailed and humpless casemaking caddisflies. The proportion of substrate composed of boulders and cobbles was also positively associated with NMDS1 axis ($p = 0.47$).

By contrast, the before and after samples for the downstream impact and control sites were similarly distributed, suggesting comparable community compositions. The RIVPACS 'reference samples' did not overlap with samples from any of the study sites. However, the upstream impact sites moved closer to the RIVPACS predictions following weir removal, indicating that the upstream impact macroinvertebrate community had become more similar to the RIVPACS reference samples. The downstream impact sites, before and after weir removal, and the before weir removal upstream impact sites were most dissimilar to the RIVPACS reference samples.

In total 20,794 individual aquatic macroinvertebrates were sorted into 53 families over the course of the study. Of these, four families accounted for more than 71% of the total sample size; non-biting midges (39%), small squaregill mayflies (12%), mud snails (11%) and gammarid freshwater shrimps (10%). The latter two families were composed entirely of three species: the invasive Jenkin's spire shell *Potamopyrgus antipodarum*, an exotic *Crangonyx* sp., and the invasive demon shrimp *Dikerogammarus haemobaphes*. Overall, 12 EPT families were recorded with a total abundance of 2,747 individuals (13% of the total macroinvertebrate abundance). The most common were net-spinning caddisflies and long-horned caddisflies, which composed 68% and 11% of the total number of EPT counted. No stoneflies were found during the study.

Costs

The costs of the weir removal were associated with staff time, professional services (feasibility, design, project management), and the price of the contractor, which together came to <£50,000.

Table 2. Summary of the GLMM for six macroinvertebrate indices and five macroinvertebrate counts. The interaction effect ratio is the predicted magnitude by which the response variable has changed following weir removal in the upstream impact samples relative to the control samples. The Relative Effect Estimate is the difference or relative change between the Estimated Marginal Means (EMMs) for the upstream impact and control sites before and after weir removal. Statistically significant results are highlighted in **bold**. The number of replicates per sampling category varied: Control Before n = 6; Control After n = 8; Upstream Impact Before = 9; Upstream Impact After = 12.

Response variable	BA * CI Interaction Effect Ratio Control vs Impact	Control Before vs After Relative Effect Estimate	Upstream Impact Before vs After Relative Effect Estimate
Macroinvertebrate count	1.7 p = 0.30	-31% p = 0.31	18% p = 0.65
% count EPT	1.68 p = 0.38	102% p = 0.15	**241% p = 0.015**
Taxon richness	0.80 p = 0.20	2% p = 0.90	-18% p = 0.12
% taxa EPT	**1.9 p < 0.01**	19% p = 0.33	**123% p < 0.0001**
LIFE score	**1.1 p < 0.01**	2% p = 0.42	**11% p < 0.0001**
E-PSI score	**2.5 p < 0.0001**	7% p = 0.42	**164% p < 0.0001**
Waterlice count	**0.05 p < 0.01**	-50% p = 0.30	**-97% p < 0.0001**
Broad-winged damselflies count	**0.02 p < 0.01**	-25% p = 0.78	**-99% p = 0.0001**
Net-spinning caddisflies count	**168.5 p < 0.0001**	70% p = 0.45	**28,649% p < 0.0001**
Northern caddisflies count	**0.05 p = 0.035**	200% p = 0.36	**-87% p = 0.019**
Green sedge caddisflies count	**18.1 p = 0.018**	-27% p = 0.70	**1231% p < 0.01**

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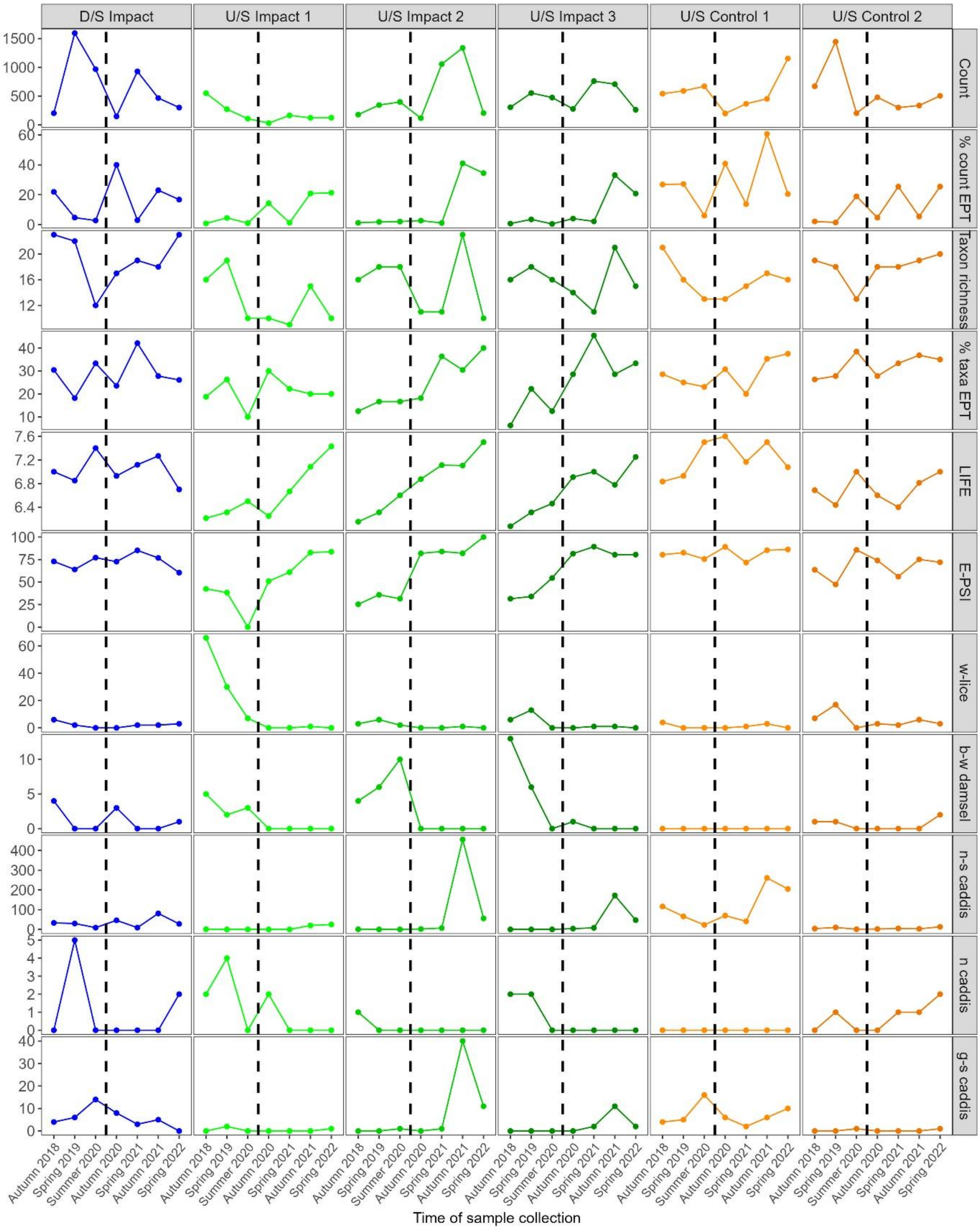

Figure 2. For each sampling site the number of macroinvertebrates counted, the percentage of the count that is mayfly (Ephemeroptera), stonefly (Plecoptera) or caddisfly (Trichoptera) (EPT), taxon richness (family level), the percentage of families that is EPT, the Lotic-invertebrate Index for Flow Evaluation (LIFE), the Empirically-weighted Proportion of Sediment-sensitive Invertebrates (E-PSI), and the counts of waterlice (w-lice), broad-winged damselflies (b-w damsel), net-spinning caddisflies (n-s caddis), northern caddisflies (n caddis) and green sedge caddisflies (g-s caddis). Each index is plotted over the seven sampling events. The dashed line separates the before and after weir removal sampling events.

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Table 3. The 35 macroinvertebrate families predicted by RIVPACS to be more likely present than absent (>50%) at the study location under minimal anthropogenic stressors. The actual presence or absence of these families in the sampling categories are indicated with symbols:
○ = absent, ● = present (1 – 9 individuals counted), ■ = present (10 – 99 individuals counted), ✚= >100 individuals counted.

	RIVPACS predictions	Down-stream		Upstream						Control			
		Before	After	Before			After			Before		After	
Family	Probability of occurrence	DS1	DS1	US1	US2	US3	US1	US2	US3	C1	C2	C1	C2
Non-biting midges (Chironomidae)	100%	✚	✚	■	■	✚	■	✚	✚	✚	✚	✚	✚
Pea clams (Sphaeriidae)	99.3%	■	■	■	●	●	●	■	●	■	■	■	■
Small minnow mayflies (Baetidae)	99.3%	■	●	○	○	○	●	■	●	■	○	■	■
Riffle beetles (Elmidae)	99.3%	●	●	○	○	○	●	●	●	●	●	●	●
Gammarid shrimps (Gammaridae)	99.0%	✚	■	■	■	●	●	■	■	✚	■	■	■
Net-spinning caddisflies (Hydropsychidae)	98.2%	■	■	●	●	○	■	✚	■	■	●	✚	●
Spiny-crawler mayflies (Ephemerellidae)	95.6%	○	○	○	○	○	○	○	○	○	○	○	○
Snail leeches (Glossiphoniidae)	94.0%	●	●	●	●	●	○	○	●	●	●	○	●
Blackflies (Simuliidae)	92.0%	■	●	●	●	●	●	■	●	■	○	●	●
Mud snails (Hydrobiidae)	91.8%	○	○	●	○	○	○	○	○	○	○	○	○
Horse leeches (Erpobdellidae)	89.7%	●	●	○	●	●	●	●	●	●	●	●	●
Small squaregill mayflies (Caenidae)	89.5%	●	●	■	■	■	●	■	●	■	✚	●	■
Northern caddisflies (Limnephilidae)	88.9%	●	●	●	●	●	●	○	○	○	●	○	●
Craneflies (Tipulidae)	88.5%	●	●	○	○	●	●	●	●	●	●	●	●
Predaceous diving beetles (Dytiscidae)	87.6%	○	○	●	●	●	○	○	○	○	○	○	○
Waterlice (Asellidae)	85.7%	●	●	■	●	●	●	●	●	●	■	●	●
Green sedge caddisflies (Rhyacophilidae)	84.8%	●	●	●	●	○	●	■	●	●	●	●	●
Ramshorn snails (Planorbidae)	83.4%	●	●	●	●	●	●	●	●	■	●	●	●
Long-horned caddisflies (Leptoceridae)	80.2%	■	■	●	●	●	●	■	■	●	●	●	■
Pond snails (Lymnaeidae)	79.4%	●	●	■	●	■	●	●	●	●	●	●	●
Crawling water beetles (Haliplidae)	78.4%	○	○	○	○	●	○	○	○	○	●	○	○
Flat-bodied mayflies (Heptageniidae)	74.7%	○	○	○	○	○	○	○	○	○	○	○	○
Lesser water boatmen (Corixidae)	71.2%	○	○	●	●	●	○	○	○	○	○	○	○
Rolled-winged stoneflies (Leuctridae)	70.5%	○	○	○	○	○	○	○	○	○	○	○	○
Springflies (Perlodidae)	70.4%	○	○	○	○	○	○	○	○	○	○	○	○
Burrowing mayflies (Ephemeridae)	70.2%	●	●	○	●	○	○	○	○	○	○	○	●
Trumpet-net caddisflies (Polycentropodidae)	68.3%	○	●	●	●	●	●	●	●	●	●	●	●
Bushtailed caddisflies (Sericostomatidae)	64.7%	●	●	○	●	■	●	●	●	●	■	●	●
Alderflies (Sialidae)	64.2%	○	○	○	●	○	○	○	○	○	○	○	○
Micro-caddisflies (Hydroptilidae)	63.6%	●	●	○	○	○	●	●	●	■	○	●	●
Valve snails (Valvatidae)	60.8%	●	●	○	●	●	○	●	○	○	○	○	○
Little brown sedges (Lepidostomatidae)	58.2%	○	○	○	○	○	○	○	○	○	○	○	○
Bladder snails (Physidae)	57.8%	○	○	○	○	○	○	○	○	○	○	○	○
Goerid caddisflies (Goeridae)	55.7%	○	○	○	○	○	○	○	○	○	○	○	○
Freshwater flatworms (Planariidae)	51.1%	●	○	○	○	○	○	○	○	○	○	○	○

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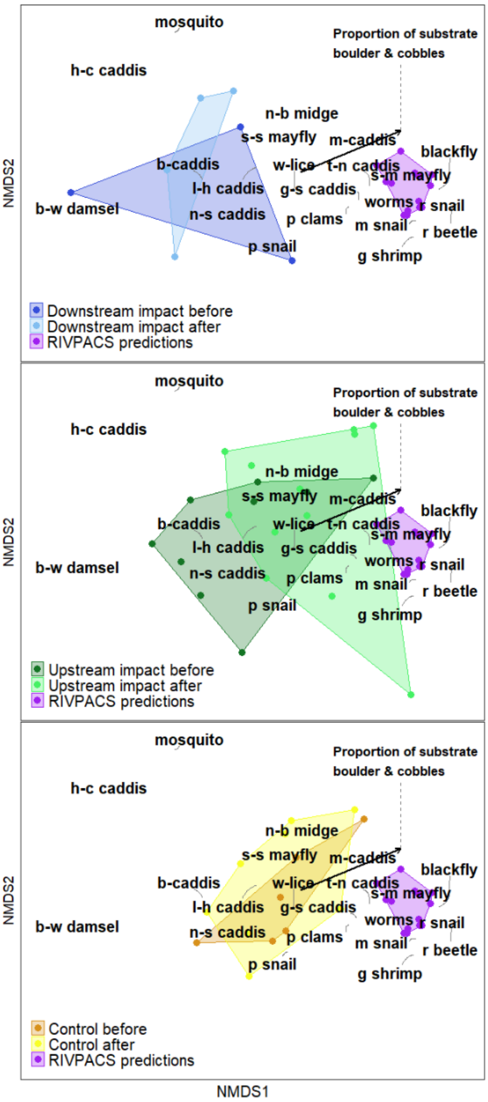

Figure 3. Non-metric multidimensional scaling (NMDS) ordination plot for the aquatic macroinvertebrate samples at all sampling sites. Each point represents one of the samples, with proximity indicating how similar they were in terms of the composition of macroinvertebrate families. The downstream impact, upstream impact and control sites are presented on separate plots to aid interpretation. The 20 most abundant macroinvertebrate taxa are positioned in the ordination, representing the distribution patterns of these taxa across the samples (b-w damsel = boad-winged damselfly, h-c caddis = humpless casemaker caddisfly, b caddis = bushtailed caddisfly, n-s caddis = net-spinning caddisfly, l-h caddis = long-horned caddisfly, g-s caddis = green sedge caddisfly, m-caddis = microcaddisfly, t-n caddis = trumpet-net caddisfly, s-s mayfly = small squaregill mayfly, s-m mayfly = small minnow mayfly, n-b midge = non-biting midge, r beetle = riffle beetle, g shrimp = gammarid shrimp, r snail = ramshorn snail, p snail = pond snail, m snail = mud snail, p clam = pea clam). Only one environmental variable, the proportion of substrate composed of boulders and cobbles, was associated with the ordination axes, with a significant correlation ($p = 0.047$), and this association is indicated by the vector.

Habitat change

The removal of Slittingmill Weir had a visible impact on habitat at the upstream impact sites (Figure 4). The water level was reduced so that the river became shallower and gravel side and mid bars were exposed, and the speed of water flow increased as was indicated by the appearance of current ripples where previously there were none. There were no obvious visual changes to the river at the downstream impact or control sites. These visual observations are reflected in the measurements made during sampling (Figure 5). Water depth reduced by approximately half at the upstream impact sites, and there was a reduction in the wetted channel width, while there was no apparent change at the downstream impact or control sites.

Figure 4. Photographs of the site of Slittingmill Weir (a) before (b) after, and of the river channel 350 m upstream of the weir (c) before (d) after the weir removal.

There was also a substantial change in substrate at the U/S Impact 1 site. Before weir removal, the substrate was estimated as being 100% ‘silt and clay’ (see Table 4), and after weir removal <50% was estimated as ‘silt and clay’, with ‘pebble and gravel’ becoming the commonest sediment type. Substrate estimates at the other sites remained similar following the weir removal.

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Table 4. Change in the average substrate composition estimates at each of the sampling sites following the weir removal.

Site		Average sediment cover estimate (%)				
		Silt and clay	Sand	Pebbles and gravel	Boulders and cobbles	Bedrock
D/S Impact	Before	1.7	13.3	35	46.7	3.3
D/S Impact	After	10	6.3	73.8	10	0
D/S Impact	Change (%)	500	-53.1	110.7	-78.6	-100
U/S Impact 1	Before	100	0	0	0	0
U/S Impact 1	After	30	5	55	10	0
U/S Impact 1	Change (%)	-70	-	-	-	-
U/S Impact 2	Before	11.7	3.3	70	10	3.3
U/S Impact 2	After	7.5	2.5	70	23.8	0
U/S Impact 2	Change (%)	-35.7	-25	0	137.5	-100
U/S Impact 3	Before	6.7	3.3	53.3	30	3.3
U/S Impact 3	After	17.5	5	52.5	27.5	0
U/S Impact 3	Change (%)	162.5	50	-1.6	-8.3	-100
U/S Control 1	Before	5	0	50	42.5	2.5
U/S Control 1	After	3.8	0	33.8	53.8	8.8
U/S Control 1	Change (%)	-25	-	-32.5	26.5	250
U/S Control 2	Before	15	3.3	45	33.3	0
U/S Control 2	After	30	0	33.8	18.8	2.5
U/S Control 2	Change (%)	100	-100	-25	-43.8	-

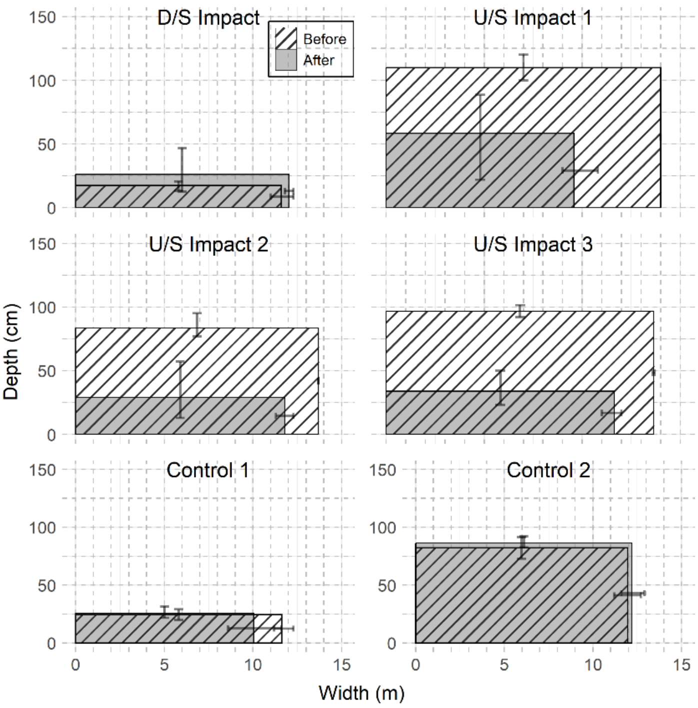

Figure 5. Average water depth and wetted width measurements at each of the sampling sites before and after weir removal. Bars represent the maximum and minimum measurements.

DISCUSSION

Empirical studies have shown that weir removal can improve the condition of river ecosystems, but not in all circumstances (Carlson *et al*. 2018; Bellmore *et al*. 2019). Urban rivers have some characteristics that could limit how a macroinvertebrate community responds to weir removal. This study tested whether the removal of Slittingmill Weir from an urban river, the Rother, led to positive changes in the macroinvertebrate community. Our results provide strong evidence for a shift in the composition of the macroinvertebrate community at the upstream impact sites following weir removal. This is despite the Rother being an urban river, with invasive non-native species now making up a large proportion of the macroinvertebrate population at our study location.

The increased proportion of taxa composed of EPT families at the upstream impact sites following weir removal is consistent with an increase in stream health. The concurrent increase in LIFE and E-PSI scores to levels comparable to those at the control sites suggests that the changes observed are due to the removal of Slittingmill Weir having an alleviating influence on flow and fine-sediment stress on the macroinvertebrate community at the upstream impact sites.

There appears to have been a short-term negative effect of the weir removal on the macroinvertebrate community, which is unsurprising given this has been found during other dam removal studies (Carlson *et al*. 2018). In this study taxon richness dips at the upstream impact sites, before rebounding by the sixth sampling event, one year after weir removal. The weir removal may also have caused a dip in the macroinvertebrate counts at all impact sites, but the control sites underwent similar but less pronounced changes in counts, so it is not clear to what degree this was an effect of the weir removal or other factors. These observations may be reassuring to those contemplating urban weir removal, as a common concern raised in such circumstances is that the mobilisation of historically contaminated sediments could cause ecological harm. Despite our study location being sited on a previously severely polluted river and a short distance downstream of a former chemical works and other heavy industry, the disturbance to the macroinvertebrate community caused by the weir removal appears short-term.

The NMDS ordination revealed that the changes to the macroinvertebrate community at the upstream impact sites following weir removal resulted in it becoming more similar to the RIVPACS reference samples. This shows that the macroinvertebrate community at these sites became closer to what would be expected to occur at the study

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location if it was in a near natural state. That the downstream impact site samples were distant from the control and reference site samples was unexpected, as the effect of the weir on downstream habitat was less visually obvious. The downstream impact site may therefore have been more influenced by the weir than we assumed, despite not being subject to the same depth and velocity modifications that occur upstream of weirs. However, this observation should be interpreted with caution due to the lack of site replicates on the downstream impact reach.

While the proportion of substrate that is boulder and cobble was the only environmental variable that was found to have a statistically significant correlation with the ordination axes, other lines of evidence suggest that habitat changes following weir removal drove a shift in the upstream impact macroinvertebrate community. Three families that underwent statistically significant declines — waterlice, northern caddisflies and the species of broad-winged damselfly present in our study, banded demoiselle *Calopteryx splendens* — are associated with slow flowing or standing water (Extence *et al*. 1999). In contrast, green sedge and net-spinning caddisflies, which underwent statistically significant increases, are associated with rapid to moderate flows (Extence *et al*. 1999). Likewise, the predaceous diving beetles and lesser water boatmen, which disappeared from the upstream impact sites, are associated with slow flowing or standing water, while small minnow mayflies and riffle beetles, which appeared for the first time, are associated with moderate to fast flows (Extence *et al*. 1999). This interpretation of habitat changes causing the shift in the macroinvertebrate community is reinforced by the changes to habitat that are clearly apparent both visually at the site and in the depth and width data for the upstream impact sites.

Of the families predicted by RIVPACS to be more likely present than absent at the study location under near natural conditions, but were consistently absent throughout the study, all but one were EPT families. Their absence from all sampling sites suggests that factors other than the impact of the weir were causing their absence. Given that EPT families are often disproportionately sensitive to pollution (Herman & Nejadhashemi 2005), it is plausible that water quality issues at the study location were responsible. This demonstrates that weir removal alone is unlikely to restore the community to its near natural state.

There are a number of limitations with the present study, and some caution should be applied to the interpretation of the results. The numbers of samples, limited across time and space due to practical constraints, restricted the statistical power of the analysis, reducing the likelihood of detecting smaller effects. The absence of statistically significant changes, for example to macroinvertebrate counts or taxon richness, should not be interpreted as evidence that weir removal had no effect on these metrices, as the small number of samples increases the likelihood of false negatives. Another limitation was that we only had one site replicate at the downstream impact reach, meaning it could not be included in the GLMM analysis. Possible future weir removal studies could aim to look for changes at the downstream impact reach or run a lengthier study to monitor for longer term changes.

A notable feature of the study is that citizen scientists and staff helped collect samples and identify the macroinvertebrates. As a result, sampling effort will have varied, and volunteers and staff working on macroinvertebrate identification ranged in experience levels, meaning some misidentification and miscounting of specimens is possible. Nonetheless, systemic error is unlikely, as the work was divided amongst a wide range of people that varied over the course of the study, and verification checks were made by a volunteer expert. Any error will therefore contribute random noise to the data and is more likely to cause a false negative than a false positive.

Despite the limitations of this study, we believe that it has produced strong evidence that weir removal in an urban river can, in the impounded upstream reach, lead to improved river habitat, an amelioration of pressures caused by flow impairment and fine-sediment and shift the macroinvertebrate community closer towards a near natural state. There are likely to be more urban river weir removal projects in the wider region over coming years as the UK Environment Agency, the regional water company Yorkshire Water, and environmental charities such as the Don Catchment Rivers Trust have formed the Great Yorkshire Rivers partnership, which has the stated target of addressing all of Yorkshire's artificial river barriers (mainly weirs) by 2043. While the primary aim of the partnership is to benefit fish populations in this region, this study demonstrates that weir removal will also likely result in ecological benefits for macroinvertebrate communities.

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