AGU ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE
10.1029/2021WR030111

Key Points:

- Four leaky barrier designs varying in porosity, longitudinal length, and color were tested in an experimental flume
- Color and complexity of barrier design impacted fish spatial usage and upstream passage
- A short leaky barrier had least impact on upstream passage

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Citation:
Müller, S., Wilson, C. A. M. E., Ouro, P., & Cable, J. (2021). Experimental investigation of physical leaky barrier design implications on juvenile rainbow trout (*Oncorhynchus mykiss*) movement. *Water Resources Research*, *57*, e2021WR030111. https://doi.org/10.1029/2021WR030111

Received 1 APR 2021
Accepted 22 JUL 2021

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Experimental Investigation of Physical Leaky Barrier Design Implications on Juvenile Rainbow Trout (*Oncorhynchus mykiss*) Movement

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Abstract Rivers have been subject to the construction of numerous small-scale anthropogenic structures, causing the alteration and fragmentation of habitats. Despite their impact on fish habitat selection, migration, and swimming performance, more hydraulic structures are being added to riverine systems. These mainly have the purpose of harnessing renewable energy or mitigating the impact of flooding, as in the case of leaky barriers that are widely used for natural flood management. By providing a sustainable and cost-effective supplement to traditional hard engineering flood risk management methods, these channel-spanning wooden barriers are constructed using sustainable, local materials, intended to slow down surface water and groundwater flow, reduce flood peaks, and attenuate the flow reaching downstream communities. Despite their increasing popularity, little is known about the design implications on fish movement or hydrodynamics. Using scaled laboratory flume experiments we investigate how the physical design of four leaky barriers varying in porosity, length, provision of overhead cover, and color, impact on fish movement and spatial usage, and the channel hydrodynamics. Our fish behavioral analysis reveals that juvenile rainbow trout (*Oncorhynchus mykiss*) movement reduces with barrier presence. Upstream passage increases with barrier color but not cover, for shorter rather than longer leaky barriers, and for a non-porous barrier compared to its porous counterpart. Barrier-specific flow alterations appear to play a secondary role compared to barrier color. Our study showed that physical barrier design and leaky barrier presence alter fish movement, and therefore care needs to be taken during the design of such natural flood management structures.

1. Introduction

Rivers are subject to the wide-scale construction of anthropogenic structures, ranging from large hydropower and reservoir dams to low-to-zero head structures such as weirs, culverts, sluices, water intakes and outtakes, and riverine turbines. These structures are still being added to expand infrastructure, mitigating flood risk, extract water, and generate electricity, such that 99% of river catchments within the United Kingdom are now modified (Jones et al., 2019). Although 80% of these structures are small-scale, only 1% of the UK's rivers remain free-flowing (Jones et al., 2019). The resulting river fragmentation poses a threat to biodiversity and in particular to fish movement (Jones et al., 2019; Reid et al., 2019) by presenting physical, chemical, thermal, and hydraulic barriers (Silva et al., 2018). This can result in movement delay (Silva et al., 2018) and increased energetic swimming costs (Enders et al., 2003). Only a small fraction of these barriers are obsolete and many are not removable. Therefore, great effort has been undertaken in retrofitting (e.g., weirs [Amaral et al., 2019], culverts [Goodrich et al., 2018]) and partially removing existing barriers (e.g., Sullivan et al., 2019), and developing fishways (Silva et al., 2018) to restore longitudinal river connectivity by enabling upstream and downstream movement of target species.

Fishways and hydraulic structures are still subject to design adjustments, including for instance the optimization of structure geometry (e.g., height, ramp length and slope, orifice arrangement and shape [Amaral et al., 2019; Silva et al., 2012]), and discharge (Plesiński et al., 2018) to increase passage performance and ensure fish migration (Amaral et al., 2019; Plesiński et al., 2018; Silva et al., 2012). Parameters influencing the attraction and passage success of fishways and other hydraulic structures include interspecies and intraspecies differences in swimming performance, hydrodynamic preferences, passage strategies, and hydrodynamic alterations (Amaral et al., 2016; Ghimire & Jones, 2013; Goodrich et al., 2018; Silva et al., 2012). Additionally visual cues, such as stroboscope lights and bubble curtains, are used to modify fish movement, including, for instance, the redirection of fish away from hydropower plant entrances (Perry et al., 2012). So far, color as a visual cue has not been used to influence fish movement but was found integral to the functioning of fish aggregation devices (e.g., Kawamura et al., 1996).

While barriers are generally undesirable and require bypass solutions, they are also used for intentional river fragmentation, which might restrict the spread of non-native invasive species (INNS) that present another major threat to biodiversity (Dudgeon et al., 2006; Reid et al., 2019). However, selective fragmentation might restrict their movement into adjacent habitats while simultaneously allowing passage of desired native species (Rahel & McLaughlin, 2020). These undesired species might be excluded by applying a range of ecological filters, based on physiological, morphological (body shape), sensory, and or behavioral attributes (Rahel & McLaughlin, 2020). Anthropogenic hydraulic structures, for instance, can act as filters to fish movement by either: (a) preventing movement of all species (e.g., dams); (b) allowing movement of all species (e.g., nature fishways); (c) allowing movement of the majority of desired fish species while reducing undesired fish species; or, ideally, (d) allowing movement of only desired species (Rahel & McLaughlin, 2020). To specifically use barriers for intentional river fragmentation, it is essential to not only understand structural, environmental, and hydrodynamic changes associated with these structures (Amaral et al., 2019; Plesiński et al., 2018; Silva et al., 2012) but also to understand species-specific differences to prevent the passage of INNS.

Particularly in the United Kingdom, many hydraulic structures have been added to river systems in the last two decades to enhance and supplement traditional flood risk mitigation schemes (Burgess-Gamble et al., 2018). As part of natural flood management (NFM) projects, structures formed by wooden logs, branches, fallen trees and boards are manually introduced into upper river catchments. These channel-spanning structures, known as leaky barriers, are designed with a gap underneath, ensuring unimpeded baseflow and fish movement. Physical leaky barrier design often depends on the local channel characteristics (e.g., channel height and width), the availability of trees on the riverbank and local materials available for construction, resulting in diverse physical barrier designs varying, for instance, in barrier height, length, log arrangement and flow area blockage (Muhawenimana et al., 2020). While these barriers allow flow through the structure, they become more watertight with time due to the natural accumulation of sediment, leaf material, and driftwood. The piling up of these materials also increases both barrier blockage, and longitudinal barrier length, with longer barriers providing an increase in overhead cover, an essential feature in river restoration (Heggenes & Traaen, 1988). The resulting shaded area has been found to be a visual stimulus associated with refuge and enabled fish to find the covered region (Moreira et al., 2020). A wide range of leaky barrier designs can already be found worldwide but in particular in the United Kingdom where predominantly engineered leaky barriers were installed as part of 60 Department for Environment, Food, and Rural Affairs-funded NFM projects ([Arnott et al., 2018; Burgess-Gamble et al., 2018], e.g., Pickering, North East England; Holnicote, South West England; Peeblesshire, South Scotland; and Shropshire, West England).

Under high flow conditions, leaky barriers provide blockage and increased hydraulic roughness to the river's main channel, leading to backwater rise upstream, which causes the flow to spill out onto the surrounding floodplains. Downstream of these barriers, a wide range of flow alterations can be observed, as depicted in Figure 1, which strongly depend on physical barrier design, including longitudinal barrier length, dowel arrangement, and porosity. Independent of physical design, for inbank flows, a reasonable proportion of the flow passes through the main gap beneath the leaky barrier leading to flow acceleration and formation of a primary jet of high streamwise velocity ($U_{jet} \gg U_0$) beneath the barrier structure (where U_{jet} is the maximum velocity of the primary jet and U_0 is the free-stream logarithmic velocity for a given elevation). This high momentum flow prevents the unobstructed gap from becoming blocked by the accumulation of sediment, leaf material, and woody debris. This primary jet maintains its maximum velocity (U_{jet}) over a certain downstream distance ($x/b_0 = (4U_0/U_{jet,max})^2$) before starting to rapidly decay (Ead & Rajaratnam, 2002; Shabayek, 2018). Leaky barriers of high blockage area (Figure 1b) may show similar flow alterations as observed for sluice gates and flow around bluff bodies. These include large recirculation zones immediately downstream of the structure (Ead & Rajaratnam, 2002), flow exiting beneath the barrier and flow overtopping the barrier top (Müller et al., 2021). Most leaky barriers, however, feature high porosity

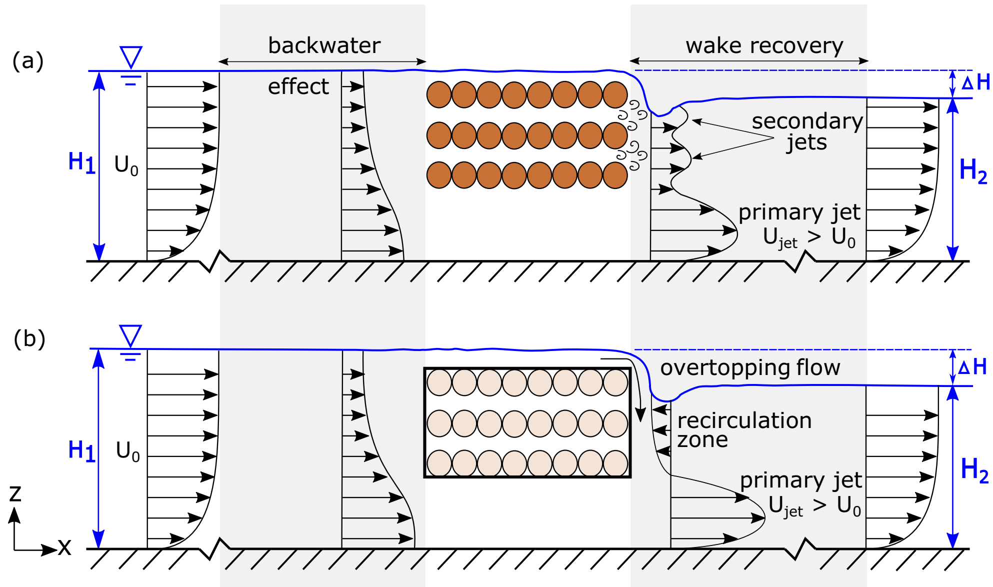

Figure 1. Main flow alterations and typical mean longitudinal velocity profiles (U) observed for porous (a) and nonporous (b); indicated by the black box around dowels) leaky barriers created from horizontal dowels (indicated by brown circles). Far upstream of the barrier, velocity profiles follow a logarithmic distribution (U_0). The increased cross-sectional blockage provided by these barriers causes a back-water effect (gray-area upstream), increasing upstream flow depth (H_1), a decrease in downstream flow depth (H_2), and therefore, a difference in the head (ΔH), and flow exiting the barrier's top. Flow diversion near the barriers is shown by lower U at barrier height and high momentum flow beneath the barriers, forming a primary jet of maximum jet velocity U_{jet} ($U_{jet} \geq U_0$). While immediately downstream of the nonporous barriers a large recirculation zone forms, porous leaky barriers allow flow through the structure, leading to the shedding of turbulent structures and smaller secondary jets. With increasing downstream distance, mean longitudinal velocities recover (gray-area downstream) until reaching their logarithmic distribution.

allowing flow through the structure (Figure 1a). The relatively small proportion of flow flowing through the internal gaps may form smaller and weaker secondary jets, also known as offset jets. These secondary jets form small recirculation zones between them and interact with each other before merging with increasing downstream distance (Wang & Tan, 2010). The flow around and through porous leaky barriers may also be analogous to the flow around horizontal cylinders or a submerged vegetation canopy. Multiple cylinder arrangements, however, has been mostly studied for low Reynolds numbers (e.g., Lam & Zou, 2010; Sumner et al., 2000; Zou et al., 2011). Only single horizontal cylinders have been analyzed for higher Reynolds numbers, more likely representing flow conditions found in riverine systems (Muhawenimana et al., 2018; Ouro et al., 2019).

Due to the flow alterations caused by different physical leaky barrier designs and the physical design dependency on channel characteristics, materials, and natural processes, leaky barriers may be classified as hydraulic or physical barriers, potentially fragmenting upper catchments. So far, only a few studies have assessed the impact of leaky barriers, or model simplifications consisting of horizontal cylinder arrangements, on hydrodynamics and fish behavior. Current physical design guidelines summarized by Dodd et al. (2016) are based on existing knowledge about fish movement and habitat usage but lack empirical evidence. Key parameters, namely total barrier height, and the gaps underneath and within the barriers, have been considered (Dodd et al., 2016), but without considering porosity, longitudinal barrier length, and flow alterations in relation to fish behavior. Our previous work on the fish response to leaky barriers revealed that although fish movement was not impeded, porosity rather than discharge influenced spatial usage and fish movement, with more fish passing upstream in the presence of a nonporous barrier (Müller et al., 2021).

This study aims to enhance the current understanding of physical leaky barrier design impacts on the aquatic environment and identify design guidelines to foster leaky barriers as natural flood risk mitigation measures. Through scaled laboratory open channel flume experiments, we investigate the effect of four conceptual physical engineered leaky barrier model designs varying in porosity, longitudinal length, and color

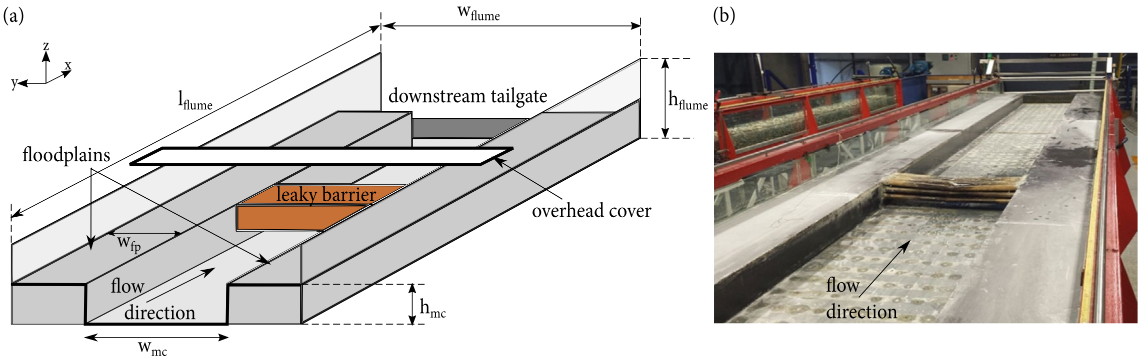

Figure 2. Experimental set-up comprising a straight, rectangular compound channel as schematic (a) and photograph (b). The main channel (*mc*) had a width $w_{mc} = 0.6\ m$ and bankfull height $h_{mc} = 0.15\ m$, and floodplains (*fp*) on either side of the main channel of width $w_{fp} = 0.3\ m$. The leaky barriers were placed within the main channel at ∼5 *m* downstream of the flume inlet. An overhead cover board was placed on top of the flume sidewalls at the same longitudinal location as the leaky barriers to ensure a similar overhead cover was provided independent of barrier length.

(orange vs. natural) on upstream and downstream hydrodynamic alterations and juvenile rainbow trout (*Oncorhynchus mykiss*, Walbaum 1792) movement, including spatial usage and upstream passage. Leaky barrier designs were adapted and scaled from those installed in Wilde Brook, Corvedale, Shropshire, UK, as part of the NFM project "Shropshire Slow the Flow-Seven Tributaries" project to mimic the natural characteristics of these barriers (Follett & Wilson, 2020; Müller et al., 2021). More specifically, we address the following questions: (a) How does barrier design, including longitudinal length and porosity, alter upstream and downstream flow?; (b) Do juvenile rainbow trout spend more time underneath longer barriers compared to shorter barriers due to the provision of overhead cover?; (c) Can visual cues (i.e., barrier coloration) increase upstream passage?; (d) Are velocity or visual cues the decisive parameter in increasing upstream movement?; and finally, (e) Do leaky barriers present a barrier to invasive non-native fish movement?

2. Methods and Materials

Hydrodynamic and fish behavior experiments were performed in a recirculating open channel flume in the Hydro-Environmental Research Centre's hydraulic laboratory at Cardiff University, UK.

2.1. Flume Set-Up

The experimental set-up is presented in Figure 2, showing the 10 *m* long (l_{flume}), 1.2 *m* wide (w_{flume}) and 0.3 *m* deep (h_{flume}) recirculating flume with a longitudinal bed slope of 1/1,000. The flume has a straight compound channel section of width $w_{mc} = 0.6\ m$, bankfull depth $h_{mc} = 0.15\ m$, and floodplains of width $w_{fp} = 0.3\ m$ on each side of the channel. Longitudinal flow direction was defined as positive in the downstream direction x, while lateral and vertical flow direction were defined as y and z, respectively. Water discharge was controlled by a pump and the water surface profile was controlled by a tailgate weir located at the flume outlet. Both, discharge and flow depth remained fixed throughout the experiments. Prior to the installation of the leaky barrier structures, uniform, subcritical flow was adopted for a bankfull flow condition, relating to a discharge $Q = 0.028\ m^3 s^{-1}$ and a flow depth $h_0 = 0.15\ m$. This flume condition, without barrier, represents the control treatment. After the installation of the barrier, a change in water surface profile was observed (Muhawenimana et al., 2020), generating gradually varied flow conditions; flow depth was measured using a point gauge.

2.2. Leaky Barrier Structures

Four leaky barrier designs (Figure 3b), comprising of a non-porous (LB1), long-porous (LB2), long, open-porous (LB3), and short-porous leaky barrier (LB4), were installed in the main channel ∼5 *m* downstream of the flume inlet, with their main characteristics depicted in Figure 3a. Each barrier was constructed using individual wooden dowels of diameter $d = 0.025\ m$, attached to a plastic plate on the main channel sides, to

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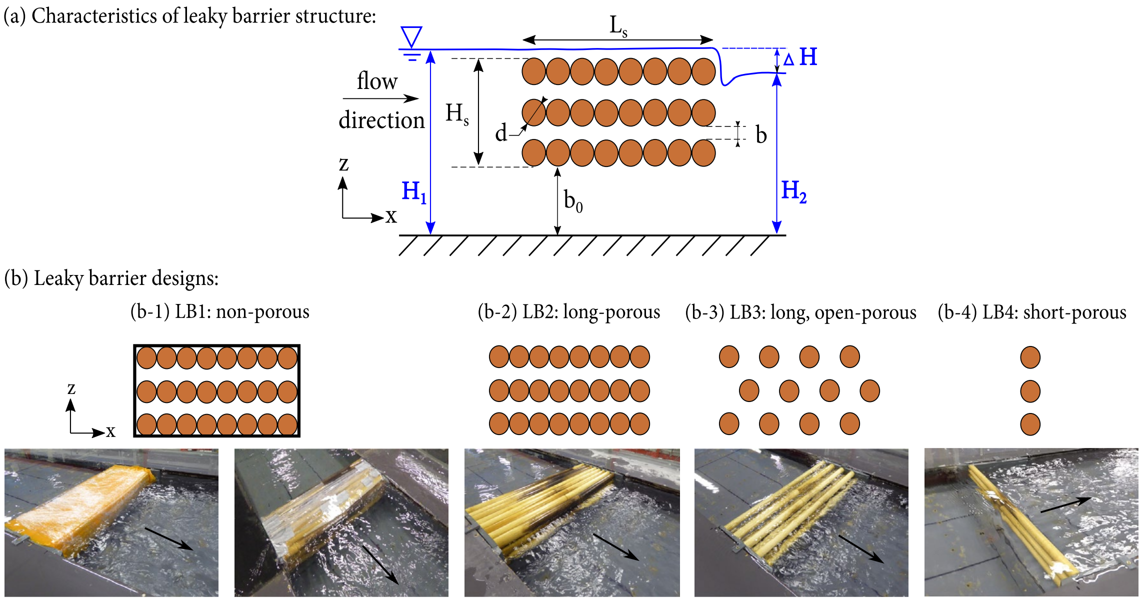

Figure 3. Main characteristics of a leaky barrier structure (a) and a schematic of the four analyzed leaky barrier structures (b) as side-view schematic (top) and top view photograph with flow direction from left to right (bottom), including a non-porous (LB1; [b-1]), two long, porous structures with aligned (LB2; [b-2]) and staggered (LB3; [b-3]) layouts, and one short, porous leaky (LB4; [b-4]) design. The non-porous LB1 was sealed with either a non-transparent orange (LB1-orange, left) or a colorless transparent (LB1-natural, right) to mimic the natural color of the barrier while the internal dowel setup remained the same.

allow ease of installation of the structures. These comprised three dowel rows in the vertical and eight dowels in the longitudinal direction, all featuring a height (H_s) of 0.1 m and a longitudinal length (L_s) of 0.2 m (Figure 3 [b-1–b-3]), except for the short-porous structure (LB4) which consisted of only one dowel row in streamwise direction ($L_s = d$) (Figure 3 [b-4]). In the designs LB2 and LB4, a vertical gap (b) of 0.0125 m was maintained between each dowel row to allow flow through, while for LB3 this is $b = 0.05\ m$. A vertical gap (b_0) of 0.05 m between the lowest dowel edge and flume bed remained present for all leaky barrier designs. All structures were designed to mimic designs employed in the field, with similar cross-sectional flow blockage, and allowing passage of baseflow and fish movement beneath the structure. Three flow blockages were analyzed by comparing two porous barrier structures (LB2 and LB3; Figure 3 [b-2 and b-3] respectively), enabling through flow, against a non-porous structure (LB1; Figure 3 [b-1]), which simulates the natural accumulation of sediment, leaf material, and woody debris within the barrier. The latter leaky barrier (LB1) was constructed by wrapping the external wooden dowels in orange (denoted as LB1 or LB1-orange, Figure 3 [b-1, left]) or transparent, colorless (denoted as LB1-natural, Figure 3 [b-1, right]) polythene to prevent flow through the structure. It should be noted that due to the presence of the vertical gap beneath barriers, the channel cross-section is still porous. Here, we solely focus on the porosity of the leaky barrier structure itself. All leaky barrier design parameters presented were geometrically scaled by a factor 1:6.7 from those found in the field, including dowel diameter, barrier height, and gap between the bed and lowest barrier edge (Follett & Wilson, 2020). A detailed explanation of the field to model barrier and flow condition scaling can be found in Müller et al. (2021).

A summary of the experimental set up for each leaky barrier tested is presented in Table 1. Physical characteristics of the barriers include number of dowels (N), structure length (L_s), frontal area (A_s), and cross-sectional blockage area (A_p) calculated as $A_s/(H_{mc}w_{mc})$. Leaky barrier structure porosity was defined as $\Phi = V_{pore}/V_{control}$ with $V_{control} = w_{mc}H_S L_S$ (no barrier present) and V_{pore} being the equivalent volume resulting from the difference of $V_{control}$ and the volume occupied by the solid leaky barrier $V_{structure}$ ($\pi(d/2)^2 n_{dowels} w_{mc}$). Hydraulic conditions include the mean flow depth (H_1 and H_2), which were based on the average water elevation measurements up to 3 m upstream and 1.8 m downstream of the barrier respectively. The difference between the mean upstream (H_1) and downstream (H_2) flow depths is ΔH. The bulk velocity is $U_0 = Q/A$ was calculated for upstream (U_{01}) and downstream (U_{02}) condition with A denoting the flow cross-section which is a function of the flow depth (H_1, H_2), and Reynolds number defined as

Table 1

*Details of Leaky Barrier Structural Properties and Hydraulic Conditions, Including Number of Dowels (N), Structure Length (L_s), Frontal Projected Area (A_s), Cross-Sectional Blockage Area (A_p), Leaky Barrier Structure Porosity (Φ), Mean Flow Depth (H_1 and H_2, With the Asterisk * Indicating Overbank Flow in Column H_1), Variation Between Up- and Downstream Mean Flow Depths (ΔH), Bulk Velocity (U_{01} , U_{02}), and Reynolds Number (Re_1 , Re_2)*

Treatment	N $[-]$	L_s $[m]$	A_s $[m^2]$	A_p $[\%]$	Φ $[\%]$	H_1 $[m]$	H_2 $[m]$	ΔH $[m]$	U_{01} $[ms^{-1}]$	U_{02} $[ms^{-1}]$	Re_1 $[-]$	Re_2 $[-]$
Control	-	-	-	-	-	0.146		-	0.32		31,474	
LB1	24	0.2	0.06	66.7	0	0.172*	0.140	0.033	0.24	0.33	18,128	31,367
LB2	24	0.2	0.05	50.0	41.1	0.158*	0.142	0.016	0.28	0.33	18,460	31,845
LB3	12	0.2	0.05	50.0	70.5	0.160*	0.145	0.016	0.27	0.32	18,413	31,647
LB4	3	0.025	0.05	50.0	41.1	0.155*	0.146	0.010	0.29	0.32	18,541	31,425

$\mathrm{Re} = U_0 R_H / \nu$ for upstream (Re_1) and downstream (Re_2) conditions, with ν denoting the fluid kinematic viscosity and R_H denoting the main channel hydraulic radius.

2.3. Velocity Measurements

A sideways-looking Acoustic Doppler Velocimeter (ADV) (Nortek Vectrino) was used to measure the three velocity components within the proximity of the leaky barrier structure. To capture a representative sample of the high-frequency turbulence fluctuations and to ensure sufficient data quality, a sampling rate of 200 Hz was applied over a sampling period ranging from 5 to 20 min. To enhance signal quality, the water was seeded by Spherical®110P8 hollow glass spheres (Potters Industries LLC) with a mean particle size of $11.7\,\mu m$ and a specific gravity of $1.10\,g/cc$, and a signal-to-noise ratio (SNR) of at least > $15dB$ and a correlation of at least > 70% were maintained by increasing the concentration of the seeding material in the water. Velocity measurements were taken at 10 locations upstream and 11 locations downstream for all leaky barriers as indicated in Figure 4. Up to $\sim 4b_0$ upstream and downstream of the barrier, the longitudinal distance between the profiles (x/b_0) was 20 mm, and this was increased to 60 mm, 100 mm, 250 mm, 500 mm and 1000 mm depending on the distance away from the barrier (Figure 4). The vertical resolution between each sampling point was 5 mm. Velocity data were filtered and postprocessed using Matlab (2019a). In a first prefiltering step, data with insufficient SNR and correlation were removed before these were despiked using an open-source toolbox (Mori, 2020; Mori et al., 2007).

2.4. Fish Behavior Experiment

Fish passage behavior tests were conducted using juvenile rainbow trout (*Oncorhynchus mykiss*) as model species, sourced from the Bibury Trout Farm. Rainbow trout were used as model species to seek proof of the concept of leaky barriers rather than to test specific species response. Rainbow trout have significantly spread worldwide (Crawford & Muir, 2008) as a result of stocking for angling purpose and farm escapees, and although non-native to the United Kingdom, can now be found in UK rivers (Fausch, 2007).

The experimental test section used for the fish behavior experiments is presented in Figure 4 and was 1.6 m long and bounded by a plastic mesh with gap size $0.005 \times 0.005\ m$, spanning the full flume width, at $\sim$0.7 m ($14b_0$) upstream and downstream of the structure. The test section was divided into three spatial zones (indicated by the different colors in Figure 4): upstream (0.7 m; green area), downstream (0.7 m or 0.875 m for LB4; purple area) and barrier region (L_s; light blue area). Hence, when comparing control versus LB4 (short, porous design), the difference in area needs to be considered as LB4 only covers one eighth of the control "barrier" area. A GoPro Hero 5 underwater camera was positioned at the center of the upstream end of the control section, immediately upstream of the mesh, pointing in the flow direction and was used to record fish spatial usage and passage behavior. These recordings were used in addition to manual recordings using stop watches to ensure that manually obtained results could be checked for accuracy. The water

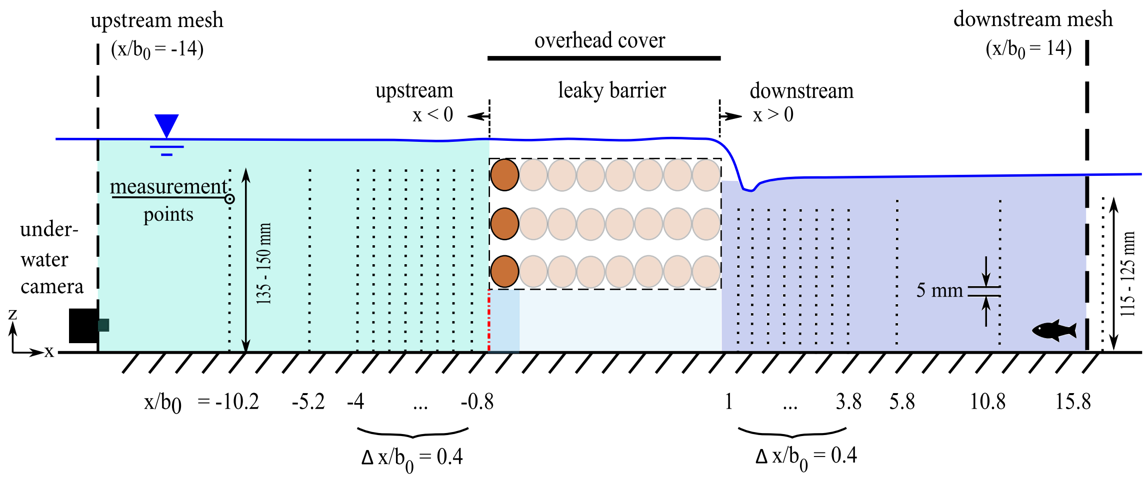

Figure 4. Longitudinal locations at which the Acoustic Doppler Velocimeter measurement were taken in the vicinity of the barriers (values of x/b_0 beneath the test section) and test section used for the fish behavior experiment. In total, 10 and 11 velocity profiles were measured upstream and downstream of the leaky barriers, respectively, starting at $\sim 0.01\ m$ above flume bed until $0.03\ m$ beneath the water surface with a vertical resolution of $0.005\ m$. Test section for fish behavior experiment was bounded by upstream and downstream mesh and divided into three regions, including upstream (green), beneath the leaky barrier (light blue), and downstream (purple). An underwater camera was positioned at the upstream end of the test section while fish were released at the downstream end. The red dotted line indicates the cut-off point for passes from the downstream and barrier region into the upstream region.

in the flume was dechlorinated (Seachem Prime Concentrated Conditioner) and chilled to $14°C$ (D-D The Aquarium Solution, DC, 2000).

Fish were maintained within a recirculating aquaculture system (RAS) at the Cardiff University Aquarium in $60-80l$ tanks of $30-40$ fish each. This system, enclosed within a temperature-controlled room maintained at $14 \pm 0.5°C$ on a 12:12 h dark-light cycle, has integrated bag and drum filters (Pall Cooperation) alongside a plastic bio media in the sump tank and UV sterilization system. Water temperature and oxygen level are constantly monitored, and nitrite levels are tested weekly (Nutrafin). Every morning, fish were fed commercial trout pellets.

Prior to the experiments, fish were transported to a temporary holding tank, adjacent to the flume, and given at least one day recovery from the 20 *min* transport. This recirculating holding tank holds $500l$ dechlorinated water (Seachem Prime Concentrated Conditioner, Tetra AquaSafe), constantly chilled to $14 \pm 1°C$ (D-D The Aquarium Solution, DC 750) with an external filter (Aquamanta, EXF 600) and aerated by an external air pump (Tetratec Aps 400). Fish were maintained in floating cages constructed from plastic mesh (hole size $5x5\ mm$) in small groups of $5-10$, depending on the number and size of fish tested.

On the test day, fish were individually introduced into the flume and given a 15 *min* acclimatization period. Fish were released in the furthest downstream section and allowed to explore the whole of the test section, experiencing a 2 *min* incremental increase in discharge over the first 10 *min* up to the test discharge level, followed by a 5 *min* acclimatization at the test discharge ($Q = 0.028\ m^3 s^{-1}$). At all times, the downstream tailgate weir remained fixed at a predetermined height set for the uniform flow condition. Each trial lasted 10 *min* in which individual fish were released at the most downstream end of the test section at the centerline of the main channel. Experiments were conducted under ambient light conditions comprising of LED lights mounted on the room ceiling and natural light supplied through the windows. During the test, the following parameters were recorded and analyzed for each barrier design: (a) percentage of time spent in each zone (upstream, barrier, and downstream) with time starting as soon as fish entered one of the regions defined in Figure 4; (b) number of upstream passes per fish with passes defined as crossing from beneath the barrier region into the upstream region (cut-off point indicated by the red dotted line in Figure 4), representing the frequency of fish passing into the upstream region; and (c) percentage of upstream passing fish, representing the number of fish passing from underneath the barrier into the upstream region. For simplification purposes, number of upstream passes per fish and percentage of upstream passes per fish were summarized under the term "passage behavior." After completion of the test (10 *min*), fish were returned to the holding tank.

After completion of the experiment, fish were transported back to RAS at the Cardiff University Aquarium. All tanks were equipped with environmental enrichment to provide refugia (e.g., plant pots) to reduce stress, and care was taken to minimize stress caused by fish handling and transportation between facilities and tanks.

All fish behavior experiments were performed after the hydrodynamic measurements and cleaning the flume so it was free of the ADV seeding material. In total, three types of experiments were conducted, each with separate batches of fish ($n_{total} = 136$). Details in terms of the fish batch and experimental type (a), (b), and (c) are given below:

(a) Leaky barrier length and porosity experiment: Fish response to four leaky barrier designs (LB1-4) was conducted under the bankfull flow condition between March 21st and April 3rd 2019 between 7 *am* and 8 *pm*. Prior to the experiment, $n = 30$ rainbow trout (mean ± s.d. mass 15.9 *g* ± 11.1 *g*, mean ± s.d. standard length 91.0 *mm* ± 21.3 *mm*) were anaesthetized using 0.02% MS-222 and tagged with 7.5 *mm* PIT-tags (ISO 11784 certified, Loligo Systems, Denmark), followed by covering the injection site with protective powder (Oraheasive powder) and allowing at least three weeks for recovery. Each fish was individually tested for each leaky barrier design and control treatment, that is, without the leaky barrier, in a random treatment order, with 1 day rest in between trials. Pit-tags were solely used to identify individuals to ensure each fish completes all treatments and were read using a handheld PIT-tag reader (Agrident, APR500 E).

(b) Cover experiment: Fish response to overhead cover was examined using $n = 20$ rainbow trout (mean ± s.d. mass 11.5 *g* ± 3.8 *g*, mean ± s.d. standard length 85.5 *mm* ± 9.2 *mm*). Overhead cover was provided by a board of 0.01 *m* thickness and longitudinal length of 0.2 *m*, spanning the full width of the flume, and positioned at a vertical distance of 0.32 *m* above the flume bed and 5 *m* downstream of the flume inlet, matching the longitudinal leaky barrier position as indicated in Figure 2; no barrier was placed within the test section during these trials. The overhead cover presence was compared against the bare flume without an overhead cover to investigate the fish's susceptibility to cover provided by different barrier designs. Similar to experiment (a), fish were anesthetized and pit-tagged prior to the experiment to allow identification of individuals. To ensure treatment randomization, 10 fish were tested first with overhead cover, while the remaining 10 fish were tested without overhead cover first. Subsequently, treatment order was reversed; hence, the fish tested withou overhead cover were then tested with cover while fish first tested with cover were tested without. The trial took place in March 29th and April 1st 2019 between 9*am* and 7.30 *pm*, allowing one day recovery between tests.

(c) Color experiment: Fish response to nonporous barrier (LB1) color was tested between March 12th and March 18th 2020 between 7*am* and 7.30 *pm*. Two barrier colors, including an orange nontransparent barrier (LB1-orange) and barrier with a colorless and transparent wrapping (LB1-natural) mimicking a more natural non-porous design, were examined using $n = 86$ rainbow trout (mean ± s.d. standard length 123.2 *mm* ± 14.5 *mm*). It should be noted that fish used in this experiment were significantly larger compared to those employed in experiments (a) and (b) (general linear model [GLM], $p < 0.0010$) as this experiment was conducted at a later stage. Therefore, fish behavior for the control case (without a leaky barrier) was monitored again to ensure there were no significant changes in behavior between the fish used in this experiment and the control case in experiment (a). No significant differences were found regarding spatial preference (GLM, $p > 0.0010$) and percentage of upstream passing fish (GLM, $p = 0.3792$) but number of upstream passes per fish was significantly lower in experiment (c) (GLM, $p < 0.0010$). Each fish was tested individually and only once. Fish remaining stationary at the furthest downstream end of the test section or impinging the downstream mesh were excluded from the analysis, resulting in the following numbers of tested individuals per treatment: $n = 32$, 30 and 24 for LB1-natural (three fish excluded from analysis), LB1-orange and control (two fish excluded from analysis), respectively.

Statistical analysis was conducted using the R v. 3.6.3 statistical software. For all three experiments, spatial preference (upstream, downstream, beneath the barrier), percentage of upstream passing fish and number of upstream passes were analyzed as key parameters. Passage behavior was used to quantify fish swimming activity and interaction between the different velocity regions. Spatial preference was analyzed using separate GLMs with Gaussian distribution and identity link for each of the spatial regions (upstream, barrier, and downstream), which allowed investigation of the differences in mean time proportion and leaky barriers as well as the fish length. Differences in means between the percentage of upstream passing fish and fish length as well as leaky barrier design were tested using a binomial GLM with a logit link function. A negative binomial GLM with squared (experiments (a) and (b)) and a quasi-Poisson GLM with identity (experiment (c)) link function was conducted using the R library MASS to analyze potential differences in means between the number of upstream passes per fish, fish length, time upstream, and leaky barrier design. Similar statistical tests were used to compare spatial preference and percentage of upstream passing fish between the control groups in experiments (a) and (c) but using a negative binominal GLM with identity link to compare the number of upstream passes per fish. Differences in fish length amongst the different experiment and test groups were analyzed using a Gaussian GLM with link function identity. Randomization was taken into account for experiments (a) and (b) by assigning an individual treatment order to each fish. Learning-based effects were assessed by analyzing the percentage of upstream passing fish per test day using a binominal GLM with logit link function in case of experiment (a). Nonsignificant variables were stepwise removed from the statistical analysis and residuals were used to assess the suitability of the test. P-value significance was taken at 0.05.

All fish behavioral experiments were approved by the Cardiff University Animal Ethics Committee and conducted under Home Office License PPL 303424 following ARRIVE guidelines (Kilkenny et al., 2010).

3. Results

3.1. Hydrodynamics

The flow characteristics developed upstream and downstream of the leaky barriers were analyzed in terms of normalized mean streamwise velocity ($\overline{u}/U_{01}$), obtained at the ADV measurement locations shown in Figure 4.

The velocity profile for the control case was measured over a single vertical profile (i.e., $x/b_0 = 0.8$, Figure 4), and features a typical logarithmic velocity distribution (Figure 5a). Leaky barriers were then installed in the flume under the same flowrate and downstream control conditions (Table 1), which resulted in a significant change in the channel hydrodynamics and water surface profile due to their presence obstructing the flow (Figures 5b–5i).

Upstream of the barriers, the mean flow distribution was characterized by a progressive reduction of the high-velocities near the free-surface layer, especially after $x/b_0 \approx -2$, and flow acceleration over the lower part of the water column, that is, $z/b_0 \leq 1$ (Figures 5b–5e). Comparing the velocity distribution immediately upstream of the leaky barrier ($x/b_0 = -0.8$), the non-porous leaky barrier (LB1) featured the highest mean velocities at gap height ($z/b_0 \leq 1$) (Figure 5b). In contrast, lower maximum velocity values were found for leaky barriers featuring a larger porosity (LB3-LB4) as their design enabled flow through the barrier structure (Figures 5d, 5f and 5h). The cross-sectional blockage provided by these barriers caused an increase in upstream flow depth. A so-called backwater rise (indicated in Figure 1) was most noticeable for barriers with lower porosity (Table 1), and hence, most pronounced for the non-porous leaky barrier (LB1). Furthermore, this backwater rise resulted in overtopping flow and upstream floodplain inundation. This effect was more pronounced for the non-porous barrier (LB1) as the difference in mean upstream and downstream flow depth (ΔH in Table 1) was double than that for the long, porous leaky barriers (LB2 and LB3), and three-fold for the short-porous design (LB4).

Immediately downstream of the leaky barriers, the flow exiting the barrier's bottom gap ($z/b_0 \leq 1$) featured high streamwise velocities (Figures 5c, 5e, 5g and 5i) as a result of the upstream flow diversion due to barrier blockage (Figures 5b, 5d, 5f and 5h). This high-momentum flow region formed a primary jet that attained mean streamwise velocity values two to three times higher than that for unobstructed flow conditions found in the control case (Figure 5a). This high-velocity jet extended over a downstream distance of up to $x \leq 4b_0$ for all designs, with highest values observed for LB1 (Figure 5c). A similar pattern was developed for all the porous barriers, albeit attaining smaller maximum velocities due to reduced flow obstruction and through flow (Figures 5e, 5g and 5i). In the case of the non-porous barrier (LB1; Figure 5c), the high-momentum

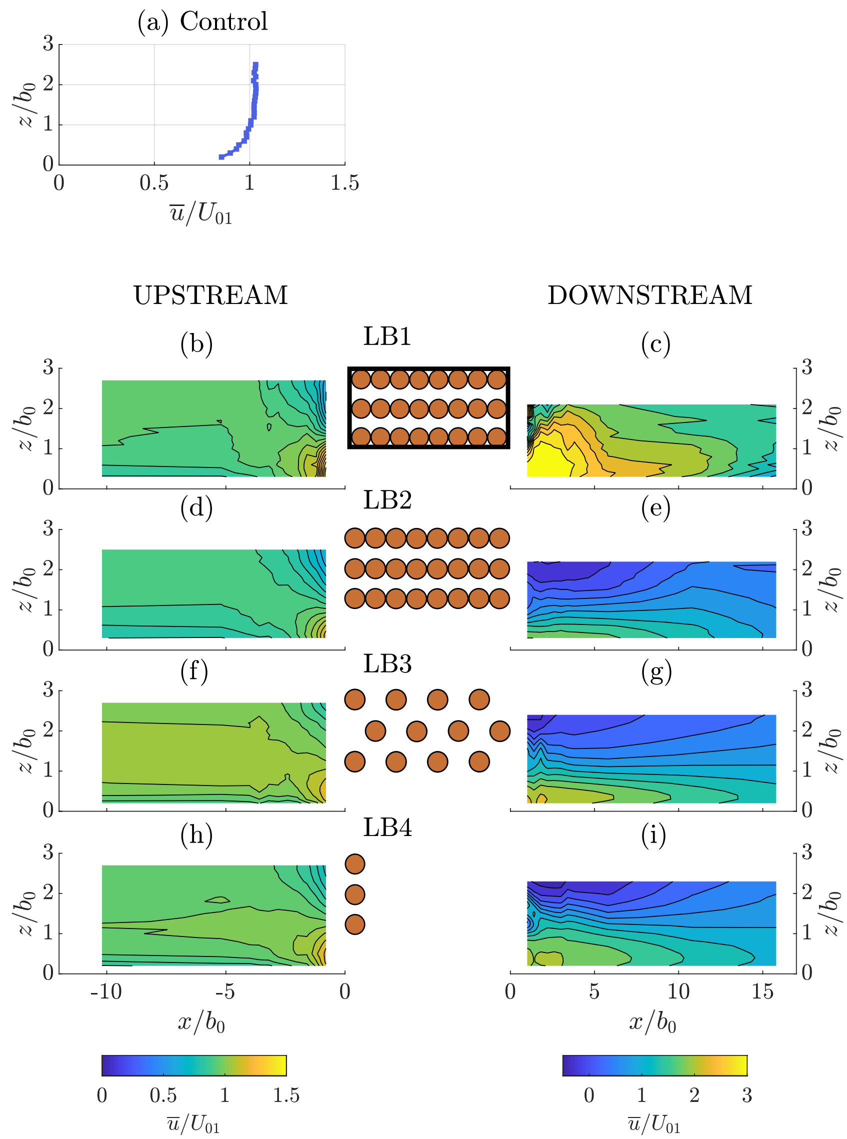

Figure 5. Time-averaged flow hydrodynamics in terms of normalized longitudinal mean velocities ($\overline{u}/U_{01}$). A single velocity profile at $x/b_0 = 0.8$ was measured for the control case (a), while the results upstream (b, d, f, and h) and downstream (c, e, g, and i) of each leaky barrier structure were determined along the main channel centerline in the x-z-plane.

flow rapidly expanded into the upper region of the barrier's wake ($z/b_0 \geq 1$). In contrast, higher velocity values were found closer to the flume bed in the case of both long-porous barriers (LB2 and LB3; Figures 5e and 5f). In the case of the short-porous barrier (LB4; Figure 5i), the highest primary jet velocities were found at mid-gap height and extended throughout the vertical main gap height ($0 \leq z/b_0 \leq 1$).

In addition to the primary jet exiting from beneath the leaky barrier, all porous barriers (LB2, LB3, LB4) developed smaller and weaker secondary jets between the dowel rows at $z/b_0 \approx 1.63$ and ≈ 2.4 (Figures 5e, 5g and 5i), which originated from the provision of distinct longitudinal paths within the barriers that allowed flow through the barrier structure. Due to momentum conservation, these secondary jets directly weakened the primary jet strength, a result of the reduced under flow. Despite the ADV equipment being unable to measure close to the dowels, these secondary jets were identified by a local increase in $\overline{u}/U_{01}$ at height of the inter-dowel gaps. Even though these jets decayed quickly after a downstream distance of $x/b_0 \approx 2$,

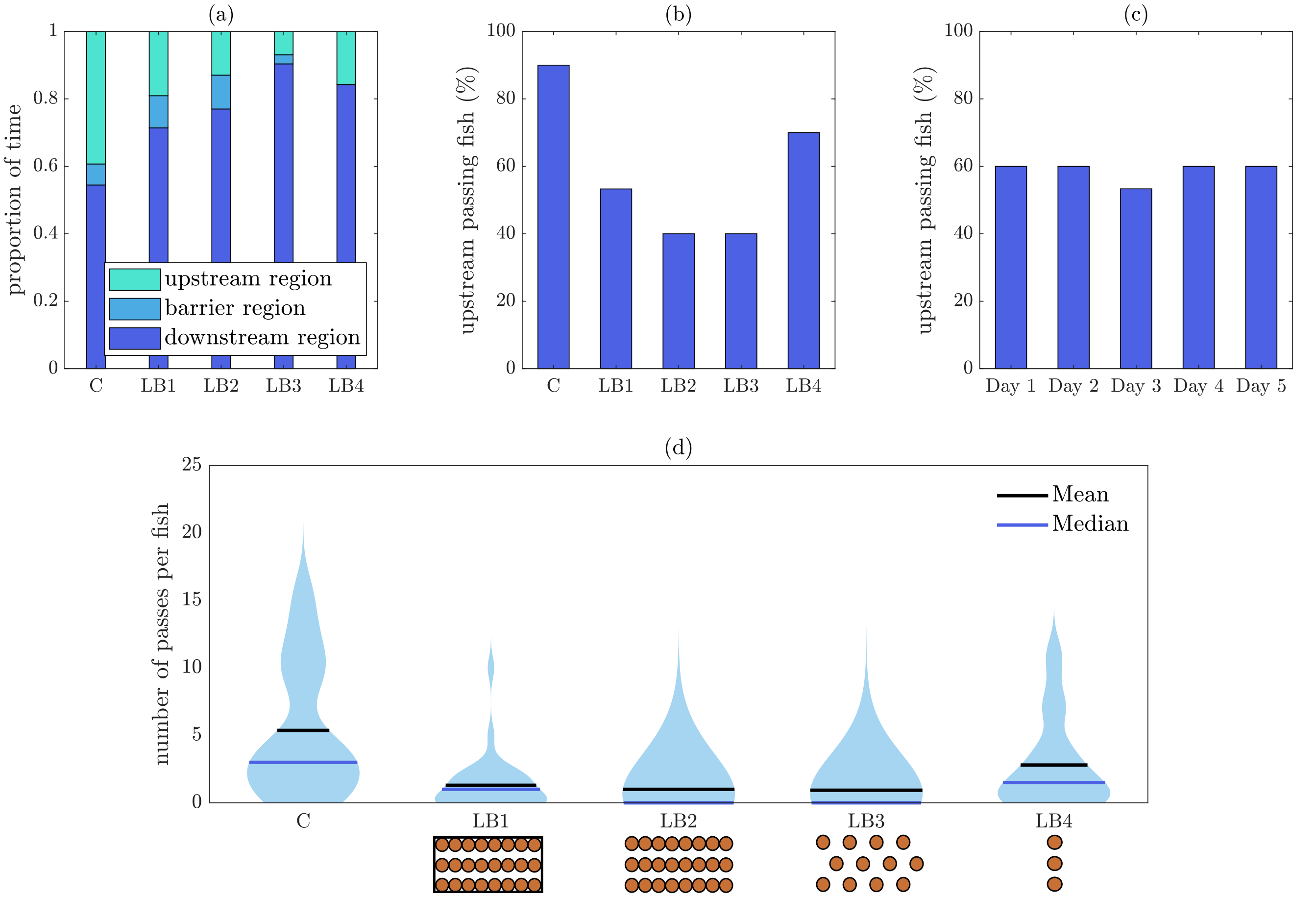

Figure 6. Impact of the tested leaky barrier structural design on fish behavior. (a) Percentage time fish spent downstream, within the leaky barrier region and upstream, (b) percentage of upstream passing fish, (c) percentage of upstream passing fish per test day independent of treatment, and (d) number of passes per fish for the no-barrier control set-up and each of the analyzed leaky barrier designs (LB1-4) with the width of the density distribution denoting frequency. Note, for simplicity, LB1-orange is denoted as LB1 in this figure.

they were particularly pronounced in the LB4 design, attaining higher velocities compared to their longer counterpart (LB2; Figure 5c).

3.2. Fish Behavior

3.2.1. Leaky Barrier Length and Porosity Experiment

Spatial behavior, analyzed in terms of time spent downstream, beneath the barrier, and upstream, showed that fish spent the least time beneath the barrier, and more time downstream than upstream (Figure 6a). Hence, leaky barrier presence significantly impacted on the time fish spent within the different spatial regions (GLM, upstream and downstream $p < 0.0010$, barrier region $p = 0.0060$). Passage behavior, including percentage of upstream passing fish (Figure 6b) and number of passes per fish (Figure 6d), was negatively affected by the barrier presence (GLM, $p < 0.0010$), and resulted in less fish passing into the upstream region. Of all of the leaky barrier designs examined, the short barrier (LB4) differed least from the control case in terms of percentage of upstream passing fish and number of passes per fish (GLM, $p = 0.1943$ and $p = 0.0186$, respectively). Although fish length did not impact spatial usage nor upstream passes per fish (GLM, spatial usage: upstream $p = 0.0660$, downstream $p = 0.0620$, barrier $p = 0.7768$; upstream passes per fish: $p = 0.1030$), it affected the number of upstream passing fish (GLM, $p = 0.0074$), with larger fish being less likely to pass upstream.

By comparing the non-porous barrier (LB1) against the two porous barriers (LB2 and LB3), we analyzed the impact of porosity on fish behavior. There was no significant difference between the three barrier porosities for the number of upstream passing fish (GLM, LB2: $p = 0.2874$ and LB3: $p = 0.4257$) and mean number of passes per fish (GLM, LB2: $p = 0.7204$ and LB3: $p = 0.5708$). A nonsignificant decrease in time spent in the upstream area occurred with increased porosity (LB3<LB2<LB1; GLM, LB2: $p = 0.4369$ and LB3: $p = 0.1191$). Hence, time spent downstream increased with increasing porosity with only the long, open-porous leaky barrier (LB3) significantly differing from the nonporous LB1 (GLM, $p = 0.0167$). Despite all three long barriers providing a similar area of cover for the fish, time spent beneath them significantly varied amongst the long, open-porous (LB3) and the non-porous (LB1; GLM, $p = 0.0321$) as well as the long-porous barrier (LB2; GLM, $p = 0.0217$), showing that fish spent less time beneath LB3 (3%) and most time beneath LB1 and LB2 (10%).

The impact of barrier length on fish behavior was tested by comparing the long, porous barrier (LB2) with the short, porous barrier (LB4). Decreasing the length of the barrier led to an increase in the number of upstream passing fish from 40% to 73% (GLM, $p = 0.0090$). Similarly, for the shorter design, mean passes per fish significantly increased 2.8 times (GLM, $p = 0.0346$). In contrast, there was no significant difference between barrier length in terms of time spent downstream and upstream (GLM, $p = 0.3582$ and $p = 0.5231$, respectively), but a higher proportion of fish spent time beneath the longer leaky barrier (LB2; GLM, $p = 0.0018$).

To avoid a learning-based bias of the experimental results due to the repeated use of fish for each treatment, the treatment-independent percentage of upstream passing fish per test day was analyzed (Figure 6c), showing that on each test day 60% of the fish passed into the upstream region, with the exception of day 3 (53%). Hence, no significant difference was found between the number of upstream passing fish and test days (GLM, $p = 0.9794$), suggesting that learning effects were negligible.

3.2.2. Fish Response to Overhead Cover Experiment

Reducing leaky barrier length alters the near wake (see Figure 5) and fish behavior, potentially due to the shortened overhead cover offering a reduced shelter and refuge region. The impact of overhead cover preference was analyzed without a barrier (control condition) which showed that spatial preference did not significantly differ amongst cover versus no-cover conditions (Figure 7a; GLM, upstream: $p = 0.3617$, downstream: $p = 0.8090$, barrier: $p = 0.0764$), with almost equal time spent upstream (cover: 38%, no-cover: 28%) and downstream (cover: 61%, no-cover: 64%) of the cover region. Although the presence of overhead cover did not impact percentage of upstream passing fish (75% and 85% for overhead cover and no overhead cover, respectively) and number of passes per fish (mean: overhead cover 4.95 and no overhead cover: 2.65, median: 2) (Figure 7c; GLM, $p = 0.0582$), fish length significantly impacted the percentage of upstream passing fish (GLM, $p = 0.0219$), with larger fish being less likely to pass upstream. Fish length also impacted time spent upstream and downstream (GLM, $p = 0.0106$ and $p = 0.0240$, respectively) with larger fish spending slightly less time upstream and more time downstream, but this did nonsignificantly impact time spent within the overhead cover region (GLM, $p = 0.6206$).

3.2.3. Fish Response to Leaky Barrier Color Experiment

A larger proportion of time was spent downstream (GLM, $p = 0.0344$) and less time was spent upstream for the LB1-natural case (GLM, $p = 0.0086$) compared to the LB1-orange case (Figure 7b). More fish were found to pass upstream (76%) when LB1-orange was present, with this percentage being significantly lower in case of LB1-natural (23%) (Figure 7d; GLM, $p < 0.001$) (Figure 7d). Similarly, the number of upstream passes per fish was significantly different amongst both leaky barrier colors (Figure 7d; median: LB1-organe: 1, LB1-natural: 0; GLM, $p = 0.0091$). Fish length did nonsignificantly impact the percentage of upstream passing fish, number of passes per fish nor the time spent underneath the barrier (GLM, $p = 0.1283$ and $p = 0.7129$, respectively) but did influence time spent upstream and downstream (GLM, $p = 0.0055$ and $p = 0.0343$, respectively).

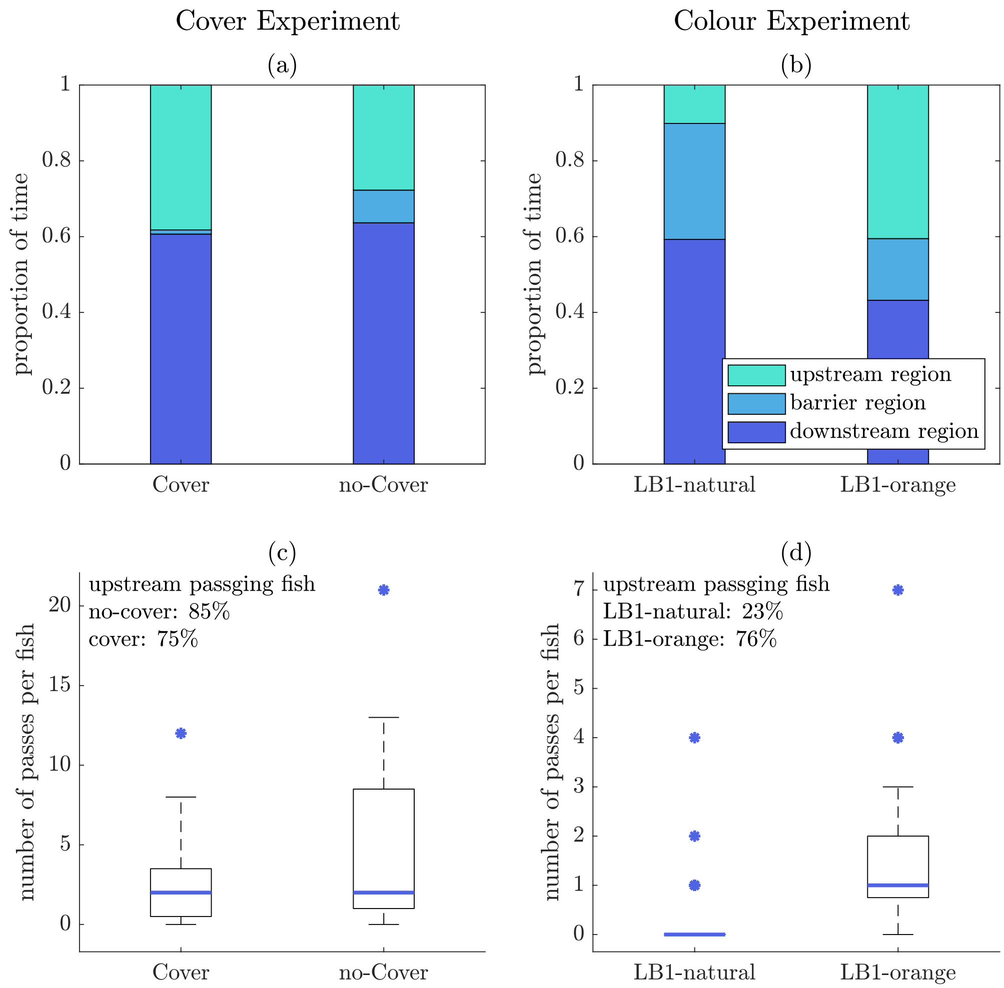

Figure 7. Fish behavior experiments investigating the impact of overhead cover presence without barrier (a and c) and leaky barrier color (b and d) on average time fish spent downstream, beneath the leaky barrier and upstream (a and b), and percentage of upstream passing fish and distribution of passes per fish (c and d). Note, for simplification, LB1-orange was previously denoted as LB1.

4. Discussion

While the four tested leaky barrier designs did not block fish movement, the presence of these physical barriers did impact on spatial usage and fish movement when compared with a no barrier free-flow scenario. Independent of barrier design, barrier presence resulted in an increased proportion of time spent downstream of the barriers and a decrease in upstream passing fish. However, two barrier designs, namely the non-porous (LB1) and short-porous (LB4) barriers, impacted least on spatial usage and fish movement compared to their long-porous counterparts. While the high-momentum flow did not prevent fish from passing into the upstream region, barrier color had the greatest impact on upstream passage. Based on these findings, it can be concluded that leaky barriers have the potential to prevent and delay fish movement by acting as physical barriers and velocity barriers, and therefore their design, maintenance, and the swimming abilities of the local species community should be considered carefully to ensure unhindered fish movement of desired fish species or prevent the spread of invasive non-native species.

Our present results show that the high-momentum flow of the primary jet, caused by the barrier's blockage effect, did not prevent upstream passage in line with the findings in Müller et al. (2021), however, only strong swimmers (i.e., Atlantic salmon [*Salmo salar*, Linnaeus, 1758] and rainbow trout [*Oncorhynchus mykiss*]) were tested. Furthermore, in our study, fish were obtained from a fish farm and therefore, fish spatial usage and swimming performance should be assumed to differ from those observed in wild fish

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(Basaran et al., 2007). The strong primary jet exiting the barrier's main gap prevents the cross-section from becoming blocked. The strength of this jet decreased with increasing porosity, as the latter allows more flow through the inter-dowel gaps of the porous barrier designs. This "through flow" led to the development of smaller and weaker secondary jets. These secondary jets are assumed to create a mixing region immediately downstream of the porous barriers due to their interaction and the interaction with the primary jet (Daubner et al., 2018; Wang & Tan, 2007). Particle image velocimetry and turbulent structure-resolving numerical modeling should be used to further investigate potential turbulent structures formed in the near wake of these porous model barriers and more naturalized barrier designs consisting of nonuniform branches and logs. Periodic shedding of turbulent structures, such as vortex streets, can impact fish swimming stability and may lead to the avoidance of the upper wake region of these barriers (Muhawenimana et al., 2019; Tritico & Cotel, 2010). In addition, weak swimmer response (e.g., cyprinids) to leaky barriers remains unknown and should be considered for high flow conditions to avoid leaky barriers becoming a velocity barrier.

While the primary jet exiting the gap below the barrier may have acted as a velocity cue for upstream passage for all barrier designs, the color and cover provided by the visually "wooden" porous barriers (LB2, LB3, LB4) and the orange non-porous barrier (LB1), may have also provided visual cues. In our study, the short-porous (LB4) and non-porous (LB1) barriers were the least physically complex and exhibited a higher percentage of upstream passing fish compared to the long-porous barriers (LB2 and LB3). When reducing barrier length to decrease complexity as in the case of the short-porous design (LB4), the provision of overhead cover decreases. Our results show no differences in spatial usage and passage behavior of juvenile rainbow trout when overhead cover was present or removed. Conversely, in our previous study on Atlantic salmon responses to non-porous and porous leaky barriers (Müller et al., 2021), we showed that salmon spent the majority of their time underneath the porous structure. In this case, the turbulent "signature" provided by the secondary jets generated by the "rough" through flow the porous barriers and the enhanced turbulent shear stress produced between the lowest dowel row and flow from underneath the barrier may have been used by fish to locate the cover (Smith et al., 2014). Atlantic salmon have been previously found to show a strong preference for overhead cover (Heggenes & Traaen, 1988), unlike rainbow trout (Butler & Hawthorne, 1968; Lewis, 1969), reflecting inter-species differences.

Besides physical complexity, the leaky barrier color was identified as another potential key parameter providing a visual cue for rainbow trout. More fish moved upstream when comparing a colored, orange barrier (LB1-orange) against a design sealed with colorless, transparent wrapping (LB1-natural), with the latter emulating a more natural design as the wooden dowels account for the barrier color. The decreased number of upstream passing fish under the natural-colored barrier was accompanied by an increase in time spent underneath the barrier, which was also found by Müller et al. (2021). Possibly the orange LB1 provides a clearer visual cue for fish passage or may not have been associated with shelter due to its unnatural color. On the other hand, the natural-colored barrier mimics more closely natural wooden formations associated with overhead cover and shelter. A study comparing a wooden against an acrylic, transparent velocity shelter showed an increase in use of the wooden structure, which was assumed to be linked to visual stimuli caused by the shade (Moreira et al., 2020). Rainbow trout possess well-developed color vision (Niwa and Tamura 1969 cited by Nakano et al. (2012), but we know little about their attraction to color and colored objects. While black bass fry were more attracted by red and brown colors (Bardach, 1950), Bermuda bream have been found to be only attracted to color if the object was in motion rather than being stationary, with highest attraction to multicolored fabric as well as orange, corresponding to longer wavelengths (Moreira, 2012). For fish, hue has been found to be more important than contrast (Kawamura et al., 1996) as well as object shape and brightness (Bardach, 1950), with color perception thought to be species-specific, and color intensity and wavelength strongly dependent on water quality (Levine & MacNichol, 1982) and ambient light conditions. It should be noted, that in our experiment, ambient light conditions varied throughout the experiment, which might have influenced fish perception of the barrier color. However, randomization of treatments and fish test order was used to account for variations in ambient light.

Treatment randomization was also applied to minimize learning effects due to the repeated exposure to the test section, flow conditions, and similar barrier designs. This issue has previously been discussed by Mallen-Cooper (1994); they showed an increase in fish successfully negotiating the fishway indicating potential habituation to the repeated exposure to certain flow conditions and structures. Conversely, our study did not show an increase in upstream passing fish with repeated use. This may be due to the variations in barrier design, creating individual wake patterns for each barrier design. However, this is an important aspect which should be further investigated due to leaky barriers often being installed in large numbers (100 plus units) to desynchronize tributary flow from that in the main river. Due to the limited design guidelines of these barriers to date and their constant interaction with natural processes (e.g., natural accumulation of driftwood), fish are likely to encounter changing physical designs and different associated wake patterns. Hence, our porous leaky barrier (LB2) may become non-porous over time, creating a barrier similar to LB1. Frequent maintenance may be required to prevent the creation of a physical, solid barrier for fish movement. In addition, while a single barrier as in our study did not block fish movement, the cumulative effect of multiple leaky barriers may significantly impact fish movement.

Although leaky barriers are primarily used as a nature-based solutions for flood risk management, they could also serve as selective barriers to river longitudinal connectivity due to their impact on fish spatial usage and upstream passage. Hence, these barriers may limit the movement and spread of invasive non-native species such as rainbow trout as shown in our study, or European catfish (*Silurus glanis*, Linnaeus, 1758), another significant INNS (Guillerault et al., 2015), while ensuring connectivity for desired, native ones (Rahel & McLaughlin, 2020). To date, rainbow trout have struggled to successfully establish populations in the majority of the UK rivers, although this may not continue to be the case with climate change (Fausch, 2007). Further research is needed to investigate the use of leaky barriers as selective barriers. This may include the understanding of species-specific differences and therefore the employment of specific barrier design to allow selective passage; for example, the reduction of gap height to exclude larger species to create a physical barrier or decreasing barrier porosity to achieve a stronger primary jet velocity to create a velocity barrier.

Our study shows that physical design modifications can influence fish behavior, in line with previous work analyzing passage efficiency of hydraulic structures (e.g. Amaral et al., 2016, 2019; Silva et al., 2012). Generalization of the present results is limited as the study was performed in a simplified environment under strong lighting conditions and the use of conceptual engineered leaky barrier models simplified through symmetrical arranged horizontal wooden dowels. In contrast, engineered leaky barrier configurations in the field are created using natural logs, characterized by irregular shape and irregular interlog gaps as well as uneven surfaces and increased surface roughness provided by the tree bark. As demonstrated, hydrodynamic alterations, particularly at barrier height ($z/b_0 \geq 1$), strongly depend on leaky barrier design and may therefore differ in a natural environment; however, the creation of a region of high momentum flow is still expected due to the preservation of the gap between the bed and the barrier to ensure unhindered baseflow and fish passage. Similarly, fish in their natural environment may respond differently to adaptations in leaky barrier design due to changes in water quality (e.g. increase in turbidity), temperature, predators, habitat availability, and swimming performance depending on life stage and species. However, the use of scaled ecohydraulic flume experiments is useful for assessing geometric and physical modifications of key design parameters of small in-stream hydraulic structures and corresponding fish response (Amaral et al., 2019).

5. Conclusion

The impact of four leaky barrier designs varying in porosity, longitudinal length, and color on fish spatial usage and upstream passage in relation to the hydrodynamic alterations was experimentally investigated. While leaky barrier presence led to a reduction in upstream passage and an increase in time spent downstream, the physical design of the barrier was found to influence these metrics. A decrease in porosity and longitudinal barrier length positively influenced the number of upstream fish passing fish and the number of upstream passes per fish. Leaky barrier color rather than wake hydrodyanamics was the decisive parameter in terms of upstream passage in the case of the non-porous barrier, highlighting the use of color as visual cue. Spatial usage did not depend on leaky barrier design as in all cases fish spent more time downstream. Our findings expand the current state of knowledge on leaky barrier design's impact on fish movement and highlight the importance of incorporating porosity, longitudinal barrier length and coloration into the design process. Using this knowledge, leaky barriers may be modified to act as selective barriers to longitudinal river connectivity and thus, limit the spread of invasive non-native species. This work contributes to adapting leaky barrier design toward green, eco-friendly hydraulic structures used for natural flood management to ensure habitat connectivity and fish migration while mitigating the impact of flooding.

Data Availability Statement

Data underpinning the results presented here are available in the Cardiff University data catalog at http://doi.org/10.17035/d.2021.0131417060.

Acknowledgments

The authors thank Paul Leach, Steven Rankmore, Gareth Castle, and Valentine Muhawenimana for technical assistance, and Rhi Hunt for providing statistical advice and the reviewers for their valuable comments. This research was funded as part of the Water Informatics Science and Engineering Centre for Doctoral Training (WISE CDT) under grant EP/L016214/1 from the Engineering and Physical Science Research Council (EPSRC).

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