The impact of extreme flood-relief pump operations on resident fish in an artificial drain and the potential for artificial habitat introduction

Abstract

Fish are ubiquitous in pumped artificial drains but channel maintenance exposes fish to high flows and predators, and fish communities may experience population-level threats if they are unable to access refuge during extreme flood-relief pump operations. We assessed the impact of an extreme flood-relief pump operation and effects of artificial habitat introduction on a resident fish community in an artificial drain in Great Britain using side-scan and multi-beam sonar. Sonar surveys before the flood found abundant aggregations of resident fish, whereas no fish were found after the flood, which suggested flood-relief pump operations significantly altered resident fish populations. Fish abundance near artificial habitats monitored before the flood were highest during crepuscular periods and was similar among three different artificial habitat designs. Our findings improve the understanding of extreme flood impacts on fish in artificial drains and demonstrate the usefulness of sonar techniques for surveying abundance and spatial distribution of fish populations before and after floods.

Keywords

fish distribution; flood risk management; multi-beam sonar (ARIS); pumping station; predator refuge; side-scan sonar

1 Introduction

Understanding the distribution, abundance, and habitat use of fish is fundamental for ecological management, conservation, and restoration of freshwater ecosystems (Kruk, 2007; Methot & Wetzel, 2013). Still, demonstrating how environmental changes, such as floods, can affect distribution of fish in freshwaters is a major challenge facing ecologists and environmental managers (Poff, 1997; Bolland *et al.,* 2015; Knouft & Anthony, 2016). In unmodified rivers with heterogeneous hydro-geomorphological features (e.g., meanders, floodplains, and unaltered flow), fish have evolved to respond to flooding by longitudinal movement (David & Closs, 2002) and lateral dispersal into inundated floodplains (Peirson *et al.,* 2008; Manfrin *et al.,* 2020), or occupy habitats that provide flow refuge (e.g., behind boulders, fallen trees and dense vegetation; Lake *et al.,* 2006). However, land reclamation and ongoing flood protection in lowland regions, achieved by channelisation, dredging, and creation of dikes, has replaced lowland riverine ecosystems with artificial drain networks (Beran, 1983; Smedema & Ochs, 1998; Gething & Little, 2020). Although heavily modified, artificial drainage networks support river biota (Rideout *et al.,* 2021) and can have similar biodiversity to unmodified lowland rivers, but fish fauna are threatened by anthropogenic management (Simon & Travis, 2010; Chester & Robson, 2013).

Water levels in artificial drains can be managed by pumping stations with multiple pumps to regulate normal water level (i.e., single pump, also referred to as duty pumping) and rare or extreme rainfall to prevent flooding (i.e., all pumps, also referred to as flood-relief pumping) (Armstrong, 1983; Beran, 1983). However, pumping station operation can negatively affect local fish fauna, by entrainment into pumps (Barnthouse, 2013) and reduced post-entrainment survival and health (Bierschenk *et al.,* 2019; Bolland *et al.,* 2019). However, most studies focused on understanding impacts on individual fish and do not consider the wider resident fish community distribution and abundance (but see Harrison *et al.,* 2019). The likelihood of fish entrainment is exacerbated by channel maintenance (i.e., sediment dredging and vegetation removal), which increases water conveyance but inadvertently removes predator and flow refuge habitats for fish (Baattrup-Pedersen *et al.,* 2018; Baczyk *et al.,* 2018; Schürings *et al.,* 2022). Further, resident (i.e., non-diadromous) fish fauna, such as roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*), are ubiquitous in pelagic zones of artificial drains but also require temporally variable access to refuge from flow and predation (Townsend & Peirson, 1988; Holmes & Hanbury, 1995; Borcherding *et al.,* 2002). Consequently, mass aggregations of shoaling fish in open water during winter is a common anti-predator strategy in artificial drains with damaged refuge connectivity (Borcherding *et al.,* 2002; Koizumi *et al.,* 2016). Fish may also aggregate at pumping stations that operate infrequently (Norman *et al.,* 2023). Furthermore, the lack of flow refuge could displace fish downstream and increase the likelihood of entrainment (Morat *et al.,* 2017). Yet, the effects of extreme flood-relief pump operation on prevailing fish communities in homogenised artificial drains with no lateral connectivity to the surrounding floodplain requires further investigation (Kruk, 2007).

More careful management of habitat in modified lowland regions is required, but is poorly understood (Chester & Robson, 2013; Schürings *et al.,* 2022) and considerations for fish habitat are lacking in pumped artificial drains. Elsewhere, artificial habitats have been introduced to supplement degraded natural habitats (Allen *et al.,* 2014) and increase local abundance of fish (Frehse *et al.,* 2021). Thus, introducing artificial habitats in artificial drains could provide fish with refuge from resident aquatic and avian predators when pumps do not operate and provide flow refuge during pump operation (Lemmens *et al.,* 2016). Structural design of artificial habitats may affect fish occupancy. For example, structurally complex designs with interstitial spacing may be necessary in predator-crowded communities, but sheltered open space may also be needed to avoid prey-crowding, although pilot studies are needed to determine local community response before permanent introduction (Bolding *et al.,* 2010). Developing such knowledge will help overcome the lack of robust monitoring and help determine the ecological function of artificial habitats and relative fish occupancy (Lindenmayer *et al.,* 2017), especially under real-world circumstances (Hale *et al.,* 2015).

The applicability of commonly used sampling techniques for understanding impacts of extreme flood-relief pump operations and artificial habitat introduction in deep and turbid artificial drains is challenging. Boat electro-fishing surveys can be used to sample fish distribution and abundance (Lyon *et al.,* 2014) and netting can be used to sample slackwater habitat use by juvenile fish in modified lowland rivers during floods (Bolland *et al.,* 2015), but both are rarely used over large spatial scales due to sample effort required. Electronic tagging would provide movement information before, during, and after flooding for a limited number of individuals (e.g., cost limitations), provided fish were tagged prior to an extreme flood-relief pump operation (Thorstad *et al.,* 2014). Alternatively, mobile horizontal echo-sounding using high-frequency side-scan sonar (SSS) is increasingly popular for understanding fish distribution and abundance (Lawson *et al.,* 2019). SSS produces a still image by emitting a sound beam sideways (left and right) to define riverbed structure and locate objects (i.e., fish) from reflected sound beam signals. The sonar is towed by a low-powered boat and can therefore provide non-invasive sampling of fish populations in large rivers that require greater spatial coverage (Papastamatiou *et al.,* 2020). Thus, SSS is an ideal tool for quantifying the distribution and abundance of fish in artificial drains. Nonetheless, SSS surveys are performed with a moving vessel so they cannot alone provide fine-scale information on the temporal rate of artificial habitat occupancy. Stationary multi-beam sonars that capture video-like observations during day and night are more appropriate for quantifying multi-species artificial habitat occupancy (Martignac *et al.,* 2015; Petreman *et al.,* 2014; Baumann *et al.,* 2016).

The objectives of this study were to determine if extreme flood-relief pump operation (using inter-annual SSS) and introduction of artificial habitat (using multi-beam sonar) affected the resident fish community in an artificial drain in Great Britain. To achieve these objectives, we quantified (1) fish distribution and abundance before (2017, 2019) and after extreme flood-relief pump operations (2021), and (2) the influence of artificial habitat structure design, diel cycle, and duty pump operation on fish abundance in artificial habitats. Artificial drains harbour a significant proportion of biodiversity in modified lowland regions, so the impact of refuge loss and extreme flood-relief pump operations on fish fauna urgently needs to be considered. We quantified the distribution and abundance of fish in an artificial drain upstream of a pumping station before and after an extreme flood-relief pump operation using SSS. Specifically, in December 2020, 131 mm of rainfall (150% of the 1981–2010 long-term average, Environment Agency, 2021) caused all six pumps (≥ 20 m^3s^{-1}) at a pumping station to operate for four days. Fish abundance in the vicinity of three artificial habitat designs introduced for flow and predator refuge were quantified during no pump and duty pump operation (prior to extreme flood-relief pump operation) using multi-beam sonar. Our findings could inform future habitat improvement work according to the Water Framework Directive (WFD; 2000/60/EC) and help water authorities and ecologists to manage local fish populations in artificial drains.

2 Methods

2.1 Study area

The Lower Nene catchment (830 km^2) in Great Britain is mostly agricultural land managed by numerous pumped artificial drains. The North Level Main Drain (NLD) is the largest, with a catchment area of 340 km^2, total length of 23 km, mean width of 23 m, and elevation of −2 m above ordnance datum (mAOD). The downstream extent of NLD terminates at Tydd pumping station (Lat: 52.738804 N Long: 0.162728 W: Figure 1a), which operated during this study either as duty pump operation to maintain upstream levels (one pump ~ 3.3 m^3s^{-1}) or extreme flood-relief operation (up to six pumps ~ 20.17 m^3s^{-1}). Like other artificial drains, resident fish populations in NLD are typical of a lowland river, including roach, pike (*Esox Lucius*), bream (*Abramis brama*), tench (*Tinca tinca*), perch, and rudd (*Scardinius erythrophthalmus*) (Environment Agency, 2022; Schürings *et al.,* 2022). The study area was a navigable 12-km reach of NLD extending upstream from Tydd pumping station (Figure 1a), which is highly maintained during winter, so habitat is significantly degraded. Early mitigation efforts to protect fish from predators and reduce entrainment into pumps during high flows at Tydd pumping station included installation of artificial habitat upstream of the pumping station (Figure 1c). River level (mAOD) was monitored at the nearest (~20 km from Tydd pumping station) river gauge in the River Welland catchment (Lat: 52.720221 N Long: -0.141261 W) (Figure S1).

2.2 Artificial habitat

Three artificial habitats were constructed using steel gabion baskets (3 mm thickness 1000 x 1000 x 1000 mm length x width x height) with 76.2 x 76.2 mm apertures (Figure 1c; Figure 2). Four one-and-a-half sized apertures (i.e., 152.4 x 76.2 mm) were created on the front-facing side of each basket. Each habitat was then constructed by joining six baskets (5000 x 2000 x 1000 mm) to encompass a volume of ~10 m^3 per habitat (Figure 1c; Figure 2), to represent patches of marginal reeds present in NLD throughout summer, whilst ensuring water conveyance was not impeded in the artificial drain.

Each of the three artificial habitats used a different design to resemble natural structures with varied complexities, to determine if overhead shelter, interstitial spacing or both affected habitat occupancy (see Bolding *et al.,* 2010). Overhead shelter was provided by marine plywood boards (16mm thickness) attached to wooden framing, and bamboo canes (6 – 8 mm thickness, 1200 mm length) were inserted in every other aperture in gabion baskets (secured with cable ties) to create interstitial spaces with ~150 mm spacing. Bamboo canes were used to reduce use of plastic in artificial habitats and mimic highly abundant common reeds (*Phragmites australis*) (Cooke *et al.,* 2023). The size and number of interstitial spaces was intended to target juvenile (0–15 cm total length, TL) and adult (15–25 cm TL) roach and similar-sized resident fish (i.e., perch), whilst excluding larger-bodied resident predator species (i.e., pike > 30 cm TL). Partial refuge (A) had bamboo canes (no overhead shelter), partial refuge (B) had overhead shelter (no bamboo canes), and complete refuge (C) had both bamboo canes and overhead shelter. Artificial habitats were installed in NLD in December 2019 (Lat: 52.738804N Long: 0.162728W) (Figure S1). Bank-side access (personnel and crane equipment) and distance from power source (Tydd pumping station) determined final placement of artificial habitats.

2.3 Sonar assessment

2.3.1 Side-scan sonar

SSS surveys used a commercially available Humminbird® Solix 15 CHIRP MEGA SI (Johnson Outdoors Inc., Racine, WI) using frequency ranges of 1150–1275 MHz in 2017 and 2019 and 780–850 MHz in 2021, powered by a 12v battery. Frequency ranges enabled detection of target fish using a total swath width of 30 m (15 m either side of the boat) to cover varying channel widths of 20–30 m. The transducer was attached to a pole at a depth of 30 cm at the front end of a small workboat with an electric outboard. SSS surveys started at the downstream extent of NLD (i.e., Tydd pumping station, including artificial habitats in 2021) and moved upstream to Clough Bridge Sluice at the centre of NLD at 2–5 km $^{h-1}$ (Figure 1a); a total distance and area of ~12 km and ~30 km^2, respectively. The reach upstream of Clough Bridge

Sluice was too narrow and shallow to survey with SSS. All surveys were performed at normal water levels (i.e., not rising or falling) in one morning (09:00–12:00) on 27 November 2017, 10 December 2019, and 17 December 2021. The last survey responded to extreme flood-relief pump operation at Tydd pumping station on 23–27 December 2020 (six pumps, 96 hours). The sampling day was intended to detect winter shoaling behaviour of resident fish. SSS tracks were converted to a 2d image in real-time on the sonar console to allow for observations of fish targets during sampling, and final outputs were processed as a 'New Sonar Mosaic' using Reefmaster® software (ReefMaster Software Ltd, West Sussex, UK).

2.3.2 Multi-beam sonar

Fish abundance was monitored at artificial habitats using Adaptive Resolution Imaging Sonar (ARIS Explorer 3000, Sound Metrics®, USA. http://www.soundmetrics.com/) on 10–18 December 2020. The ARIS was installed on an L-shape steel pole (2 x 1 m) using a SoundMetrics AR3-rotator at a depth of ~2 m (Figure 1c). Data and power cables were routed to a bankside weatherproof box with a sonar command module and laptop with remote internet connection (Panasonic TF-19). During the 8-day deployment, each artificial habitat was imaged for two consecutive days. To image refuge (A) and (C), the pole was driven into the riverbank between the two structures. After (C) was imaged, the ARIS was rotated to image (A). The ARIS was later moved between refuge (A) and (B) to image refuge (B) (Figure 1c). The position was aligned with the leading edge of artificial habitats, and imaging of artificial habitat structures was used to confirm correct orientation of the sonar.

The ARIS was operated using SoundMetrics software (ARIScope V2.6.3.1559) in high frequency mode (1.8 MHz, 96 0.3° x 14° beams, 512 bins) with a window length of 8.4 m (starting 3 m from point of transducer) at 9.7 frames s^{-1} (fps), receiver gain at default, and focus set to auto to account for changes in fish distance from the transducer. This range allowed for an appropriate resolution to capture fish targets ≥10 cm (Maxwella & Gove, 2007). Continuous observations were captured except when data collection was interrupted to maintain equipment and reposition the ARIS. Files were time and date stamped (hh:mm:ss – dd/mm/yyyy) and stored in 10-minute intervals.

2.4 Analysis of sonar data

2.4.1 Fish abundance in North Level Drain

SSS survey data were used to estimate fish abundance by counting fish targets in the final image produced by Reefmaster. Data were processed in ImageJ v1.53e (Schneider *et al.,* 2012), which has been effective for enumerating fish targets in SSS data (Bollinger & Kline, 2017; Lawson *et al.,* 2019). To provide a standardised measure of area, a transect was drawn across the river width (25 m) and calibrated to 758 ± 1 pixels. Once calibrated, approximate fish lengths were measured from fish shapes and individual region of interest (ROI) were applied to light and dark backgrounds to identify acoustic shadows cast by fish shapes and acoustic reflections of fish (Figure 3). Fish were then counted by applying the findMaxima tool and adjusting background (light, dark) and detection tolerance (0 – 45) to minimize over- and under-plotting of fish targets. Points plotted by findMaxima were scrutinised by applying a 'within tolerance' threshold to ensure plotted points corresponded to fish targets. Total area analysed was 840 m^2 in 2017 and 990 m^2 in 2019. Fish abundance was then estimated as the total survey area divided by 10 (i.e., fish abundance·10 m^2), which enabled comparison between side-scan density throughout NLD and multi-beam density at artificial habitats.

2.4.2 Fish abundance at artificial habitat

To quantify temporal variability, fish abundance data were sub-sampled into four two-hour discrete sample periods over a 24-hour day (dawn = civil twilight ± 1h 06:30–08:30, daytime = 11:30–13:30, dusk = civil twilight ± 1h 15:30–17:30, night-time = 23:30–01:30). Multi-beam sonar surveys of artificial habitats were performed during duty pump operation (one pump, 30 hours) for 64% of the total sample range; 35% of dawn, 85% of dusk, 83% of midday, and 52% of midnight samples (Figure S1). Flow velocity during duty pump operation was 0.25 m s^{-1}, estimated by measuring speed of debris floating downstream in the centre of multi-beam images. Overall duration of sonar footage included 24 hours of ARIS images.

Counts of fish occupying the space immediately adjacent to artificial habitat structures (~14 m^2; Figure 4) were taken by an experienced reviewer every 15 minutes (individuals·1 frame·$15min^{-1} \pm 5\ s^{-1}$) and calculated as fish abundance·10 m^2. Background subtraction was applied if floating debris reduced resolution of fish targets. Playback speeds were adjusted as necessary, and quick backward and forward navigation allowed observation of fish interacting with artificial habitats. Fish size was approximated using the ARIS measurement tool when fish were perpendicular to the sonar beam.

2.5 Statistical analysis

Fish abundance from side-scan and multi-beam sonar surveys were not normally distributed (Shapiro-Wilk normality tests: R function 'shapiro.test'), so non-parametric tests were used for comparisons and results were summarized as medians and inter quartile ranges (IQR). To assess the impact of extreme flood-relief pump operation, Wilcox rank-sum tests (R function 'wilcox.test') were used to compare fish abundance between 2017 and 2019 (pe-flood) and 2021 (post-flood) SSS surveys. To assess fish abundance at artificial habitats, Kruskal-Wallis rank-sum tests (R function 'kruskal.test') were used to compare fish abundance from multi-beam surveys between three artificial habitat designs (A– C; Section 2.2) and between four photoperiods (dawn, day, dusk, night). Fish abundance at artificial habitats was also compared between no-pump and duty-pump operations using a Wilcox rank sum test. All data were analysed using R version 4.0.2 in RStudio 1.4.11 (R Core Team, 2022; RStudio Team, 2022) and figures were created using R packages 'ggplot2', 'ggpubr', 'gridextra' and 'cowplot'.

3 Results

3.1 Fish distribution and abundance in North Level Drain

During 12-km SSS pre-flood surveys, 5,213 fish (~10–20 cm TL) were identified in November 2017 and 1,474 in December 2019 (Figure 5a; Figure 5b; Table S1). Fish were identified at only one location near a road bridge, ~1 km upstream of Tydd pumping station, of 70-m length, 25-m width, and 2.4–2.7 m depth (Figure 1b; Figure S2). Abundance was significantly higher in 2017 (median = 63, IQR = 15.5 fish·10 m^2) than 2019 (median = 15.4, IQR = 6.95 fish·10 m^2; Wilcox rank sum: W = 144 p = <0.001; Figure S2; Figure S3) (Figure 6). During the post-flood SSS survey in December 2021, no fish were identified and the reach had only clearly defined riverbanks (Figure 5c; Figure S4).

3.2 Fish abundance at artificial habitats

Median abundance (individuals·1 frame·15min^{-1}) did not differ significantly among artificial habitat structure types (Kruskal-Wallis: χ^2_2 = 0.82, p = 0.66), and 881 fish were identified near the partial refuge (A median = 4.29, IQR = 5.89 fish·10 m^2), 786 near the partial refuge (B median = 3.57, IQR = 8.04 fish·10 m^2), and 556 near the complete refuge (C median = 3.21, IQR = 8.21 fish·10 m^2; Figure 7a; Table S2). Fish counts differed significantly among photoperiods (Kruskal-Wallis: χ^2_{23}= 50.87, p = <0.001), with highest abundance at dawn (median = 9.29, IQR = 17.7 fish·10 m^2) and dusk (median = 5, IQR = 6.79 fish·10 m^2), and lowest abundance during the day (median= 2.86, IQR = 2.86 fish·10 m^2) and night (median = 2.14, IQR= 4.82 fish·10 m^2) (Figure 7b). Fish abundance near all artificial habitats was significantly higher when the duty pump at Tydd pumping station was not operating (median = 7.86, IQR = 9.64 fish·10 m^2) than when one duty pump was operating (median = 2.14, IQR = 5.71 fish·10 m^2; Wilcox rank sum: W = 2667, p = <0.0001) (Figure 7c). Although not identified to species, the size range of shoaling fish (10–20 cm) was likely a multi-species assemblage of cyprinids and percids. Five large predator-sized fish (120 – 135 cm) imaged were most likely pike, based on body shape. Artificial habitat structures were easily identified in postextreme pump operation surveys (17 December 2021), but no fish were identified near artificial habitats (Figure 5d; Figure S4).

4 Discussion

While not direct evidence, effects of heavily degraded longitudinal habitat, isolated lateral connectivity, and extreme flows exceeding fish swimming capability combined to suggest that highly abundant fish aggregations we observed prior to the flood in 2017 and 2019 were displaced downstream (e.g., Poff & Zimmerman, 2010) and removed from NLD by entrainment during the extreme flood-relief pump operation in December 2020. Anglers consistently reported greatly reduced catches of adult resident fish (i.e., > 15 cm roach) from NLD throughout 2021, which we later corroborated by SSS surveys in December 2021. Fish have evolved to live in rivers with in-channel habitat heterogeneity and laterally connected floodplains, which provide flow refuge during elevated river levels and floods (Peirson *et al.,* 2008). However, fish fauna in artificial drains are continually threatened by homogenisation of habitat during winter and are laterally isolated from floodplain refuges (Chester & Robson, 2013). Furthermore, flow velocities upstream of the pumping station studied here far exceeded recommended targets (0.3 m s^{-1}) by operating more pumps to increase volume of water discharged during a rare flood event (Flikweert & Worth, 2012). In-channel flow velocity in pumped artificial drains (here ~1.5 m s^{-1} with six pumps operating) can greatly exceed those of natural rivers (Lake *et al.,* 2006) and swimming capability of fish (Baumgartner *et al.,* 2009). Roach, for example, have slender body-morphology poorly adapted for living in fast-flowing conditions, with an estimated sustained swimming capability of two minutes at 0.7 m s^{-1} flow velocity (Clough & Turnpenny, 2001). Quantified estimates of entrainment and mortality during flood events are lacking, but global reviews by Barnthouse (2013) and Harrison *et al.* (2019) both report a similar potential for population-level mortality during extreme operations as suggested here. The long-term impacts remain to be quantified, but recovery from extreme floods in channelised rivers similar to the artificial drain studied here can occur when only few adults survive (Juradjda *et al.,* 2006). However, the catchment studied here was relatively small, with heavily degraded habitat, and the pumping station would prevent re-colonisation from further downstream, something that can occur in natural longitudinally connected rivers (Tummers *et al.,* 2016; Benitez *et al.,* 2018).

Fish occupancy of artificial habitats could only be studied (using multi-beam sonar) pre-flood (2020) because the entire artificial drain was void of fish post-flood and therefore the effectiveness as flow and predator refuge was unclear. During our multi-beam surveys, fish aggregated around artificial habitats and followed a crepuscular pattern commonly described for pelagic fish communities vulnerable to predation (Pitcher & Turner, 1986). Maximal abundances at dawn and dusk may be associated with movements toward or away from artificial habitats, like diel movements to and from natural refuge habitats (e.g., Hohausova *et al.,* 2003). In contrast to previous findings (Bolding *et al.,* 2010; Daugherty *et al.,* 2014; Baumann *et al.,* 2016), we found no significant difference in fish abundance among habitat designs, perhaps because of poor habitat placement (Hale *et al.,* 2015), lack of predator stimulus (i.e., avian piscivores), or methodological limitations. Indeed, fish abundances were also significantly reduced during duty pump operation, possibly attributed to fish seeking flow refuge inside artificial habitat (e.g., Costa *et al.,* 2019) and thus could not be imaged by multi-beam sonar. Overall, our findings are useful for habitat management decisions and highlight the importance of monitoring artificial habitats under real-world conditions (i.e., Hale *et al.,* 2015) to understand the influence of diurnal processes, artificial habitat design, and pump operation on the feasibility of introducing artificial habitat to supplement degraded natural habitat in artificial drains.

4.1 Future research

A combination of side-scan and multi-beam sonar used herein provided high spatial coverage and enumeration of fish in a drain and fine-scale analysis of habitat occupancy, and thus could be used to guide future studies of flooding in modified freshwaters. The coincidence of an extreme flood event during our study cannot be planned or implemented in an empirical study design due unpredictability of such events. But, if an opportunity arose to study these conditions again, this work would benefit from an increased temporal rate of SSS surveys (i.e., immediately before and after an extreme flood-relief pumping event). Additionally, although no pollution incidents or fish kills were in the upstream drain, other factors may have influenced changes to fish composition, and therefore, future research should attempt to validate fish losses after extreme flood-relief pump operations. Indeed, whilst not possible at Tydd pumping station, due to the volume of water pumped presenting a risk to people, equipment, and fish in nets, collection of entrained fish from pump outlets would directly quantify the number of fish entrained (e.g., Baumgartner *et al.,* 2009). Alternatively, incorporating telemetry data and tracking fish could be used to confirm downstream displacement of fish and pumping station entrainment time (Thorstad *et al.,* 2014), although this would need considerable foresight to ensure tagged fish were not released immediately prior to an extreme flood event.

Future artificial habitat research needs to understand effectiveness of full-scale habitat restoration efforts to provide predator and flow refuge for resident fish because poorly placed artificial habitats are ineffective (Hale *et al.,* 2015). The size, number and spatial distribution of habitats required to support resident populations must be fully determined. Additionally, reaches upstream of pumping stations where artificial habitats can be installed need to be identified, with reference to locations where fish are abundant and vulnerable to predation and flow displacement. Telemetry techniques (e.g., passive integrated transponder tags) could be used to quantify the number of fish inside artificial habitat during floods (e.g., Teixeira & Cortes, 2007), although large numbers of fish may need to be tagged in large freshwater systems and all artificial habitat installations could not likely be studied.

4.2 Conclusions and management implications

Populations of resident fish in lowland artificial drains are highly abundant and thus managers and ecologists have a responsibility to understand the impact of habitat degradation and extreme flood-relief pump operations on the distribution, abundance, and behaviour of fish. The results presented here are the first to provide a quantitative estimate of distribution and abundance of resident fish in an artificial drain with a high-capacity pumping station, before and after a rare extreme flood-relief operation and at artificial fish habitats using side-scan and multi-beam sonar. During our investigation at a high-capacity pumping station (total capacity = 20.17 m^3s^{-1}), a coincidental rare extreme flood event (131 mm rainfall over 31 days;

150% of the 1981–2010 average) caused all six pumps to operate for four days. We demonstrated that thousands of fish were potentially displaced from a homogenised artificial drain. In future years, climate change will drive an increased necessity for flood-relief pump operations (Chang *et al.,* 2013; Hannaford, 2015), and thus exacerbate the problem demonstrated herein to increase the necessity for management actions. Therefore, managing flood risk must be balanced with protecting local biodiversity of fish fauna in artificial drains (Rideout *et al.,* 2021). Indeed, while safer operations of pumping stations tend to focus on fish-friendly pumps for diadromous fish (Bierschenk *et al.,* 2019), we demonstrated a need for flood risk management to be more ecologically sensitive by providing alternative refuges in heavily maintained artificial drains to prevent population-scale impacts on resident fish. Artificial habitat can be introduced into artificial drains, but further investigation is needed to understand long-term effectiveness as flow and predator refuges. Overall, our findings suggest that extreme flood-relief pump operations significantly alter the abundance of resident fish upstream of pumping stations and our proposed management actions will be useful for ensuring long-term survival of resident fish communities in pumped artificial drains around the world.

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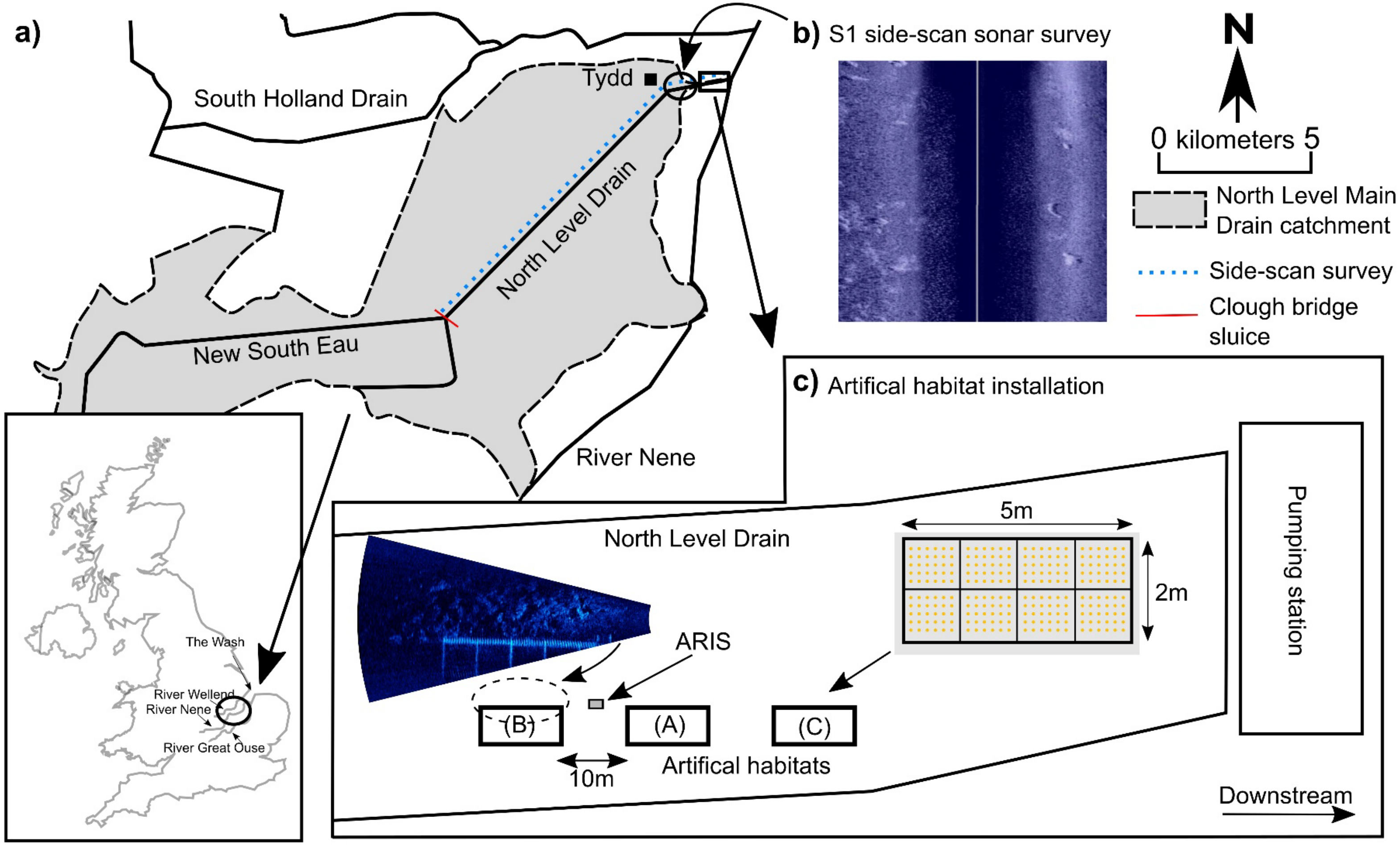

Figure 1 a) the location of the study catchment (bottom left) and North Level Drain catchment, (52.737735N, 0.148511W), Great Britain, sampled on 27 November 2017, 10 December 2019, and 17 December 2021 including side-scan survey reach (blue dotted line). b) representative image of side-scan sonar survey. c) a schematic representation (not to scale) of the artificial habitat installation, showing the position (52.738804N, 0.162728W) of the structures partial refuge (A – bamboo), partial refuge (B – shelter) and complete refuge (C – shelter & bamboo) with a diagram of habitat structure (grey shading represents cover, orange circles represent bamboo canes), representation of ARIS insonified window and the downstream pumping station.

Figure 2 Photographs of three artificial habitat designs installed upstream of Tydd PS (52.738804N, 0.162728W) of North Level Drain (52.737735N, 0.148511W), Great Britain, on 10 December 2019. From left to right, partial refuge (A – bamboo), partial refuge (B – shelter) and complete refuge (C – shelter & bamboo). Inset photo shows bamboo canes installed through apertures in steel cages. Positions of artificial habitats differ in this photo from the final installed positions (Figure 1c).

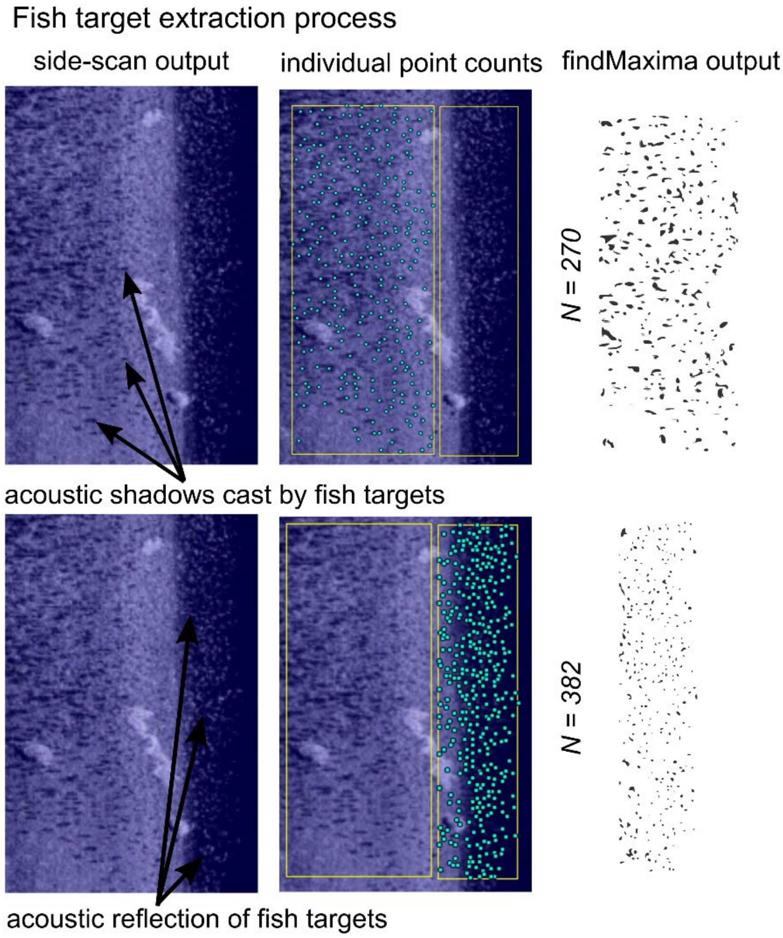

Figure 3 A representation of fish target extraction method used for enumerating fish in the side-scan sonar survey images from North Level Drain (52.737735N, 0.148511W), Great Britain, on 27 November 2017, 10 December 2019, and 17 December 2021. The findMaxima outputs and counts are generated from ImageJ.

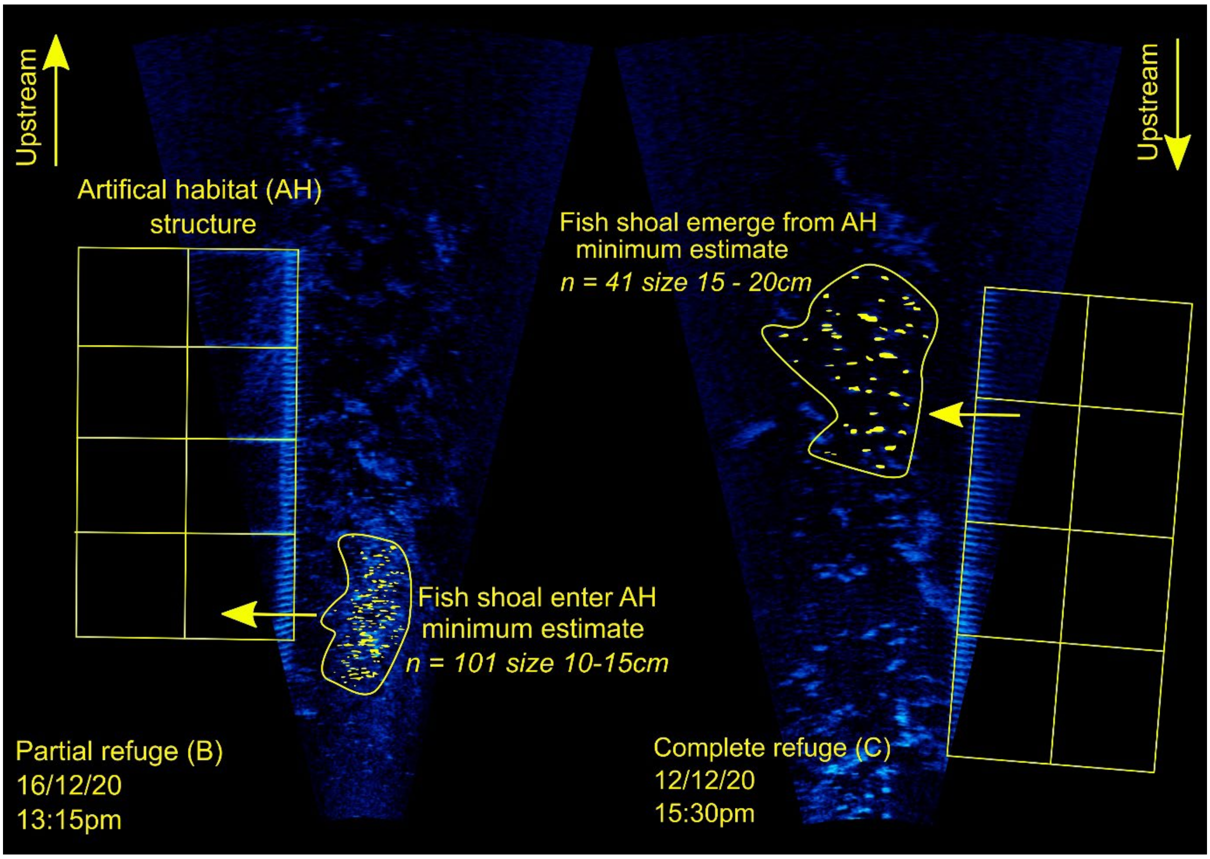

Figure 4 A schematic representation of artificial habitat structures overlaid on raw multi-beam sonar images of artificial habitats, taken in position in the artificial drain of North Level Drain (52.737735N, 0.148511W), Great Britain, 10–18 December 2020. Upstream arrows are relative to the position of artificial habitats in Figure 1c. Fish counted in frame, including estimated size indicated by circled yellow marks.

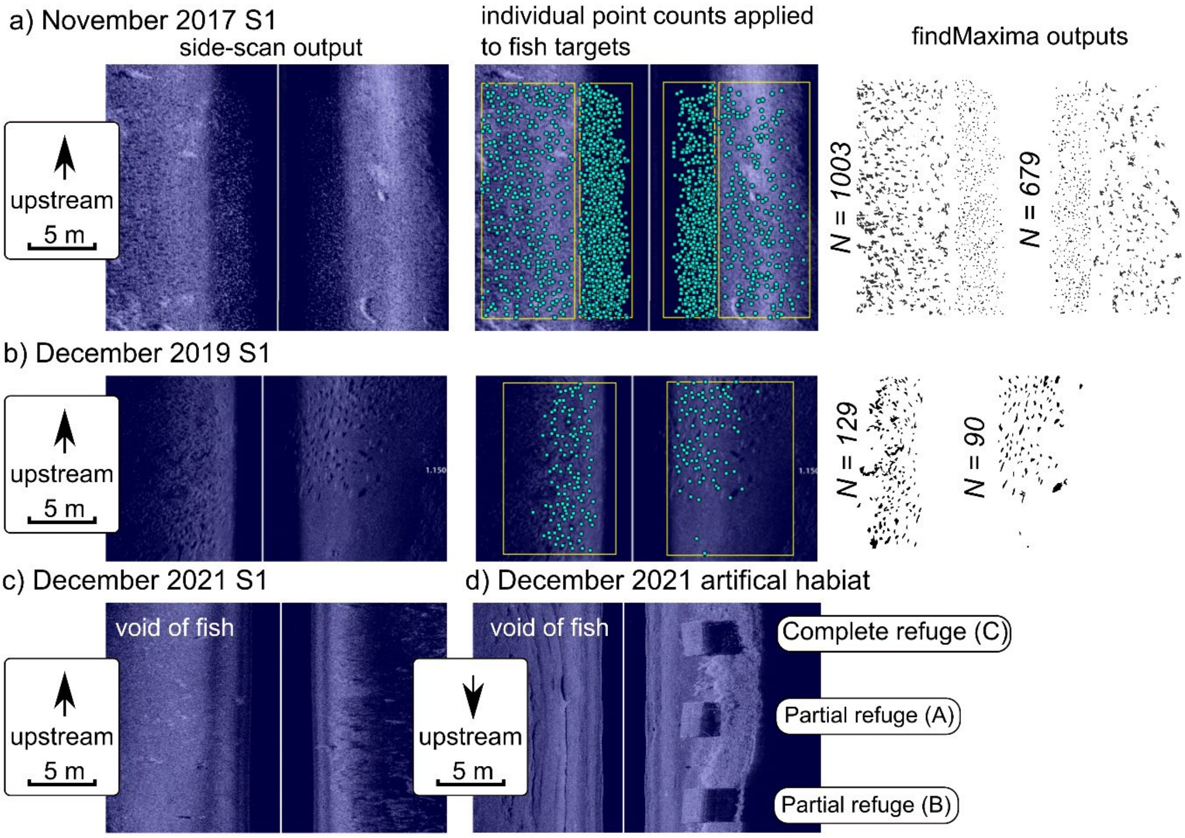

Figure 5 Composite image from North Level Drain (52.737735N,0.148511W), Great Britain, with a representation of the side-scan survey S1 (downstream to upstream) for a) 27 November 2017, b) 10 December 2019, c) 17 December 2021.d) shows artificial habitat also imaged on 17 December 2021 (52.738804N, 0.162728W) (Figure 1c). findMaxima output presented from ImageJ.

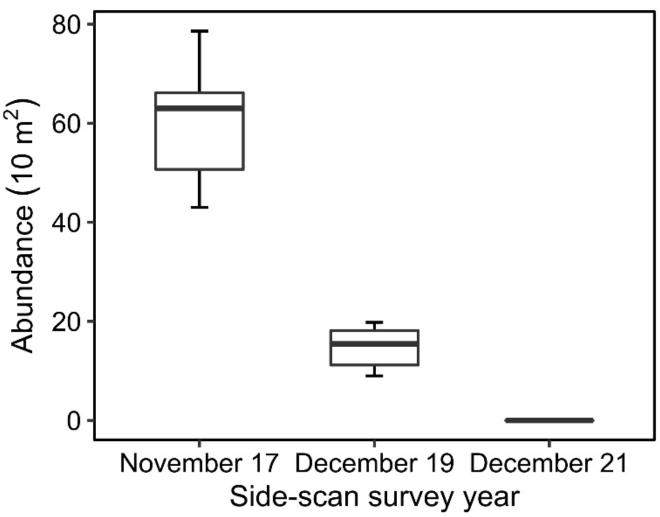

Figure 6 Median abundance estimated from fish counts in side-scan sonar images of North Level Drain (52.737735N, 0.148511W), Great Britain, on 27 November 2017, 10 December 2019, and 17 December 2021.

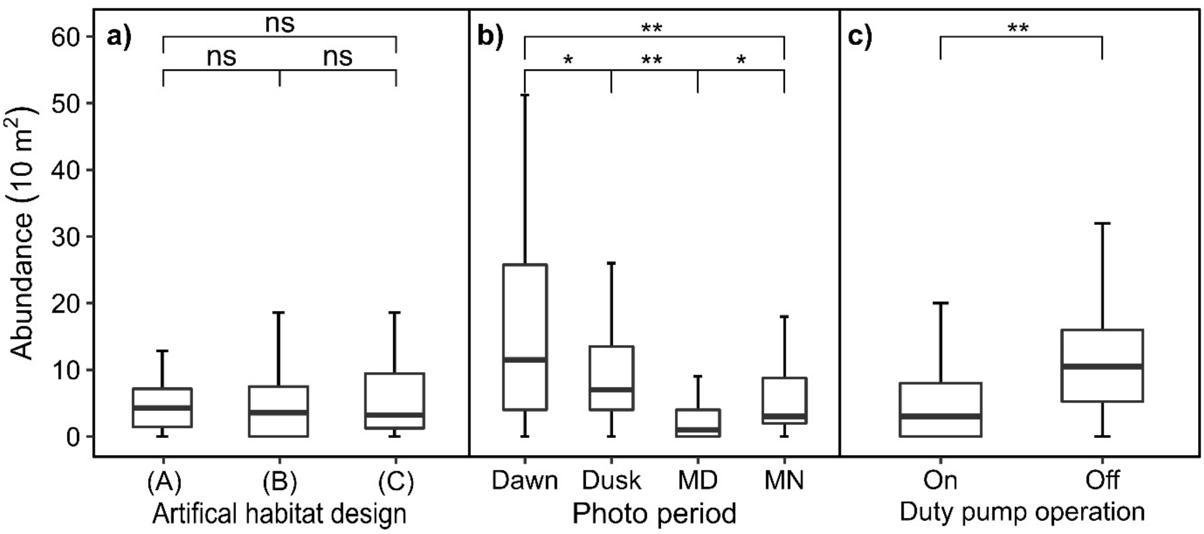

Figure 7 Median fish count near: a) artificial habitats, with partial refuge (A – bamboo), partial refuge (B – shelter) and complete refuge (C – shelter & bamboo) in the North Level Drain (52.737735N, 0.148511W), Great Britain, 10–18 December 2020. b) fish accounts across photo period MD = midday, MN = midnight and c) fish counts during duty pump operation. Significance between categories indicted by Wilcoxon rank sum (ns = not significant, * = P ≤ 0.05, ** = P ≤ 0.001).

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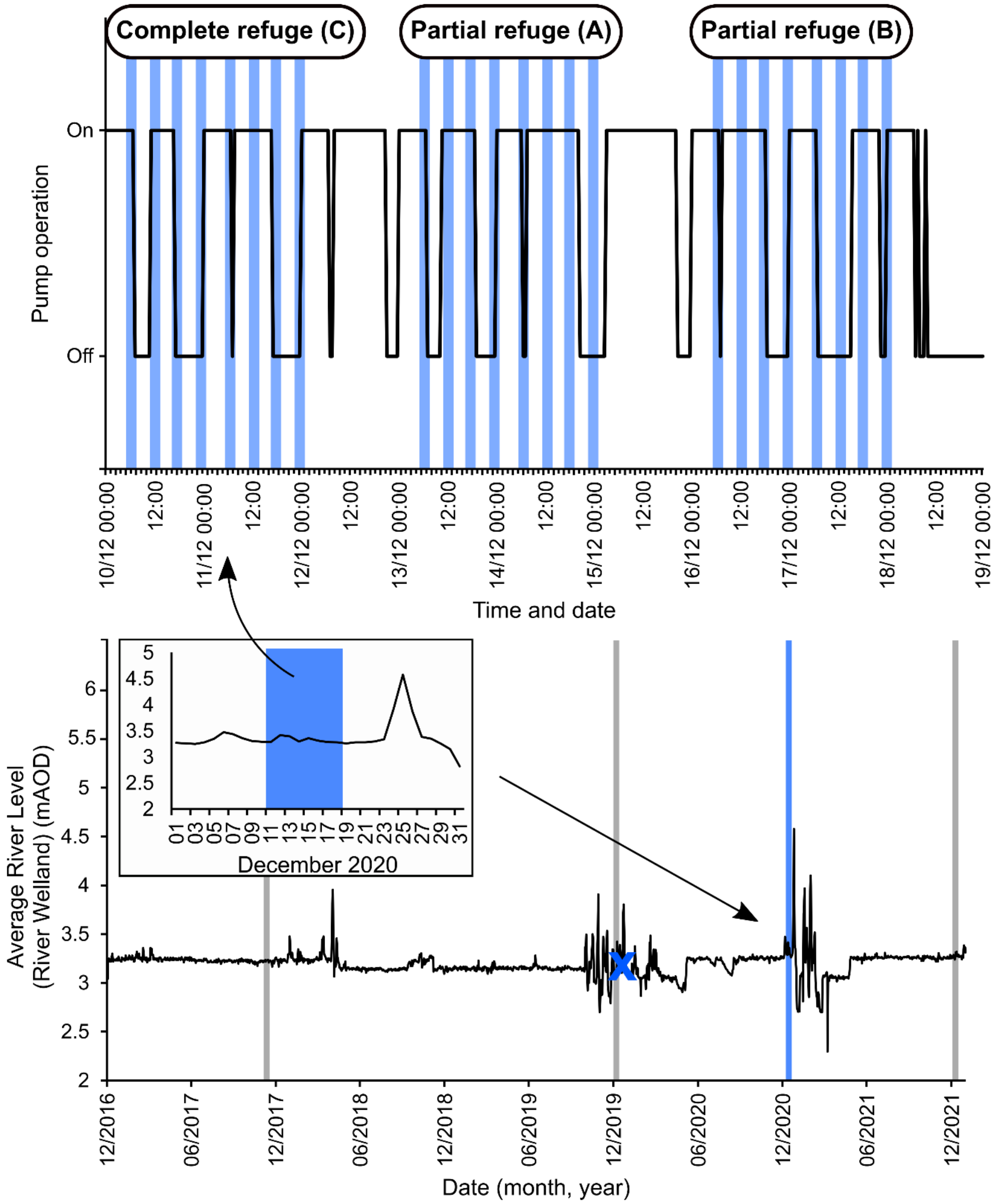
Table S1 Side-scan sonar survey results throughout the study period. Region of Interest (ROI) specifies where counts were taken on light and dark backgrounds. Total fish count given by findMaxima outputs (ImageJ).

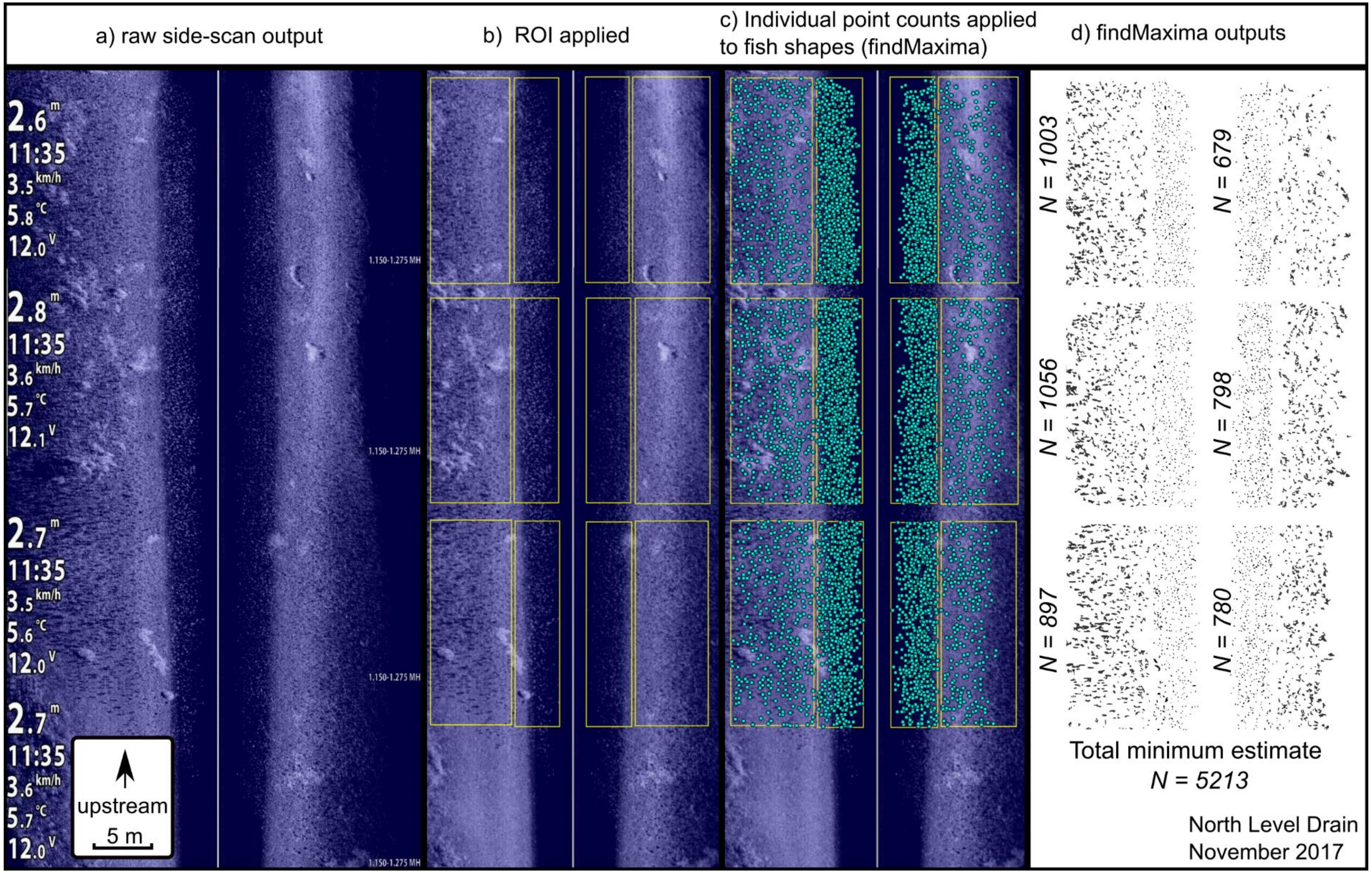
	Total area (m^2)		*n* ROIs		Fish count	
Sample year	Surveyed (at S1)	Analysed	Light	Dark	Total	Estimated fish abundance (10 m^2)
November 2017	1600	840	6	6	5213	63
December 2019	1600	990	8	4	1474	15.4
December 2021						
(main drain)	1600	0	-	-	0	0
(artificial habitats)	900	0	-	-	0	0

Table S2 Multi-beam survey results from artificial habitat sampled on 10 – 18 December 2020.

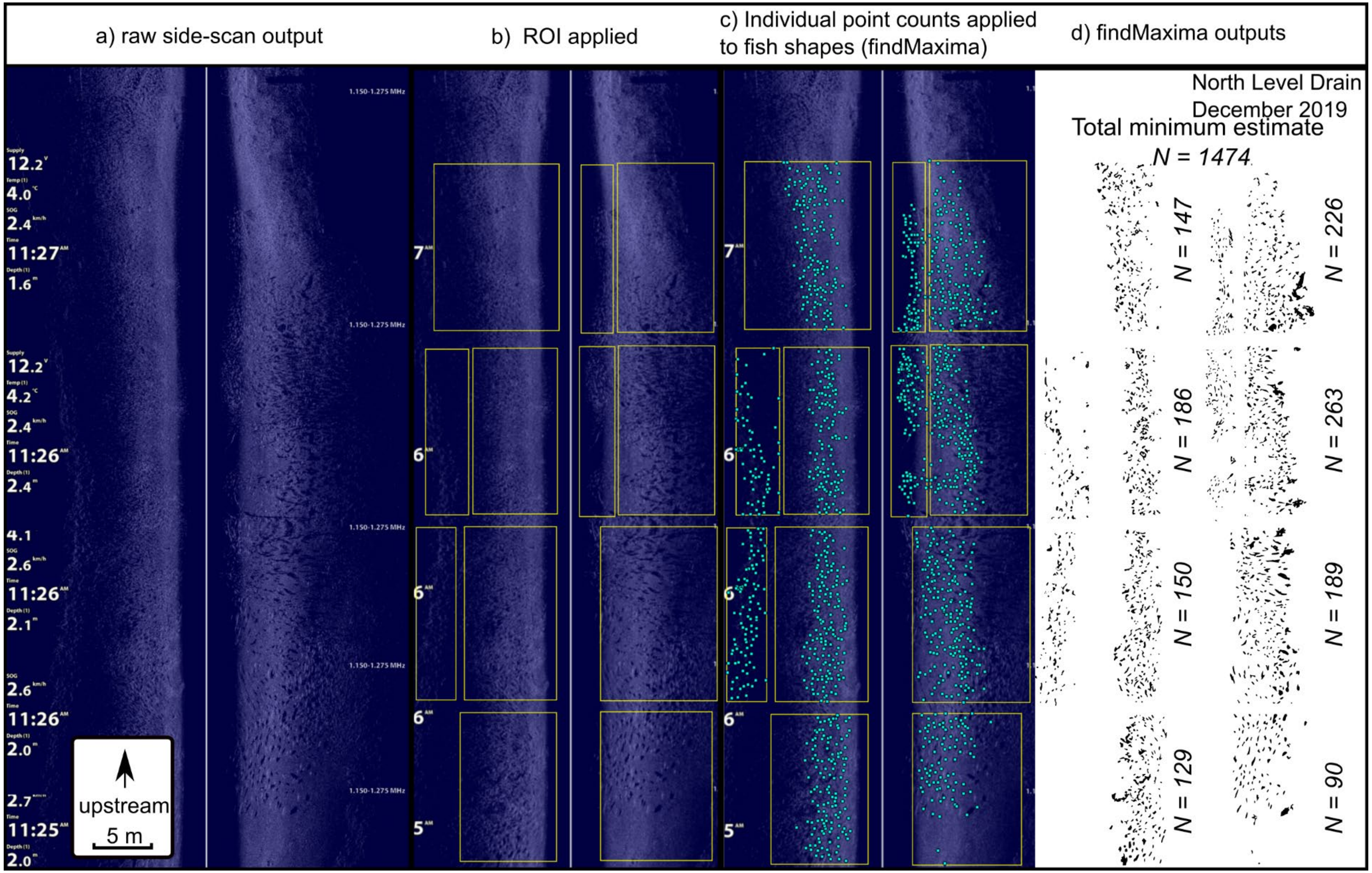
Artificial habitat (photo period)	Estimated fish abundance (10 m^2)				Hours duty pumped during sample (%)	
	Median	Min	Max	IQR		
Complete refuge	3.21	0	30	8.21	9	(75%)
Dawn	6.78	0.71	18.57	8.21	1.50	(37.50%)
Day	0.71	0	2.85	1.42	4	(100%)
Dusk	10	2.14	30	4.64	2	(50%)
Night	1.78	0	12.85	6.07	1.50	(37.50%)
Partial refuge (A)	4.29	0	80.70	5.89	10.75	(89.50%)
Dawn	19.2	0	80.74	22.50	1.25	(31.25%)
Day	1.48	0	12.14	5.17	4	(100%)
Dusk	4.64	0	12.85	3.57	4	(100%)
Night	3.21	0	7.14	3.92	1.50	(37.50%)
Partial refuge (B)	3.57	0	72.10	8.04	10.50	(87.50%)
Dawn	13.21	0	47.14	21.25	1.50	(37.50%)
Day	0	0	72.14	7.32	2	(50%)
Dusk	3.21	0	18.57	3.75	4	(100%)
Night	2.14	0	12.85	3.57	3	(75%)



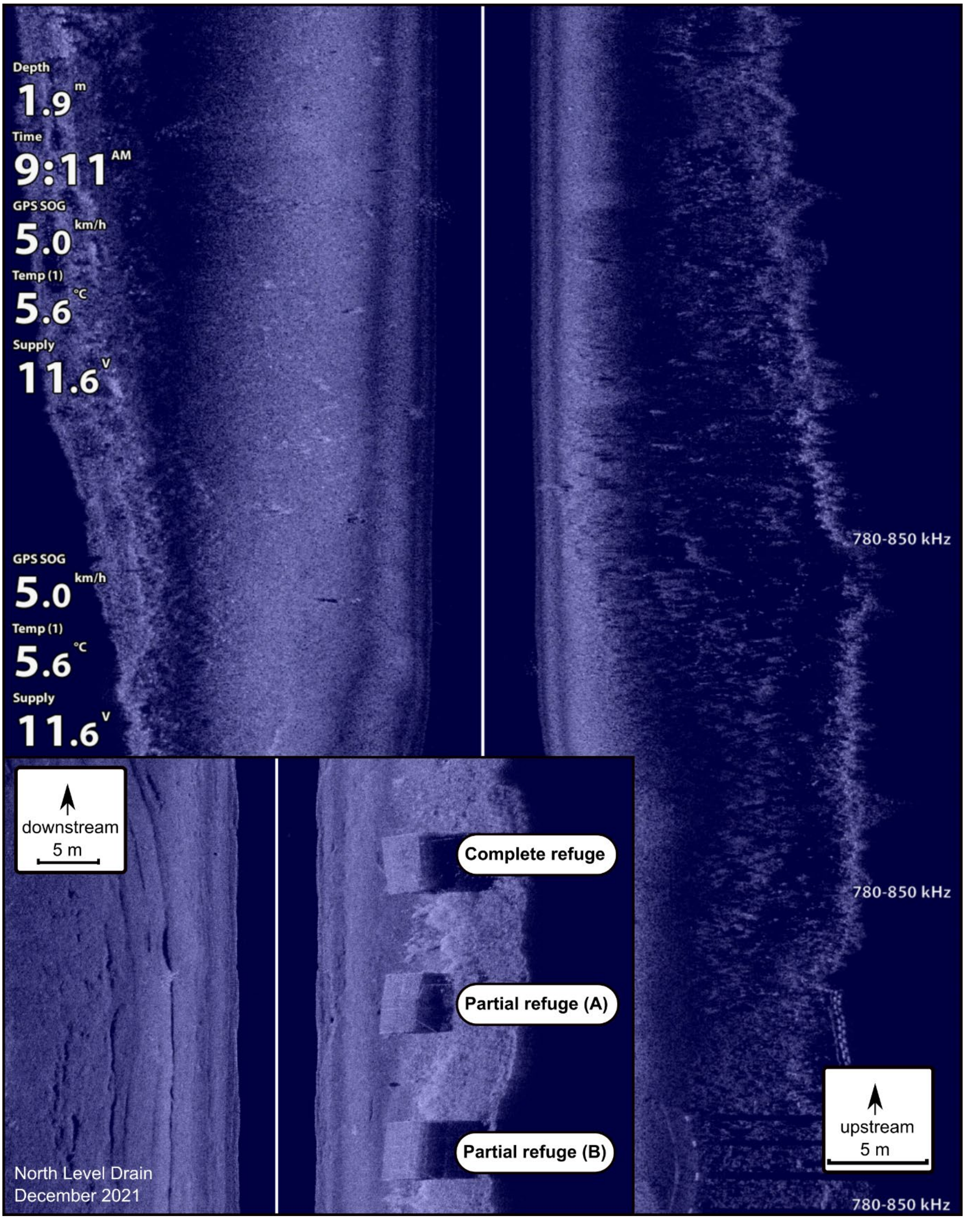
Supplementary Figure 1 (top) pump operations at Tydd pumping station on 10 – 18 December 2020 and (bottom) average daily river level (mAOD) recorded in the River Welland (52.720221 N,-0.141261 W) adjacent to North Level Drain catchment between December 2016 and December 2021. Vertical grey bars indicate date of side-scan surveys. The blue cross indicates when artificial habitats were installed upstream of Tydd pumping station, and the vertical blue lines indicate when the ARIS sonar surveys were performed (inset figure for clarity).



Supplementary Figure 2. Composite image from North Level Drain (52.737735N,0.148511W) with a representation of the side-scan survey (downstream to upstream) for 27 November 2017. The enumeration process is shown as a) – d).



Supplementary Figure 3. Composite image from North Level Drain (52.737735N,0.148511W) with a representation of the side-scan survey (downstream to upstream) for 10 December 2019. The enumeration process is shown as a) – d).



Supplementary Figure 4. Composite image from North Level Drain (52.737735N,0.148511W) with a representation of the side-scan survey (downstream to upstream) for 17 December 2021. Inset image shows artificial habitat scans.