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RESEARCH ARTICLE

Assessing methods to improve benthic fish sampling in a stony headwater stream

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Abstract

1. Electrofishing is a well-established and widely used method for surveying fish populations. Nonetheless, its effectiveness is impacted by numerous factors, including water chemistry, habitat type and fish species. Both physiological and behavioural responses make bottom-dwelling 'benthic' fish which lack swim bladders (e.g. European bullhead *Cottus gobio*) particularly difficult to survey by electrofishing.
2. We compare the performance and practicalities of electrofishing for benthic fish at a rocky northern English headwater stream with two sampling methods originally designed for crayfish surveys; the triple drawdown method which involves repeated dewatering of a site, and the Pritchard Trap method which involves sunken traps filled with natural substrate that samples a small, fixed (0.25 m^2) area of river bed.
3. Both the Pritchard trapping and triple drawdown methods provided similar high-density population density estimates for bullhead which were at least 2.5–5 times higher than predicted from electrofishing derived sweep depletion curves.
4. Electrofishing and the triple drawdown method are both resource-intensive, requiring expensive equipment and a team of trained operatives. These approaches also pose a risk to fish and non-target organisms. In contrast, Pritchard Traps provide a cost-effective passive, low risk survey method requiring minimal training and only one operative. Pritchard traps, therefore, show particular promise for benthic fish surveying and monitoring.

KEYWORDS
bullhead, density estimates, electrofishing, population demographics, Pritchard trap, sampling bias, triple drawdown

1 | INTRODUCTION

Fish strongly influence the structure and functioning of freshwater ecosystems (Reynolds, 2011). At the same time, habitat modifications, pollution, overfishing, alien species invasions and climate change render freshwater fish one of the most threatened groups of vertebrates (Reid et al., 2013). Our knowledge of the influence of fish on freshwater ecosystems as well as fish population trends and conservation status hinges on gaining quantitative estimates on the densities of different species.

Fish populations can be surveyed using a variety of methods, including netting (e.g. seine netting; Neilson & Johnson, 1983; Pierce et al., 1990), trapping (e.g. minnow traps, Bloom, 1976; Bryant, 2000) acoustic telemetry (Crossin et al., 2017) and electrofishing (Beaumont, 2016; Reynolds, 1996). Electrofishing, widely used in stream biological monitoring, involves applying an electric field in the water to temporarily incapacitate fish, allowing them to be caught (Beaumont, 2016). Many physical factors affect the efficiency of electrofishing, including water clarity, depth and conductivity, substrate type and fish species. Benthic fish are notoriously difficult to capture by electrofishing, owing to their relatively small body size, behaviour and preference for staying close to the riverbed. Some benthic fish show a poor electrotactic response (Beaumont, 2016; Cowx, 1983), with some taxa also lacking a swim bladder (e.g. species in the Cottidae), reducing their buoyancy and thus the effectiveness of the anodes' pull. Further limitations to electrofishing relate to benthic species being associated with structures like cobbles and boulders that partially shield them from electric fields rendering incapacitated animals inaccessible. Whilst electrofishing and other contemporary methods have proven suitable and effective in sampling many species in various freshwater systems, a strong need persists for new methodologies that generate reliable quantitative data on benthic fish populations.

In some instances, benthic invertebrate sampling techniques have been adapted to sample benthic fish, for example Hess samplers and Surber samplers to survey European bullhead *Cottus gobio* in English chalk streams (Harrison et al., 2005; Woodward et al., 2008). These benthic invertebrate survey methods proved successful at quantitatively sampling bullhead, chiefly due to their sedentary nature. Recent methodological advances in surveying freshwater crayfish also show potential promise for benthic fish survey. The habitat requirements of benthic fish and crayfish often overlap (Bubb et al., 2009; Ruokonen et al., 2014), and methods that successfully survey crayfish within benthic habitats could hence reasonably be expected to also catch benthic fish. In this study, we investigate whether two recently developed crayfish survey techniques are suitable for quantitative benthic fish population assessment. The triple drawdown (TDD) technique introduced by Chadwick et al. (2021) involves repeated draining and re-wetting of an isolated section of a watercourse, with hand-removal of available refuges and river biota. The sequential capture of specimens from target species also allows for depletion analyses (e.g. Carle & Strub, 1978), facilitating estimates of the total population present and of the efficiency of the method (see Chadwick et al., 2021, for further details). The Pritchard Trap (PT) is a passive sampling trap, comprised of a collapsible mesh bag and quadrat (0.5 m × 0.5 m) set into the available substrate, which provides quantitative estimates of crayfish population demographics upon retrieval (≥4 days deployment time; see Pritchard et al., 2021).

In this study, we assess performance and practicalities of the two aforementioned crayfish survey methods against conventional electrofishing for surveying benthic fish, especially European bullhead *C. gobio* (hereafter 'bullhead'), in a rocky headwater stream in Northern England. We firstly hypothesize that both TDDs and PTs allow for quantitative assessments of benthic fish population densities. We further hypothesize that PTs require a minimum deployment time of 4 days to robustly survey benthic fish, based on the 4-day deployment required for crayfish. When comparing the ability of each method to produce robust demographic data on benthic fish populations, we hypothesize that electrofishing underestimates benthic fish population sizes when compared to both TDD and PT survey results.

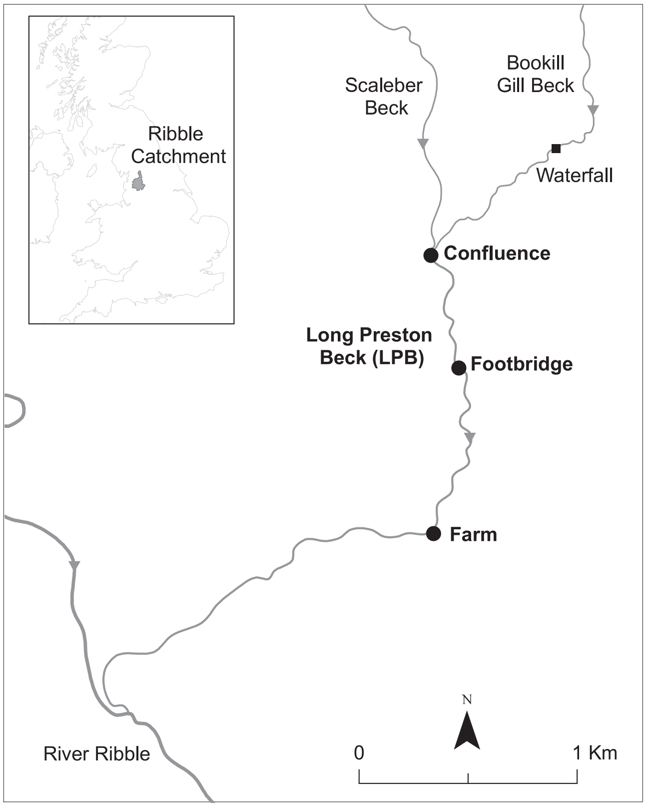

FIGURE 1 Site map showing study area, including the three study sites, Confluence, Footbridge and Farm along Long Preston Beck (LPB)

2 | MATERIALS AND METHODS

2.1 | Site description

The study was conducted at the upland headwater stream Long Preston Beck (LPB) in the Ribble catchment, North Yorkshire (Figure 1). Resident fishes at LPB include pelagic species: brown trout *Salmo trutta*, Atlantic salmon *S. salar* and minnow *Phoxinus phoxinus*, and benthic species: bullhead, stone loach *Barbatula barbatula* and European eel *Anguilla anguilla*. LPB is approximately 4 m wide along the study reach and joins the main River Ribble ~2.3 km downstream. The system is heavily impacted by signal crayfish *Pacifastacus leniusculus* invasions that have resulted in strongly varying fish population densities and localized fish extinctions (Peay et al., 2009). We established three study sites with prevailing fish populations along LPB: 'Confluence', 'Footbridge' and 'Farm' (Figure 1). Water depth across the sites averaged 10–25 cm during summer. The site area was 45.5 m^2 at both Conflu-

TABLE 1 Summary of field studies including sites, survey methods, survey area and year

Sampling Method	Year	Months	Site(s)	Sample size (m^2)
Electrofishing	2018	July–August	Confluence Footbridge Farm	One sweep (~45.5 m^2) Three sweeps (~45.5 m^2) Four sweeps (~50 m^2)
Triple drawdowns	2018	July–August	All	45.5–50 m^2 Four sweeps
Pritchard Trap (deployment time experiment)	2019	June–September	All	$n = 3$ (0.75 m^2)
Pritchard Trap (low sampling effort to assess population densities)	2018	July–August	Footbridge and Farm	$n = 4$ (1 m^2)
Pritchard Trap (repeat sampling to assess population structure)	2019	June–September	All	$n = 30$ (7.5 m^2)

ence and Footbridge and 50 m^2 at Farm. Each site comprised a series of pools and riffles, with in-channel substrate dominated by cobbles and boulders.

2.2 | Survey design

The study comprises two main components. Firstly, the performance of each survey method (electrofishing, TDDs and PTs) was assessed individually. Sweep depletions were evaluated for electrofishing and TDDs to generate total fish population estimates and to assess method efficiencies. PTs were tested over a range of deployment intervals (see below) at all sites to establish the minimum deployment time required to reach stable fish density estimates. Secondly, the three survey methods were compared to evaluate their ability to generate robust density and population demographic data for benthic fish.

Surveyed fish were collected by net (TDDs and electrofishing) or by hand (PTs) and placed in large buckets filled with frequently replaced cool, well-oxygenated water, that were kept in the shade. All fish were identified to species level, and total length (TL, mm) was measured and recorded on site. For electrofishing and TDDs, all young-of-year (YoY) bullhead were recorded as 20 mm TL based on measurements of a sub-sample of YoY at site. Once processed, fish were released immediately downstream of the site. A method statement and FR2 fishing licence was approved by the Environment Agency. The 'check, clean, dry' (NNSS, 2018) procedure was strictly followed, and all equipment was disinfected with either Virkon S Aquatic™ or FAM® 30 (iodophor based) between each use.

2.3 | Performance electrofishing, TDDs and PTs

2.3.1 | Electrofishing

Electrofishing was undertaken at each site (summer 2018, Table 1) by three trained (Institute of Fisheries Management) and experienced operatives using a Smith-Root 400w LR-20B Electrofishing backpack system. A single anode was employed by one operative, whilst the remaining two operatives used nets to capture fish. Stop nets (2 mm mesh size) were installed at the upstream and downstream limits of the site to prevent immigration or emigration of fish during electrofishing sampling and between electrofishing and TDD, with the electrofishing carried out in preparation of the subsequent TDDs (see below). The entire wetted area of each site was fishable and in reach of the anode and nets. However, there was a low water depth at places along the channel margins and a small number of immovable boulders within the channel at each site. A single electrofishing sweep was undertaken at Confluence, with no consecutive sweeps due to time constraints before the TDD. Three consecutive sweeps were undertaken at Footbridge, and four consecutive sweeps were undertaken at Farm. The multiple sweeps at Footbridge and Farm allowed depletion analyses to be carried out using the Carle–Strub maximum weighted likelihood method (Carle & Strub, 1978) in the FSA package (Ogle, 2018) in R Studio version 1.1.463 (RStudio Team, 2020). Total population estimates were generated, which allowed method efficiency to be calculated as the total number of fish caught as a percentage of the total estimated population. Density estimates were then calculated as the number of fish caught over the site area – and the expected density using the estimated total population over the site area.

2.3.2 | Triple drawdowns

TDDs were undertaken at each site immediately after the electrofishing surveys on each isolated stretch of LPB (summer 2018; Table 1). Given the large size of the dewatered river sections for the TDD of 45–50 m^2, two Honda Trash pumps (2 and 3 inches), four sweeps and 6–10 operatives were required at each site. All other aspects of the TDD approach were consistent with Chadwick et al. (2021). Multiple sweeps at each site allowed depletion analyses to be calculated using the same method as described above. This allowed for the generation of total population estimates, method efficiency and, in combination of site area measurements, fish density estimates for the TDD.

2.3.3 | Pritchard Traps

Specifications and general operation of PTs followed the approach described in Pritchard et al. (2021). The PTs comprised of a rigid

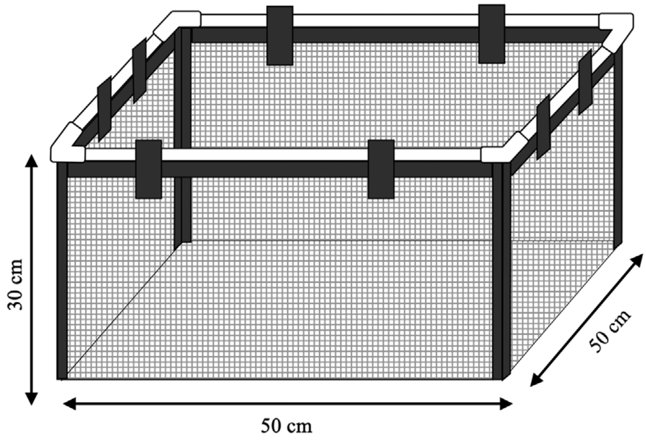

FIGURE 2 Technical drawing of the PT illustrating the plastic quadrat attached to the square mesh bag (Pritchard et al., 2021)

quadrat made up of four detachable plastic pipes (50 cm in length, 2.15 cm in diameter) attached to a green mesh bag (mesh size of 1.9 mm × 1.9 mm) with a base sampling area of 0.25 m^2 and 30 cm tall side panels (Figure 2). Further details of PT materials and construction can be found in Pritchard et al., 2021; Supporting Information, SI).

Each PT was set by clearing substrate such as cobbles and gravel from a 0.25-m^2 trap footprint within the river channel and collecting it into a bucket (Figure 3a). The PT was then pressed flat against the exposed riverbed (10–20 cm substrate depth), with the side panels folded flat under the quadrat, and quadrat corners were weighted down with large cobbles. The collected substrate was then placed on top of the flattened PT to reform the channel profile and set the trap (Figure 3b). PTs were set throughout the channel, including pools, riffles, central channel and margins. PTs were placed at least 2 m apart to avoid disruption between PTs upon retrieval. Cobbles were the dominant substrate type at each trap location. Deployment of one PT took one operative approximately 15 min. PTs were set using only naturally occurring substrate and left submerged for the entire deployment time with no disruption. To retrieve a PT, one operative carefully approached the set PT and pulled the quadrat sharply upwards causing the side panels to extend and entrap any animals within the PT.

A deployment time experiment was undertaken (summer 2019; Table 1) to establish the minimum deployment time required for fish numbers recorded in the PTs to stabilize. PTs were deployed at each site (n = 3 per site) for five time intervals; 1, 2, 4, 7, and 10 days. Upon retrieval, the traps were carefully emptied, with substrate from the traps separated into one bucket, and fish specimens into another. Fish were processed as described above and then released back into the site. PTs were reset in the same position using the same substrate for each time interval. Benthic fish species were grouped together to generate total fish numbers captured during each trapping event. Detection rates were calculated as the percentage of PTs with at least one individual benthic fish captured.

2.4 | Comparison of methods (electrofishing, TDD and PT)

The fish data generated through each method were compared to determine differences in estimated community species structure. Density estimates and population size structure of bullhead as the dominant benthic fish species in the system were also explored across all three methods. Additional PT sampling was undertaken in 2018 with a low sampling effort (n = 4) for density estimates at Footbridge and Farm

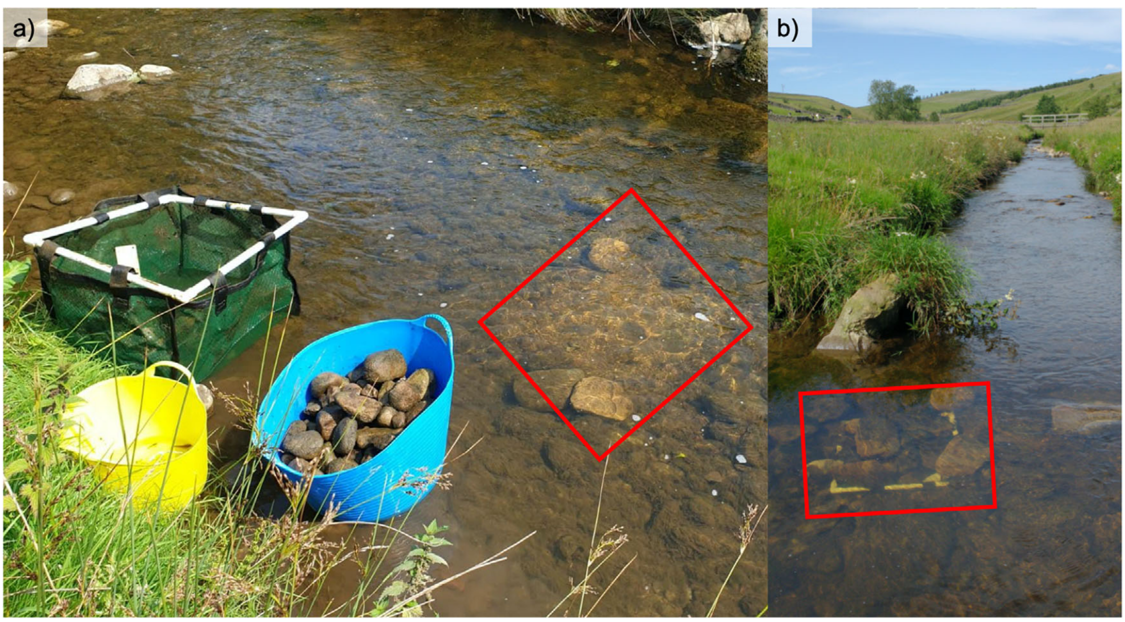

FIGURE 3 Photographs of a PT: (a) ready to be set into outlined area and filled with naturally occurring substrate collected into a bucket and (b) set into the riverbed

prior to secondary sampling by electrofishing and TDD. Repeat PT sampling was also undertaken in summer 2019 (Table 1) to increase sample size (n = 30; 7.5 m^2) in order to enable robust comparisons of population demographics. In all these sampling events, PTs were deployed for a minimum of 4 days. An estimate of true fish density for the three sites was generated through summing all fish physically removed via electrofishing prior to the TDD and the total TDD-derived population estimate (Carle–Strub) for each site. Comparative analyses of the methods were carried out in SPSS (version 27) for statistical descriptors on demographic data. We used the ggplot 2 package (Wickham, 2016) in R (version 3.5.1) for the graphical representation of the population structures.

3 | RESULTS

3.1 | Performance of methods

3.1.1 | Electrofishing

At Confluence, 51 benthic fish (SI) were caught in a single electrofishing sweep (Figure 4a). At Footbridge, a total of 241 benthic fish (SI) were caught over three sweeps (138, 55, and 48, respectively, Figure 4b). Capture efficiency was estimated at 84%, resulting in a total population estimate of 287 (standard error (SE) 16.19), with lower and upper 95% confidence intervals of 255.3 (SE 0.36) and 318.7 (SE 0.55) specimens. At Farm, a total of 259 benthic fish (SI) were caught over four sweeps (70, 72, 75, and 42, respectively; Figure 4c). Capture efficiency was estimated at 45.1%, resulting in a total population estimate of 574 (SE 160.07) specimens, with lower and upper intervals of 260.3 (SE 0.04) and 887.7 (SE 0.23). All fish were released outside the isolated river stretches following recording of species and size.

3.1.2 | Triple drawdowns

Following the completion of electrofishing at the isolated river sections, the four subsequent, consecutive TDD sweeps at Confluence caught an additional 352 benthic fish individuals (152, 100, 54 and 46, respectively; Figure 4a, SI). Capture efficiency was estimated at 83.2%, resulting in a total population estimate of 423 (SE 20.12) specimens with lower and upper intervals of 383.6 (SE 0.29) and 462.4 (SE 0.42). At Footbridge, an additional 1253 benthic fish were caught over four TDD sweeps (837, 302, 54 and 60, respectively, Figure 4b, SI) following the electrofishing. Capture efficiency was estimated at 98.6%, resulting in a total population estimate of 1271 (SE 5.10) individuals, and with lower and upper intervals of 1261 (SE 0.63) and 128 (SE 0.68), respectively. At Farm, 1332 benthic fish were caught over four TDD sweeps (637, 309, 256 and 130 respectively, Figure 4c, SI). Capture efficiency was estimated at 86.9%, resulting in a total population estimate of 1532 (SE 29.36), with lower and upper intervals of 1475 (SE 0.37) and 1590 (SE 0.43), respectively.

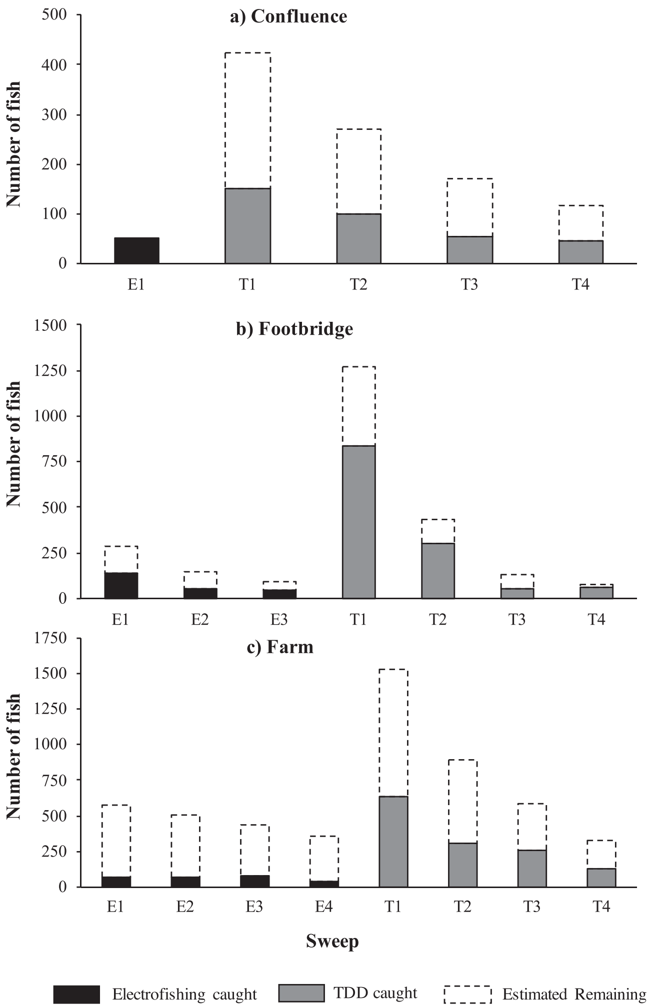

FIGURE 4 Number of benthic fish caught in each electrofishing sweep (E, black bar) and by the subsequent TDD sweeps (T, grey bar) in the same, isolated river sections. Carle–Strub depletion-based total population estimates, calculated separately for each method (dashed lines), indicate how many fish were available to be caught in each sweep according to the depletion curves for the respective method

3.1.3 | Pritchard Trap deployment time

PTs successfully sampled benthic fish at all sites (Confluence, Footbridge and Farm). Benthic fish were reliably detected after the minimum deployment time of 1 day at all the sites (Figure 5). At Footbridge and Farm, PTs consistently (29/30) detected fish presence across all time intervals. At Confluence, individual detection was more variable (6/15), but fish were detected at each time interval except 7 days, where no fish were captured.

Fish numbers generally stabilized after 2 days, but with high fluctuations at Confluence where the overall lowest density of fish was recorded. Furthermore, while a high density was recorded at Footbridge after only 1 day, subsequent data showed an increase in observed numbers with time, and peak density estimates for every site were only reached at the maximum exposure time interval of 10 days.

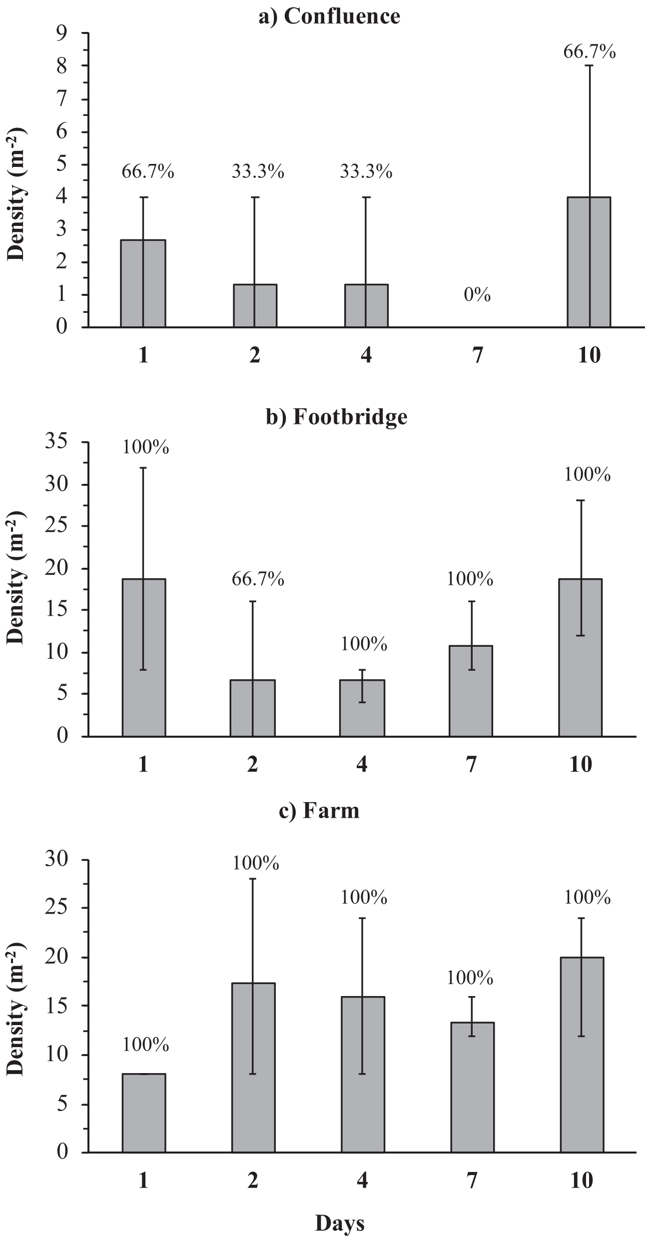

FIGURE 5 Density of benthic fish (m^{-2}) generated from PTs (2019, $n = 3$, 0.75 m^2) after deployment times of 1, 2, 4, 7 and 10 days. Error bars show deviation from average of minimum and maximum catch densities. Benthic fish detection rates (as the percentage of PTs containing any benthic fish specimens) are presented above each bar

3.1.4 | Comparison of electrofishing, TDD and PT-based fish surveys

Population structure and density

Three benthic fish species were sampled at the sites: bullhead, stone loach and European eel (hereafter eel). All sampling methods consistently found bullhead to be the most abundant species at all study sites. Of the electrofishing-derived population, bullhead comprised 82.4–94.2% of the population and stone loach 5.8–17.6%. Electrofishing caught one eel at Farm (0.4% of the population). Of the individuals captured during the TDDs, 81.8–97.5% were bullhead, 2.2–16.5% stone loach and 0.3–1.7% eel. Eel were sampled at all sites through the TDDs (four to six individuals/site). In the PT-derived benthic fish population based on repeat sampling in 2019, 76.3–86.1% of individuals represented bullhead, with the remaining 13.9–23.7% representing stone loach. No eels were captured by the PTs.

All methods detected a much lower density of fish at Confluence relative to Footbridge and Farm (Table 2). Overall, electrofishing generated density estimates that represented only ~20% of the estimates generated by both TDDs and PTs at each respective site in the same year (Table 2). The TDD and PTs at Confluence produced very similar density estimates, as did the TDD and 2018 PT surveys at Footbridge and Farm. The 2019 intensive repeat PT sampling generated lower benthic fish densities than PT sampling in the previous year – although still considerably higher than the 2018 electrofishing derived density estimates. When compared to total density estimates, electrofishing caught 10.6–15.9% of all available fish at the sites, while TDDs caught 74.1–82.7% and 2018 PTs generated density estimates of between 69.8% and 84.3% of all available fish.

All methods captured bullhead across a wide range of size classes (20–89 mm total length). Bullhead size class distributions derived from electrofishing and TDDs were widely analogous, showing juvenile (20–25 mm TL) dominated populations, with further, distinct cohorts between 30 and 40 mm TL and 60 and 70 mm TL (Figure 6). The repeated PT sampling (2019) also detected these distinct cohorts, despite being deployed June to September and therefore sampling throughout the main growth season for the species. However, proportionally, PTs did not catch as many juvenile fish as electrofishing and TDDs, instead catching more of the larger two cohorts.

4 | DISCUSSION

4.1 | Performance of the methods

The TDD and PT techniques were both originally developed to generate quantitative data on crayfish populations. Evaluation of these methods in a rocky headwater stream nonetheless clearly shows their ability to generate valuable information on benthic fish population density and structure. Whilst the assumed capture efficiency generated through electrofishing data ranged from 45% to 84%, and the assumptions of the depletion analyses were satisfied, these two alternative techniques also confirmed that the total number of benthic fish actually available to be caught was severely underestimated by the electrofishing depletion curves. Indeed, subsequent TDDs revealed total population estimates to have 3.2–5.3 times more fish than were estimated to be present based on the electrofishing surveys. This would suggest that the reduction in fish captured during electrofishing sweeps was not due to a true reduction in fish present in the site via removal, but that the fish present became progressively less catchable. Fish catchability could be affected by a number of factors, for example behavioural responses to repeated electric shock, or the physical disturbance of prior sweeps causing fish to seek shelter. The fishable area of the site

TABLE 2 Benthic fish densities recorded from electrofishing, triple drawdowns (TDDs) and Pritchard Traps (PTs; $n = 4$ in 2018; $n = 30$ in 2019). Estimated totals result from adding the specimens caught by electrofishing to the estimates resulting from the TDDs on the same, isolated stretch of river

Site	Method	Bullhead density (m^{-2})	Stone loach density (m^{-2})	Eel density (m^{-2})	Total benthic fish density (m^{-2})
Confluence	Electrofishing	0.9	0.2	0.0	1.1
	TDD	6.3	1.3	0.1	7.7
	Total estimate	8.4	1.9	0.1	10.4
	PT (2019)	6.0	1.9	0.0	7.9
Footbridge	Electrofishing	5.0	0.3	0.0	5.3
	TDD	26.7	0.7	0.1	27.5
	Total estimate	32.1	1.0	0.1	33.2
	PT ($n = 4$, 2018)	26.0	2.0	0.0	28.0
	PT ($n = 30$, 2019)	9.1	1.5	0.0	10.5
Farm	Electrofishing	4.6	0.5	0.02	5.2
	TDD	26.0	0.6	0.1	26.6
	Total estimate	34.6	1.1	0.1	35.8
	PT ($n = 4$, 2018)	25.0	0.0	0.0	25.0
	PT ($n = 30$, 2019)	14.3	2.4	0.0	16.7

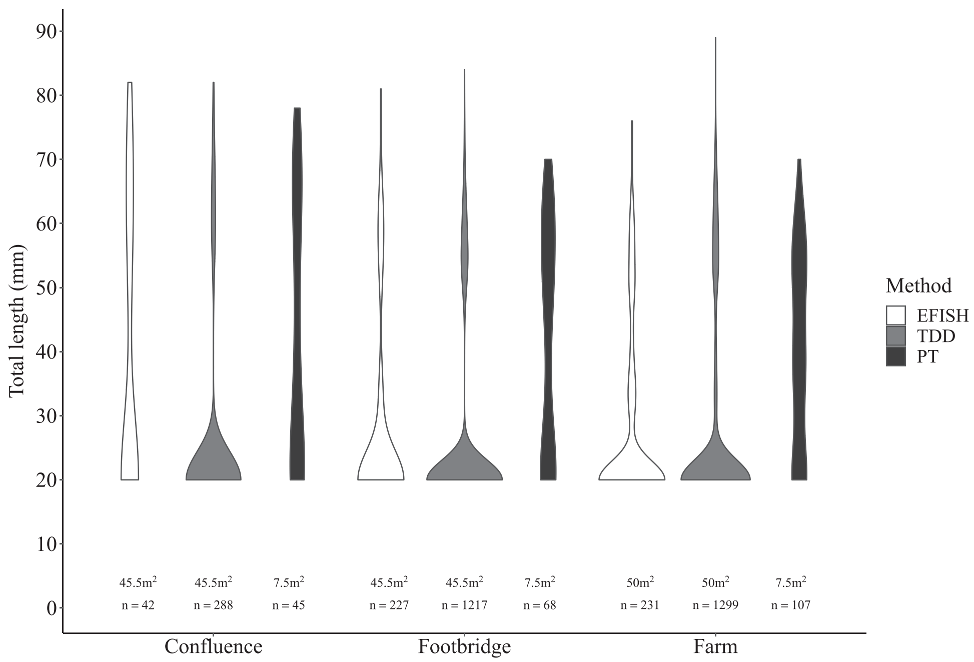

FIGURE 6 Bean plot (i.e. probability density of the catch data) of bullhead size class distribution (mm TL) captured through electrofishing (2018), TDDs (2018) and repeated PTs (2019) across study sites. The area sampled using each method (m^2) and the number of bullhead captured (n) is also denoted

(m^2) and electrofishing setup, such as the number of operatives or anode devices, could also influence the effectiveness. The TDD, however, systematically removes available refugia from the channel, leaving no place for fish to hide, resulting in a much higher catchability. While the ability to produce total population estimates through sweep depletion analyses is a valuable tool in fish stock assessments for both monitoring and managing wild and stocked fisheries (Cowx, 1983; Vehanen et al., 2013), our results highlight methodological constraints potentially limiting the reliability of such assessments.

The PTs produced density values generally congruent with the TDDs and sampled a wide range of size classes even after a minimum deployment time of just one day. However, the observed population structure of bullhead in PTs showed an even size class distribution – which differed strongly from both other methods that indicated a strong juvenile dominance. These pronounced observed differences can be related to a number of potential causes. When compared with the 'single point in time' samples generated by our electrofishing and TDD surveys, these differences could, for example, represent real changes in the population structure over the PT sampling season that included the summer months when bullhead growth rates are highest. It has been noted that, in productive systems, bullhead can attain lengths of 50 mm within their first year (Mills & Mann, 1983). As such, we can therefore expect much smoother population structures due to growth effects in the PT samples.

Furthermore, antagonistic interactions and competition between bullhead and invasive signal crayfish could influence PT samples. Signal crayfish have been shown to be dominant over bullhead and exclude bullhead from refugia (Bubb et al., 2009). Although Bubb et al. (2009) found no evidence of changes in the response of bullheads to different sized crayfish, it is possible that juvenile bullhead are more sensitive to crayfish presence, especially given crayfish can predate on small bullhead (Guan & Wiles, 1997, 1998). Predation of smaller size classes of bullhead over the summer season could also cause a smoothing effect on the population structure. Nevertheless, PTs can effectively capture both bullhead and crayfish concurrently (SI 2). Whilst the evaluation of behavioural interactions between crayfish and bullhead goes beyond the scope of this study, PTs may present a suitable method to explore such interactions in the future.

Alternatively, differences in size structure could be due to bullhead behaviour. The PTs function by passively sampling specimens that are utilizing the specific substrate within the trap area. Therefore, PT catches are likely to be strongly associated with the immediate habitat where they are set. Bullhead can demonstrate size-dependent microhabitat use and habitat preferences (Davey et al., 2005; Van Liefferinge et al., 2005), for example juveniles preferring areas with deeper water (Van Liefferinge et al., 2005) that were potentially underrepresented by the PT locations. Bullhead are relatively sedentary fish, and local movements of populations are often attributed to disturbance to the benthos (Smyly, 1957). Bullhead also exhibit a strong 'homing instinct' and will repeatedly return to a particular stone (Smyly, 1957). Juvenile fish may be more sensitive to disturbance and take longer to colonize the recently disturbed habitats within PTs. The fact that the number of fish sampled in PTs peaked at all sites at the maximum deployment time (10 days) supports this theory, but further research using PTs within various microhabitats and over longer deployment times is required for verification.

Overall, both TDDs and PTs in our view present promising new tools to survey and monitor benthic fish communities, generating much more representative data than traditional electrofishing surveys. The TDD may be better suited to reach scale assessments and broad community structure, whereas the PT can function at a microhabitat level, with both approaches providing strong insights into local population densities. The PT performed very well for the benthic species (bullhead and stone loach) present in the studied rocky headwater and future work should evaluate the efficacy of the method for other benthic species such as gudgeon (*Gobio gobio*) in other aquatic systems.

4.2 | Practicalities of the methods

Further to the performance, consideration of practical requirements, resources and risks associated with survey methods strongly influence their suitability. Electrofishing is a well-established method, but requires a suite of expensive specialist equipment and a team of 2–3+ trained operatives (Evans et al., 2017). Physical site characteristics could also limit effectiveness, such as water chemistry or turbidity. Applying an electric field into a watercourse furthermore poses a risk to operatives and biota, as for example the electric shock can cause fish to suffer burns and fractures, and it can cause crayfish to lose chelipeds (Alonso, 2001).

Survey effort of TDDs is comparable to electrofishing surveys in that they are resource intensive and expensive to undertake, requiring specialist equipment, trained operatives and multiple sweeps (Chadwick et al., 2021). TDDs are also limited to sites with good access such that watercourses can be easily over-pumped and dewatered (Chadwick et al., 2021). Repeated dewatering could also pose a risk to both target and non-target organisms, and thus TDDs need to be undertaken with utmost care and consideration.

PTs, in contrast, require a lower sampling effort (one operative required for ~15 min to deploy and ~15 min to extract one trap and process the catch) and hence may present a more cost-effective approach. PTs are relatively cheap to build and easy to transport, so are suitable for remote survey locations. The passive nature of the trap reduces animal welfare considerations, with minimal impact to bycatch. Whilst PT sampling necessitates two site visits for deployment and subsequent collection, working hours are still considerably lower than for TDDs and electrofishing. PTs are, however, potentially limited to substrate type and with high specificity to microhabitats. As of yet, PTs have only been tested in rocky headwaters where cobbles are the dominant substrate type. Further work is needed to assess their effectiveness in other aquatic systems.

4.3 | Implications for conservation and management

Bullhead are the only freshwater cottid found in the United Kingdom (Tomlinson & Perrow, 2003). They are a protected species listed on Annex II of the European Commission Habitats Directive (Boon & Lee, 2005; Knaepkens et al., 2005). The ability to monitor their populations is crucial to understand population trends and assess conservation status in the face of various stressors, including invasive species like the signal crayfish (Guan & Wiles, 1997). Methodological constraints and poor catchability have limited effective population assessments of benthic fish, and the importance of such species within ecosystems has likely been underestimated (Harrison et al., 2005). Benthic fish such as bullhead may be considered keystone species in some systems where they attain high abundances and have an intermediate trophic position (Harrison et al., 2005; Woodward et al., 2008). Bullhead have strong associations with substrate type, often preferring coarse gravel and cobble (Welton et al., 1983) which can vary between the seasons (Harrison et al., 2005). As a result, the ability to accurately record their densities within small habitat is paramount to better understand their behaviour and ecology. While the shock of electrofishing can cause fish to rapidly dart between habitats (Harrison et al., 2005), the PTs now offer a passive method to explore specific habitat preferences, recruitment patterns and response to stressors.

5 | CONCLUSIONS

Electrofishing severely underestimates the abundance of benthic fish throughout the rocky headwater study system – even where depletion curves were used to extrapolate 'true' population densities. Fish behaviour and site characteristics such as substrate type may have limited its effectiveness. TDDs and PTs prove effective at surveying benthic fish and generating detailed demographic data. However, site characteristics and resources may limit the wider application of TDDs for benthic fish. The PT presents a cost-effective approach with a low sampling effort and low risk to non-target organisms. Further research is required to assess the effectiveness of PTs in other aquatic systems, but the method shows great promise for the assessment of benthic fish populations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

E.G.P conceived the ideas and designed the initial methodology with inputs from the other authors; E.G.P, D.D.A.C and P.B collected the data; E.G.P analysed the data and, together with J.C.A., led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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DATA AVAILABILITY STATEMENT

Data available via the University College London (UCL) Research Data Repository. https://doi.org/10.5522/04/16896547.v1 (Pritchard et al., 2021b).

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