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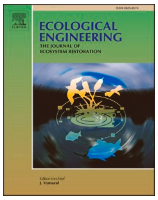

Hydraulic conditions created by a ‘large’ diameter Cylindrical Bristle Cluster fish pass

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ABSTRACT

Cylindrical Bristle Clusters (CBCs) provide a multi-species fish passage solution at sloped weirs. Configurations trialled to date (min. diagonal spacing between CBCs up to 0.17 m) were designed to facilitate passage of relatively small (e.g. < 30 cm) potamodromous species and may hamper the movements of larger bodied (e.g. > 40 cm) fishes, such as adult anadromous salmonids. Therefore, in this study, the hydraulic conditions created by an array of large diameter (0.13 m) CBCs positioned farther apart than in previous studies (min. diagonal spacing 0.29 m) was assessed to determine whether conditions would be suitable for facilitating the passage of small-bodied fish while also providing sufficient space for larger individuals to manoeuvre. Two experiments were conducted in an open channel flume. Experiment 1 quantified the hydraulic conditions created by a model Crump weir when unmodified and with CBCs installed in supercritical flow (*Fr* 1.23–3.01) on the 1:5 downstream sloping face under a low (0.08 $m^3 s^{-1}$) and high (0.23 $m^3 s^{-1}$) discharge. Patches of low water velocity were created in the wake of the CBCs, and the median (time and space averaged) velocity was reduced under both low (30.1%) and high (22.3%) discharge. Based on estimated burst swimming speeds of two common European species, the roach (*Rutilus rutilus*) and brown trout (*Salmo trutta*) (0.16 m long, swimming at 15.1 °C), this reduction in velocity would facilitate upstream passage. Experiment 2 documented the vertical velocity profile and shear stress characteristics (a measure of turbulence) within the CBC array. Unlike in Experiment 1, the CBCs were installed on the flat base of the flume and under subcritical flow (*Fr* = 0.31) to generate sufficient water depth. The velocity was reduced (up to 22.5%) at depths that did not exceed (> 2 cm above) the height of the bristles. Above these depths, velocity was (up to 14.6%) higher compared to open channel conditions upstream of the CBC array and a vertical shear layer was evident. As the main hydraulic benefits of CBCs occur at depths that do not exceed the bristles, their height should be tailored to site specific conditions (e.g. size of target fish species and/or depth of water at infrastructure). Field-based research is needed to determine velocity reduction at longer weirs and under a wider range of flows than can be tested under flume conditions. How the hydraulic characteristics of submerged CBCs differ from those described here with those that occur in the field when installed on a steep sloping weir under supercritical flow should be further investigated.

1. Introduction

River connectivity facilitates natural fluvial processes by enabling the longitudinal, lateral and vertical movements of matter and organisms within a river corridor or catchment (Wohl, 2017). Rivers have been disconnected, however, by a variety of instream barriers that span the channel width (e.g. weirs, sluice gates and road crossings) and that in some regions form a dense network as a result of a long history of river engineering (e.g. Belletti et al., 2020 for Europe). The fragmentation of rivers due to instream barriers is associated with habitat modification and degradation. For obsolete, unsafe or uneconomical structures (Foley et al., 2017), their removal may provide cost-effective means of mitigating negative ecological impacts and restoring ecological function (Birnie-Gauvin et al., 2018). For those structures that provide important societal benefits, such as power generation, water supply, flood protection and flow monitoring, alternative methods other than removal

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are needed to enhance sustainability.

Low-head gauging weirs are commonly installed as part of flow monitoring networks in many parts of the world. In the UK, common designs include Crump and Flat-V weirs, both of which have a triangular longitudinal profile and standard 1:5 sloped downstream face (Armstrong et al., 2010), creating shallow high velocity flow conditions (Chow, 2009) that are challenging for upstream moving fish (e.g. Montali-Ashworth et al., 2020 for roach *Rutilus rutilus*; Vowles et al., 2017 for European eel *Anguilla anguilla*; Russon et al., 2011 for river lamprey *Lampetra fluviatilis*; Lucas and Bubb, 2005 for European grayling *Thymallus thymallus*; Lucas and Frear, 1997 for barbel *Barbus barbus*). Fish passes have been designed for retrofit on the downstream face to mitigate impeded upstream movement, such as the Low-Cost Baffle (LBC) fish pass (Servais, 2006) and more recently the Cylindrical Bristle Cluster (CBC) fish pass (Montali-Ashworth et al., 2020). Effective fish passes should enable the passage of multiple native species while not compromising the ability of the weir to gauge flow.

The CBC fish pass is a promising design specifically developed to aid upstream fish movement at gauging and other sloped weirs. CBCs consists of cylindrical clusters of 3 mm diameter bristles positioned at a density of ca. 0.1 (defined as $[N_c*\mathrm{d}^2]/D^2$, where N_c is the number of bristles within the cluster, d is the bristle diameter and D is the cluster diameter). A cluster of bristles is preferred to a solid cylinder as the flow-induced vibration of each bristle element more effectively dissipates hydraulic energy (Kucukali and Hassinger, 2018) creating longer regions of low velocity flow in their wake (Nicolle, 2009). A staggered array of CBCs is fixed onto the downstream weir face, reducing water velocity and increasing depth, while also providing multiple unimpeded routes for fish to ascend (Montali-Ashworth et al., 2020). The lower flow impedance created by an array of CBCs in comparison to the more traditional baffled designs means they can be placed relatively close to the crest of gauging weirs without compromising hydrometric properties of the structure. For example, LCBs are typically placed >0.7 m from the weir crest to prevent gauging accuracy being compromised (Lothian et al., 2019). In a laboratory study, CBC arrays placed 0.4 m from the crest of a model Crump weir did not impact gauging over a range of flows (Montali-Ashworth et al., 2020).

CBC arrays can create hydraulic conditions favourable for fish passage. Laboratory experiments using roach (ca. 0.16 m in length) indicate that passage efficiency of a model Crump weir increases from 0% when unmodified to ca. 30% when retrofitted with CBCs (of 0.03 m diameter and with a minimum diagonal spacing of 0.06, 0.10 or 0.15 m) (Montali-Ashworth et al., 2020). In a subsequent field study on the River Adur (West Sussex, UK), passage efficiency of chub (*Squalius cephalusi*) increased from 0% to 52% at a Crump weir (1.2 m wide and 7 m long) when a CBC array (of 0.05 m diameter and with minimal diagonal spacing of 0.17 m) was installed, although several other species were not observed to pass, possibly because they were unmotivated to do so (Montali-Ashworth et al., 2020). Further laboratory experiments tested a greater range of cluster diameters (0.03, 0.05 and 0.07 m) and spacings (0.10 and 0.15 m) and identified that higher passage efficiencies (> 80%) of roach (ca. 0.15 m in length) were associated with a lateral cluster spacing to diameter ratio of <5 (Montali-Ashworth et al., 2021). Under these configurations, larger patches of low water velocity are created in the wake of clusters and extend to the cluster immediately downstream. This prevents an increase in velocity prior to the flow reaching the next downstream cluster, maximising the area of low velocity available for fish to utilise (Montali-Ashworth et al., 2021). Fish were frequently observed exploiting these regions by "zigzagging" between low velocity zones as they ascended the weir. This suggests that increasing the cluster diameter and spacing them farther apart will help ease passage for multiple fish species and sizes so long as a lateral (centre to centre) spacing (S_c) to diameter (D) ratio of <5 is maintained and there is adequate room for fish to manoeuvre.

To date, CBC arrays have been designed and tested with the view to facilitate upstream passage of potamodromous fish in the UK, which as adults tend to be smaller than diadromous (e.g. salmonid) species. For example, the average body length of roach (a common potamodromous cyprinid in Europe) and size at maturity is approx. 0.25 m and 0.14 m, respectively (Muus and Dahlström, 1968; Froese and Pauly, 2023), and potamodromous adult brown trout are considerably smaller (e.g. 0.15–0.32 m) than those with an anadromous lifecycle (e.g. 0.43–0.77 m) (see Lothian et al., 2019). CBC configurations tested to date would hamper the movements of larger migratory fish. There is a need to optimise the design to accommodate a wider size range of target fish, but increasing the cluster spacing without changing the diameter risks providing insufficient availability of low velocity areas that the small-bodied fish require to progress upstream. As such, there is a need to test larger diameter CBCs that are spaced farther apart than in previous studies to determine whether adequate low water velocity zones will be created for smaller fish while ensuring sufficient space for larger individuals to manoeuvre.

Two experiments were conducted in which an array of 0.13 m diameter CBCs (hereafter referred to as 'large diameter') with a lateral (centre to centre) spacing of 0.60 m was tested in an open-channel flume. Experiment 1 assessed the hydraulic conditions created at a model Crump weir when unmodified and retrofitted with the CBC array under a low (0.08 $\mathrm{m}^3\ \mathrm{s}^{-1}$) and high (0.23 $\mathrm{m}^3\ \mathrm{s}^{-1}$) discharge. The experiment: (1) quantified and compared water depth and velocity on the downstream weir face when unmodified and retrofitted with the CBC array; and (2) evaluated whether water velocities created on the downstream weir face would impede upstream passage of two small common European species: roach and brown trout (0.16 m long), based on available burst swimming performance data (i.e. speeds that can be maintained for <20 s; Beamish, 1978). As fish may swim over, rather than through, the CBC array under high flows, as has been observed for baffled designs (Dodd et al., 2018 for the Low-Cost Baffle fish pass), Experiment 2 investigated the vertical velocity profile within and above the CBC array. This provided the first opportunity to quantify the patterns of turbulence (reported here as shear stress) created by the CBC array, which are described and interpreted within the context of fish passage performance.

2. Materials and methods

2.1. Experiment 1: Hydraulic conditions created at a model Crump weir

A model Crump weir with the hydrometric standard design of a 1:5 downstream and 1:2 upstream slope (Fig. 1) spanned the width of an indoor open-channel flume (21.4 m long, 1.37 m wide and 0.6 m deep) at the International Centre for Ecohydraulics Research (ICER), University of Southampton, UK. To create uniform flow conditions, a polycarbonate flow straightening screen (0.10 m thick) was installed five metres upstream of the weir crest that was itself located midway along the flume length (Fig. 1). An upward-facing Acoustic Doppler Current Profiler (ADCP) (Sontek IQ, San Diego, CA, USA) placed four metres upstream of the weir crest and on the bed of the flume measured discharge every 10 s. A low (mean ± SD: 0.082 ± 0.006 $\mathrm{m}^3\ \mathrm{s}^{-1}$; discharge per unit width: 0.060 $\mathrm{m}^2\ \mathrm{s}^{-1}$; depth at weir crest: 0.08 m) and high flow rate (mean ± SD: 0.232 ± 0.006 $\mathrm{m}^3\ \mathrm{s}^{-1}$; discharge per unit width: 0.169 $\mathrm{m}^2\ \mathrm{s}^{-1}$; depth at weir crest: 0.15 m) was tested between 12 and 20 February 2020 when the weir was both unmodified (hereafter control) and retrofitted with an array of CBCs on the downstream face (hereafter treatment).

CBCs (0.13 m diameter) consisted of polybutylene terephthalate bristles (0.003 m diameter, $n = 210$) protruding upright (slightly off vertical) 0.10 m from a plywood disc (0.135 m diameter, 0.006 m thick; Fig. 1b). The clusters were attached to the weir in a staggered configuration with a lateral (S_c) and diagonal (S_d) centre to centre spacing of 0.60 m and 0.42 m, respectively (Fig. 1c). This resulted in an S_c / D ratio of 4.6. The minimum lateral (0.47 m) and diagonal (0.29 m) spacing between clusters was deemed sufficient for large migratory salmonids to

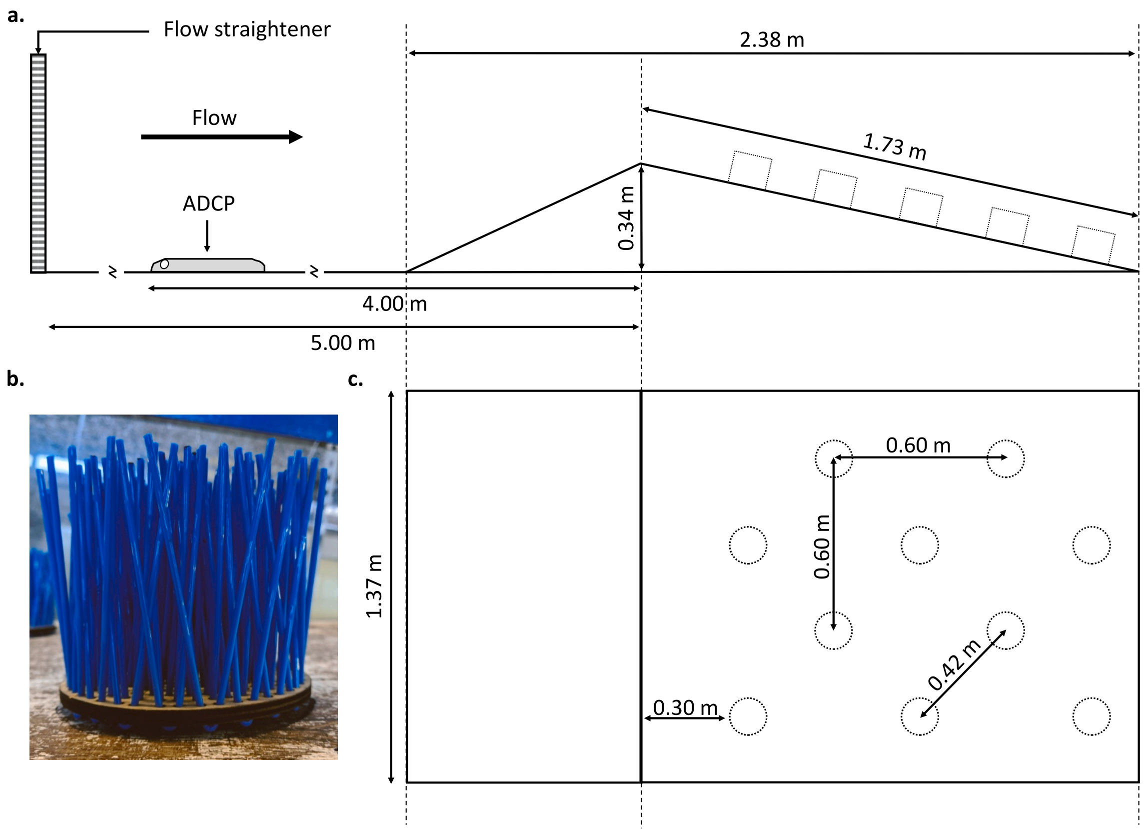

Fig. 1. a. Side view of a model Crump weir installed in an open-channel flume, 4 m and 5 m downstream of an Acoustic Doppler Current Profiler (ADCP) and flow straightening screen, respectively, b. Cylindrical Bristle Clusters (CBC) comprising 210 upright bristles mounted onto a 0.006 m thick plywood disc and c. Plan view of the up- and down-stream weir face. The dotted rectangles and circles on the downstream weir face in a. and c. respectively, show the position of the CBCs when they were installed.

manoeuvre because it approximated the minimum recommended gap (0.30 m) at vertical slot fishways in the UK (Armstrong et al., 2010). The most upstream row of CBCs was placed 0.30 m from the weir crest (Fig. 1c).

Water velocity was measured using an electromagnetic flow meter (Valeport Model 801, Totnes, UK) averaged over 20 s within a region that spanned from 1.00 m upstream to 2.75 m downstream of the weir crest. During the control, measurements were taken at 0.25 m longitudinal intervals and at seven equidistant points across the width of the channel at both the substrate (approx. 0.02 m from weir face / base of the flume) and mid-column (60% depth). In instances where it was not possible to record mid-column velocity due to insufficient depth on the downstream weir face, the substrate velocity was used in analysis. During the treatment, additional velocity measurements were taken on the downstream weir face to ensure the hydraulic heterogeneity was adequately captured (locations indicated by crosses in Fig. 3). Water depth was measured using a point gauge at the same (x, y) locations as for velocity. In regions near the CBCs where turbulence caused the surface water level to fluctuate, depth was estimated to be that which was in contact with the point gauge for approximately 50% of a 30 s period. In highly turbulent water (e.g. hydraulic jump region), a minimum and maximum depth was recorded at the central position along the transect as the lowest and highest value where water contacted the point gauge during a 30 s period. Depth for the predefined measurement locations was assigned a random value between the minimum and maximum for that transect. Spatial variability in velocity was linearly interpolated within the hydraulically mapped region using the ‘akima’ package in RStudio (v3.6.0). Differences in water velocity and depth between control and treatment conditions were tested using a Wilcoxon rank-sum test in RStudio (v3.6.0). Flow regime was categorised using the bulk Froude number with values lower and >1.0 indicating subcritical and supercritical flow, respectively. During the control, the bulk Froude number was calculated using temporally and spatially averaged velocity and depth at the weir crest and between the crest and hydraulic jump as: $Fr = u/\sqrt{gD}$ where u is the longitudinal component of water velocity, g is acceleration due to gravity and D is water depth. During the treatment, Froude number was calculated at the crest, between the crest and CBC array and within the CBC array using the same approach as above.

To compare water velocity on the downstream weir face with fish burst swimming performance, mid-column water velocities were resampled from interpolated data at 14 equidistant points along transects that spanned the width of the weir at 0.15 m longitudinal intervals. Median, minimum and maximum values for each transect were compared against the median and upper 90% Confidence Interval (CI) burst swimming performance of roach and brown trout estimated using the SWIMIT Model v3.3 (Clough et al., 2004). Fish standard length (0.16 m) and water temperature (15.1 °C) values used to estimate swimming performance were based on an experimental study conducted by Montali-Ashworth et al. (2020).

2.2. *Experiment 2: Vertical velocity profile within a CBC array*

The CBC array used in Experiment 1 was attached to a plywood board (2.00 m long, 0.01 m thick) and fixed to the base of the flume at maximum tilt (1:200 [0.5%] slope) (Fig. 2). This was required to create sufficient water depth to investigate the vertical velocity profile created by a submerged array of CBCs, which was not possible to achieve on the downstream weir face in Experiment 1. At the upstream extent of the plywood board, located at the same longitudinal position as the weir

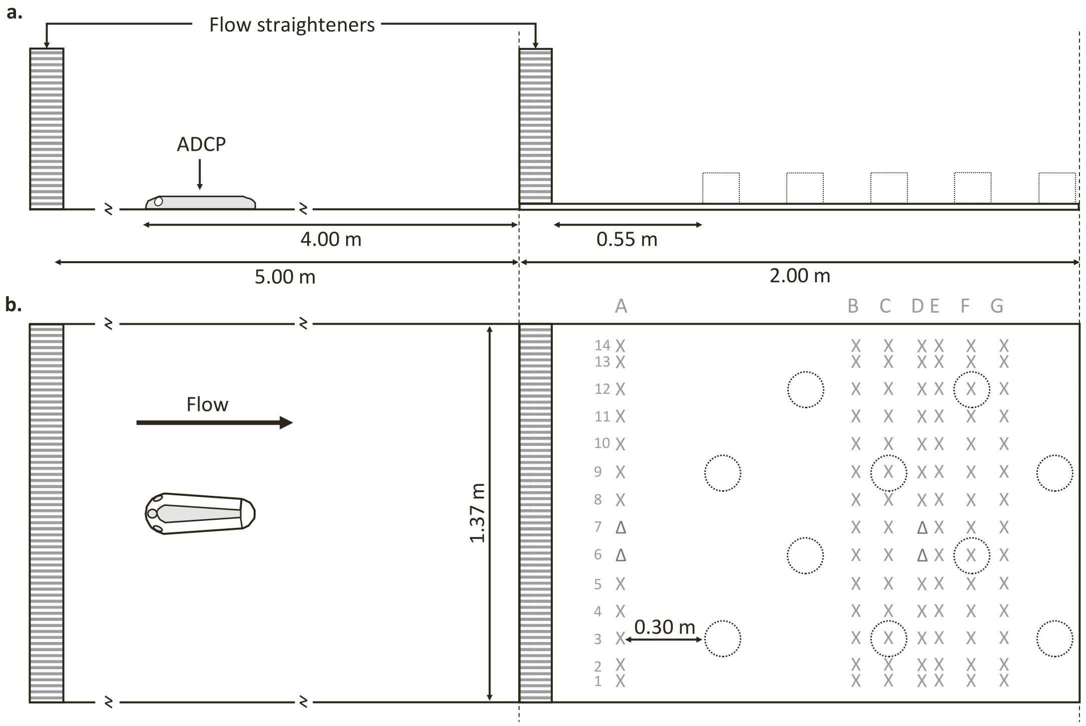

Fig. 2. a. Side view of an open-channel flume with CBCs (dotted rectangles) mounted onto a plywood board and installed flat onto the flume base and b. Plan view showing the staggered array of CBCs (dotted circles) with crosses denoting Acoustic Doppler Velocimeter measurement locations (letters A – G and numbers 1–14 allow identification of sampling points). Triangles indicate the locations of the ADV measurements plotted in Fig. 8 (vertical velocity profile). An Acoustic Doppler Current Profiler (ADCP), located 4.55 m upstream of the first row of CBCs recorded flow rate.

crest in Experiment 1, an additional polycarbonate flow straightening screen (0.10 m thick) was installed 0.55 m upstream of the first row of CBCs (Fig. 2). The vertical velocity profile of the CBC array was tested under a single discharge (mean ± SD: 0.240 ± 0.011 m^3 s^{-1}; discharge per unit width: 0.175 m^2 s^{-1}), measured every 10 s using an ADCP located four metres upstream of the plywood board (Fig. 2), between 11 and 13 March 2020.

An Acoustic Doppler Velocimeter (ADV; Vectrino+, Nortek-AS, Norway) was used to instantaneously measure water velocity in the longitudinal (u), lateral (v) and vertical (w) direction. Measurements were taken at seven longitudinal transects (A – G in Fig. 2b). The first was located 0.30 m upstream of the CBC array and the remaining six within it (Fig. 2b). At each transect, up to 14 measurements were taken across the width of the channel at 0.10 m intervals, with the exception of those next to the flume wall that, due to constraints as to where the ADV could be positioned, were 0.06 m from the nearest lateral measurement point (Fig. 2b). This measurement grid was sampled at five water depths: ‘substrate’ (sampling 0.010 m from flume base), ‘mid-bristle’ (sampling 0.056 m from flume base), ‘above bristle’ (sampling 0.132 m from flume base and 0.020 m above bristle height), ‘mid-water column’ (sampling at 0.206 m from flume bed and halfway between the top of bristles and water surface), and ‘surface’ (sampling at 0.230 m from the flume bed). ADV measurement closer to the water surface was not possible as air entrainment around the probe can compromise data accuracy. Some points were omitted because they were within an area occupied by a CBC. Each ADV measurement sampled a volume of 0.09 cm^3 at a frequency of 50 Hz over 60 s. Mean (± SD) water depth, measured using a metre rule at each ADV measurement location was 0.31 ± 0.004 m.

Raw ADV data were filtered using a velocity cross-correlation method (Cea et al., 2007) and the time averaged (overbar) velocity component calculated. Froude number was calculated using temporally and spatially averaged longitudinal velocity and depth upstream of and within the CBC array. The mean velocity vector (modulus) was calculated as: $V = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}$ where $\overline{u}$, $\overline{v}$ and $\overline{w}$ are the mean longitudinal, lateral and vertical velocity components (m s^{-1}), respectively. Turbulence was quantified as horizontal and vertical shear stress, which provides a measure of the turbulent flux of fluid momentum exchange (Enders et al., 2017) and is used here to indicate the dominant orientation of turbulence within a CBC array. Horizontal and vertical shear stress was calculated as $\rho\overline{u'v'}$ and $\rho\overline{u'w'}$, respectively. ρ represents the density of water and u, v and w the longitudinal, lateral and vertical velocity components, respectively. The overbar and prime represent time averaging and the fluctuating velocity component, respectively (Enders et al., 2017). Spatial variability in the mean velocity vector, horizontal shear stress and vertical shear stress was linearly interpolated within the hydraulically mapped region of the CBC array using the ‘akima’ package in RStudio (v3.6.0).

3. Results

3.1. *Experiment 1: Hydraulic conditions created at a model Crump weir*

During the control and in line with the normal functioning of a gauging weir, bulk flow at and between the crest and the hydraulic jump was subcritical and supercritical, respectively (Table 1). Water accelerated as it flowed down the weir face until meeting the hydraulic jump (Fig. 3a, b, e and f), attaining a higher average and maximum water velocity during high compared to low discharge (Table 1). Water depth (± SD) at the weir crest was 0.08 (± 0.001) m and 0.15 (± 0.000) m and was lower on the downstream weir face during low compared to high discharge (Table 1).

The longitudinal flow profile on the downstream weir face was influenced by the installation of the CBC array (Fig. 4). Bulk flow at the crest was subcritical under both discharge regimes (Table 1) and transitioned to supercritical between the crest and upstream of the CBC array and remained so within the CBC array, upstream of the hydraulic jump (Table 1). Zones of low water velocity were created on the downstream weir face in the wake of the bristle clusters as flow was impeded (Fig. 3c,

Table 1
Hydraulic conditions created on the downstream face of a model Crump weir (from crest to hydraulic jump) when installed in a flume and either unmodified (control) or fitted with an array of Cylindrical Bristle Clusters (treatment).

Weir treatment	Discharge ($m^3 s^{-1}$)	Streamwise velocity [mean ± SD (range), $m s^{-1}$]	Depth [mean ± SD (range), m]	*Fr* at crest	*Fr* on downstream weir face
Unmodified	Low (0.08)	1.74 ± 0.52 (0.73–2.32)	0.05 ± 0.02 (0.03–0.08)	0.87	3.01
Unmodified	High (0.23)	1.98 ± 0.54 (0.96–2.66)	0.09 ± 0.03 (0.05–0.15)	0.86	2.46
Fitted with CBCs	Low (0.08)	1.19 ± 0.56 (−0.13–2.03)	0.06 ± 0.03 (0.01–0.11)	0.84	1.67; 2.17*
Fitted with CBCs	High (0.23)	1.60 ± 0.53 (0.04–2.41)	0.11 ± 0.03 (0.04–0.17)	0.87	1.23; 1.54*

* The first value reports the *Fr* number between the weir crest and upstream of the CBC array, the second for the region within the CBC array (upstream of the hydraulic jump).

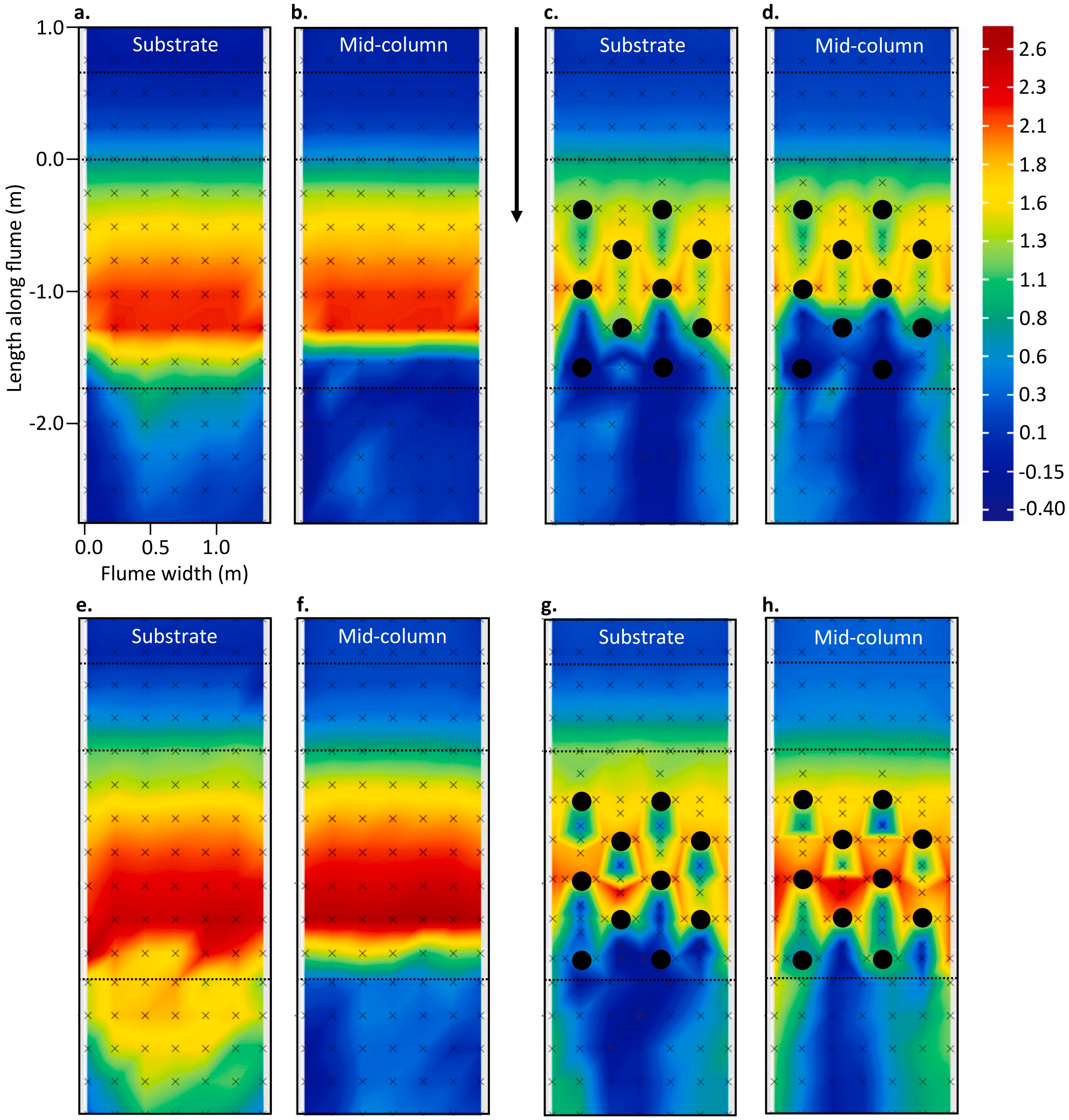

Fig. 3. Water velocity ($m s^{-1}$) in the downstream direction (u) when a Crump weir, installed in a flume, was unmodified (low discharge: a, b; high discharge: e, f) and retrofitted with CBCs (low discharge: c, d; high discharge: g, h). Panel a, c, e and g show substrate velocities while b, d, f and h show mid-column velocities. Crosses denote the locations of the velocity measurements, the horizontal dashed lines depict the upstream extent, crest and downstream extent of the weir and the arrow indicates direction of flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

d, g and h) resulting in a reduction in median velocity during low (30.1%; Wilcoxon rank-sum: $z = -6.43, r = -0.43, p < 0.001$) and high discharge (22.3%; Wilcoxon rank-sum: $z = -6.51, r = -0.43, p < 0.001$) (Fig. 5a). Maximum water velocity was reduced under low and high discharge (Table 1) and the velocity range increased when CBCs were installed (Table 1). The low velocity wakes extended to the next

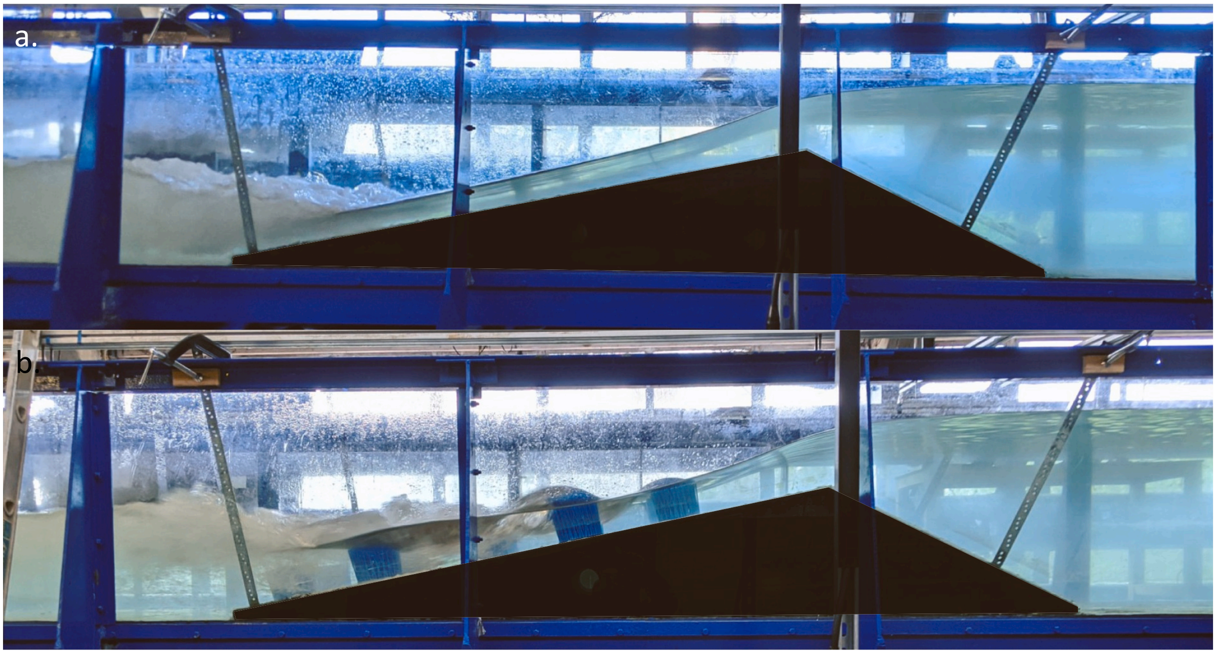

Fig. 4. Example of the longitudinal flow profile of a model Crump weir installed in an open-channel flume when unmodified (a.) and retrofitted with a CBC fish pass (b.) under high flow (0.23 $m^3 s^{-1}$).

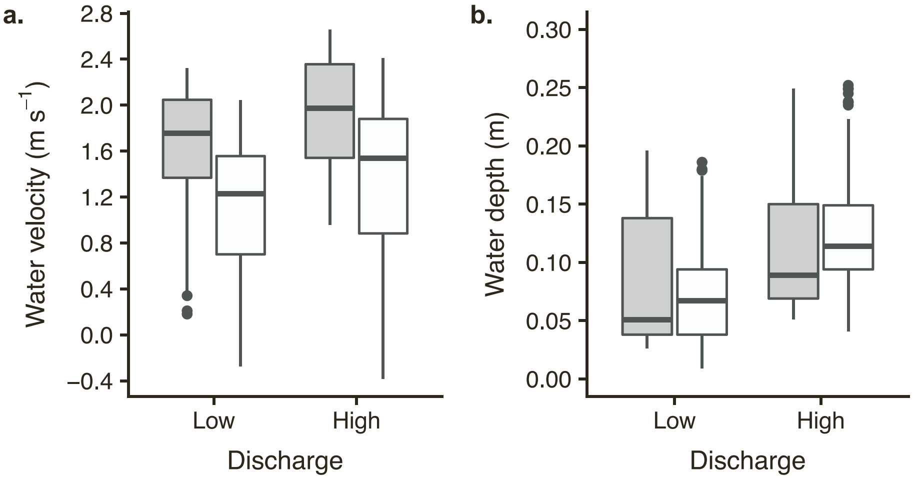

Fig. 5. a. Water velocity and b. depth on the downstream face of a model Crump weir installed in an open-channel flume under a low (0.08 $m^3 s^{-1}$) and high (0.23 $m^3 s^{-1}$) discharge when unmodified (grey) and retrofitted with an array of Cylindrical Bristle Clusters (clear). Horizontal lines represent the median, boxes define the 25th and 75th percentile, whiskers represent maximum and minimum values and outliers (> 1.5 X the interquartile range) are shown as dots.

downstream cluster under low but not high discharge (Fig. 3c, d, g and h). Water depth at the crest was not influenced by the CBCs (mean ± SD under low: 0.08 ± 0.000 m and high discharge: 0.15 ± 0.001 m) while on the downstream weir face it remained unaffected and increased during low (Wilcoxon rank-sum: $z = -0.07$, $r = -0.01$, $p = 0.948$) and high discharge (Wilcoxon rank-sum: $z = -2.61$, $r = -0.24$, $p < 0.01$), respectively (Fig. 5b). Minimum depth was lower during low compared to high discharge, and lower compared to the control (Table 1).

During the control, the velocity profiles along transects that spanned the width of the downstream face were homogenous and mostly higher than the modelled median burst swimming speed of roach and brown trout (0.16 m in length and swimming at 15.1 °C; Fig. 6). These upstream moving fish would encounter water velocities that exceed their estimated median burst swimming speed (1.39 m s^{-1} for roach; 1.35 m s^{-1} for trout) after ascending approximately 0.33 m and 0.14 m of the weir under low and high discharge, respectively. Velocities were not measured to be below the estimated median burst swimming speeds until approximately 0.23 m and 0.19 m from the weir crest. During the treatment, the velocity profiles along the same transects were more heterogeneous (Fig. 6). Under low discharge, the range of water velocities generated by the CBCs was below (or equal to) the estimated median burst swimming speed of roach and trout along the length of the downstream weir face (Fig. 6a, b). Under high discharge, the water velocity range exceeded the median burst swimming capabilities at some locations, but the array reduced water velocity along the length of the downstream weir face to within the 90% CI of burst swimming capability for both species (Fig. 6b).

3.2. Experiment 2: Vertical velocity profile within a CBC array

When the CBC array was installed flat on the base of the flume the flow was subcritical ($Fr = 0.31$ upstream of and within the CBC array).

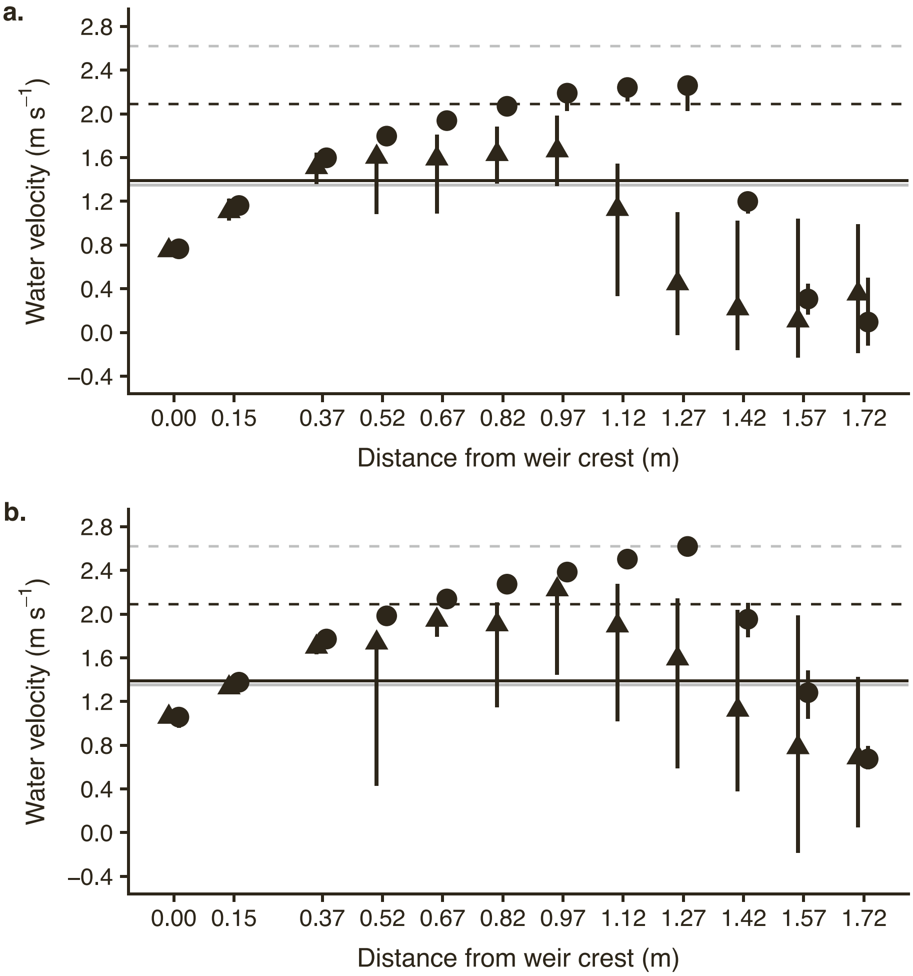

Fig. 6. Median (symbols), minimum and maximum (vertical bars) water velocity along transects that spanned the width of the downstream face of a Crump weir under low (a.) and high (b.) discharge when the weir was unmodified (circles) and retrofitted with CBCs (triangles). The weir crest is at 0.00 m and the downstream face extends to 1.73 m. The solid black and grey lines represent the median burst swimming speed of roach (1.39 m s^{-1}) and trout (1.35 m s^{-1}) estimated using SWIMIT Model v3.3 (Clough et al., 2004) and assuming a body length of 0.16 m and temperature of 15.1 °C. The dashed black and grey lines represent the upper 90% CI of roach (2.09 m s^{-1}) and trout (2.62 m s^{-1}) burst swimming speed.

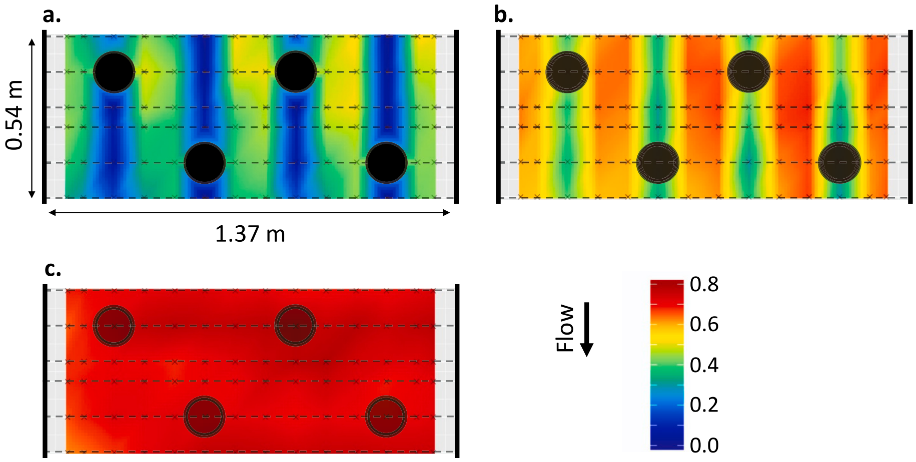

Fig. 7. Velocity (V; m s^{-1}) profile at (a.) substrate, (b.) above bristle and (c.) surface water depths within a CBC array installed flat on the base of an open channel flume. Solid circles indicate locations of CBCs and dashed lines the transects across which Acoustic Doppler Velocimeter measurements were recorded. Note that for brevity the interpolations for mid-bristle and mid-water column depths are not shown due to their similarity to (a.) and (c.), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Mean velocity measured at the substrate, mid-bristle and above-bristle depths was 2.0%, 22.5% and 2.7% lower for the measurement points taken within the array when compared to an upstream control section. In contrast, mean velocity measured at the mid-water column and surface depths within the array (9.4 cm and 11.8 cm above bristle height) were 11.1% and 14.6% higher, when compared to those taken upstream. Low velocity wakes created by CBCs extended to the cluster immediately downstream at depths within and ≤ 2 cm above the bristle height (Fig. 7a, b). At these depths, zones of low and high velocity were created in regions within and between the wakes, respectively (Fig. 7a, b). These zones of relatively low and high velocity were absent at depths >2 cm above the bristle height, where velocities were higher and spatially homogenous (Fig. 7c). The vertical velocity profile upstream of the array followed that expected of an open channel, with lower velocities recorded near the substrate and increasing to the mid-water column (Fig. 8). The vertical velocity profile at locations within the array but between the wakes created by CBCs followed a broadly similar distribution (Fig. 8). Velocities in the wake of a CBC were substantially lower and increased rapidly once above the bristle tips (Fig. 8).

The zones of low and high velocity at water depths within the bristle height created horizontal shear stress, which was absent at the mid-column and surface depths (Fig. 9). The large vertical velocity gradient just above the bristle tips created areas of vertical shear stress which were absent at other depths (Fig. 10).

4. Discussion

To optimise the design of a novel low-cost fish passage solution for small sloping weirs, this study quantified the hydraulic conditions associated with an array of Cylindrical Bristle Clusters (CBCs) of larger diameter (0.13 m) and spaced farther apart (0.60 m) than those previously tested (Montali-Ashworth et al., 2020, 2021). We aimed to create sufficient hydraulic heterogeneity to provide zones of low velocity needed to enable small potamodromous species, such as roach (*Rutilus rutilus*) and brown trout (*Salmo trutta*), to pass a weir, while also providing the space required by larger anadromous species, such as adult Atlantic salmon (*Salmo salar*) and sea trout (*S. trutta*), to manoeuvre. In Experiment 1, when installed on the downstream face of a model Crump weir in an open-channel flume, CBCs enhanced hydraulic heterogeneity. The CBC array reduced median velocity under two different discharge regimes (high and low), creating conditions likely conducive to upstream passage of small (e.g. 0.16 m body length) potamodromous fishes. In Experiment 2, assessment of the vertical velocity profile when a flat CBC array was installed on the base of the flume under subcritical flow suggests that the velocity reduction occurs at depths within (and ≤ 2 cm above) the bristle height. Immediately above the bristles, an area of vertical shear stress is evident. The limitations of this study relate to a restricted range of flows, water depths and size of weir that could be tested under flume conditions and so field-based research should now validate the results of this experimental study and further determine the reductions in velocity on the face of longer weirs and under a greater range of flows than tested here. Any resulting improvements in multi-species fish passage should be quantified.

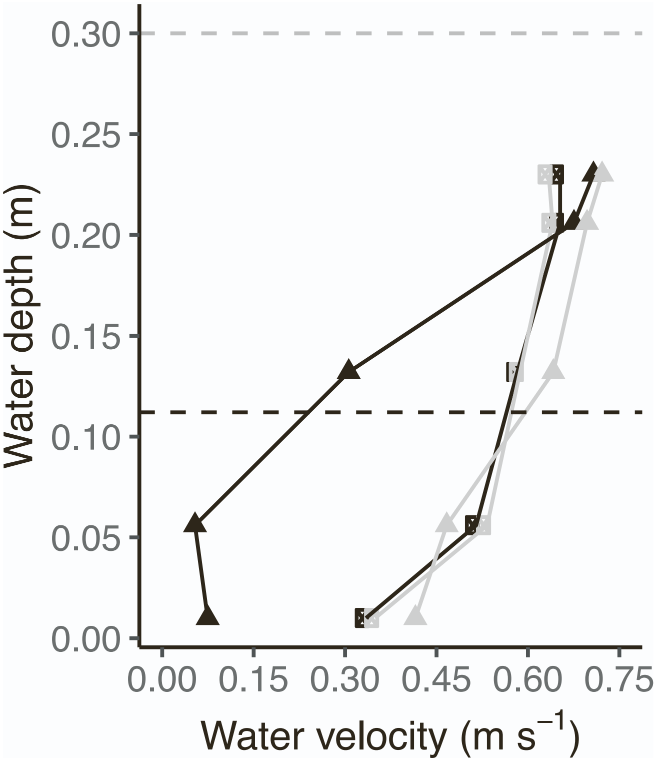

Fig. 8. Vertical velocity (V) profiles upstream (circles) and within an array (triangles) of CBCs installed in an open channel flume. For profiles within the array, the black and grey lines are in and between a CBC wake and correspond to measurement points D6 and D7 in Fig. 2, respectively. For profiles upstream of the array, the black and grey lines correspond to measurement points A6 and A7 in Fig. 2, respectively. The horizontal dashed black and grey lines show the bristle height and water depth, respectively.

In Experiment 1, zones of low water velocity were created on the downstream face of the model weir in the wake of CBCs. Under the low discharge regime, these low velocity zones extended to the cluster immediately downstream as expected for configurations with a bristle cluster spacing to diameter ratio < 5 (see Montali-Ashworth et al., 2021). Under such conditions, upstream fish passage efficiency is enhanced as velocity does not increase prior to reaching the next downstream cluster and thus larger zones of low velocity are created for ascending fish to exploit (Montali-Ashworth et al., 2021). Under the higher discharge, low velocity wakes did not extend from one cluster to the next, with localised zones of high velocity present downstream of some CBCs. This was caused by water plunging over the top of the CBCs and suggests that there may be a specific ratio of water depth to bristle height where the design is compromised, resulting in a reduction in the size and connectivity of low velocity zones for fish to swim through. Roughness elements that aim to improve fish passage at river infrastructure should be designed to maximise interconnected zones of low water velocity (Magaju et al., 2021). For CBCs, this might be achieved by using longer or more flexible bristles to reduce (or eliminate) plunging flow. Although water velocity on the downstream face was reduced, changes in water depth were less obvious. Median depth was unaffected and higher during low and high discharge, respectively. The relatively low flow impedance of CBCs is advantageous when retrofitting gauging weirs as they can be placed closer to the crest without compromising hydrometry (Montali-Ashworth et al., 2020). This is in contrast to baffled designs, such as the Low-Cost Baffle fish pass, which needs to be placed considerably farther from the crest (e.g. 0.74 m) than the CBCs, providing opportunity for velocity to accelerate to speeds that may limit fish passage (Lothian et al., 2019). The limited impact of CBCs on water depth under low discharge, while beneficial from a flow gauging perspective, may be problematic for fish passage if there is inadequate space for fish to swim or the additional drag encountered near the water / air interface lowers swimming performance (Clough and Turnpenny, 2001). In such instances, the weir may present a depth, rather than velocity barrier. As fish passage research has tended to focus on the relationship between swimming capability and water velocity, a better understanding of how flow depth influences passage over sloped weirs would be valuable.

When the weir was unmodified in Experiment 1, water velocity on the downstream weir face quickly (after approx. 0.2 m) accelerated to above the modelled median burst swimming speed of roach and brown trout (0.16 m in length and swimming at 15.1 °C). This suggests a high

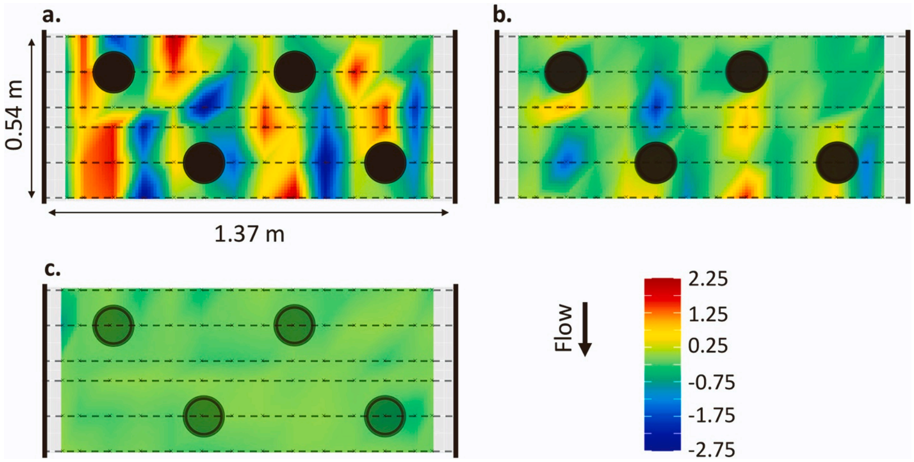

Fig. 9. Horizonal shear stress (N m^{-2}) at (a.) substrate, (b.) above bristle and (c.) surface water depths within a CBC array installed flat on the base of an open channel flume. Solid circles indicate locations of CBCs and dashed lines the transects across which Acoustic Doppler Velocimeter measurements were recorded. Note that for brevity the interpolations for mid-bristle and mid-water column depths are not shown due to their similarity to (a.) and (c.), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

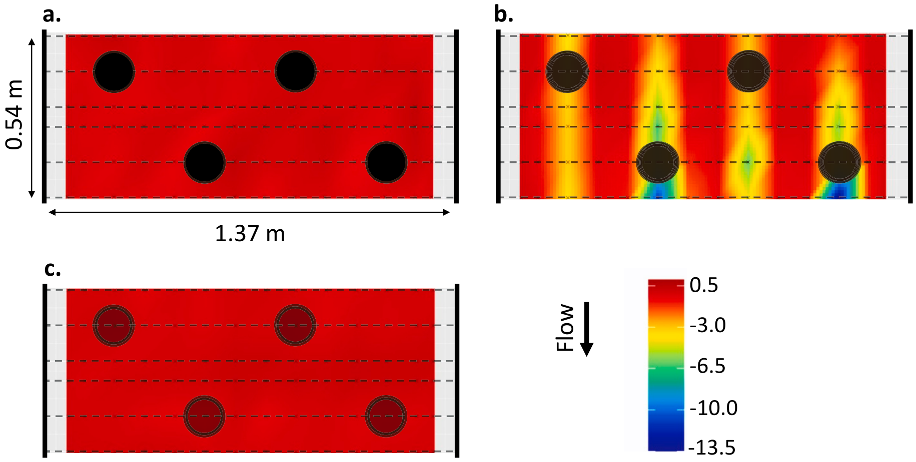

Fig. 10. Vertical shear stress (N m^{-2}) at (a.) substrate, (b.) above bristle and (c.) surface water depths within a CBC array installed flat on the base of an open channel flume. Solid circles indicate locations of CBCs and dashed lines the transects across which Acoustic Doppler Velocimeter measurements were recorded. Note that for brevity the interpolations for mid-bristle and mid-water column depths are not shown due to their similarity to (a.) and (c.), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

probability of forming a complete barrier to upstream movement as velocity over a large area of the downstream weir face exceeded swimming performance (approx. 68% and 81% for low and high discharge, respectively). This rapid acceleration in water velocity emphasises the importance of minimising the distance between roughness elements and the weir crest. The greater heterogeneity and reduction in median water velocity on the downstream weir face due to the installation of CBCs is likely to facilitate upstream passage of small potamodromous fishes as water velocities dropped to below the estimated (90% CI) burst swimming speeds of both species (Clough et al., 2004). As a result, the modified weir may enhance upstream movements, as indicated for roach that, under flume conditions, benefitted from an increase in passage efficiency from 0 to 35% at a Crump weir on which a CBC array was installed and where maximum water velocities were like those observed in this study (2.2 m s^{-1}) (Montali-Ashworth et al., 2020).

In Experiment 2 we quantified the vertical velocity profile and shear stress associated with the CBCs. This was achieved by installing the CBCs flat on the base of the flume to create sufficient depth so that the CBCs were fully submerged. In so doing, the bulk flow was subcritical (unlike on the face of the weir in Experiment 1) and thus deviating from conditions that would typically occur on many sloped weirs in field settings, and clearly those involved in hydrometry. Nevertheless, this set-up enabled initial insight to be gained in relation to the hydraulic heterogeneity and patterns of turbulence, in terms of shear stress, that might be expected in a more realistic setting. For fish navigating through an array of CBCs the hydraulic benefits occur at depths within the height of the bristles. Within this region, wakes of low velocity extended from one CBC downstream to the next and elevated levels of horizontal shear stress were apparent, indicating a lateral fluid momentum exchange between the low velocity wakes and higher velocities in-between. A similar horizontal flow pattern has been observed in other brush-type (Kucukali, 2019) and staggered roughness element (Magaju et al., 2021) fish passes and can facilitate upstream passage of cyprinids and salmonids (Kucukali et al., 2019). The rapid velocity acceleration above the CBCs created a layer of vertical shear stress; a similar condition to that observed with dense vegetated flow in which an inflection point exists above the canopy (Chen et al., 2011) and vortices do not penetrate to the bed or surface (Nepf, 2012). Due to the high vertical shear stress accompanied by more rapid water velocities above the CBC array when compared to open channel conditions, fish swimming is expected to be more challenging. In instances where high levels of submergence might be expected, the use of longer and/or more flexible bristle elements might be an effective way of reducing vorticity in the vertical shear layer above CBCs (Chen et al., 2011), thus maximising potential hydraulic benefit for fish passage. How the hydraulic characteristics of submerged CBCs differ when the slope is steep and the flow supercritical (as is the case for most gauging weirs), requires further investigation and preferentially field validation.

The CBC fish pass described is low cost, easy to retrofit and can be optimised for site specific conditions, potentially providing an important technology in a "toolbox" for adaptive river management and restoration of habitat connectivity for fish. The benefit of CBCs will likely be greatest when deployed at low-head structures, by far the most common in many regions (e.g. Europe; Belletti et al., 2020), that are unlikely to be removed (e.g. gauging weirs) and when successful passage for only a proportion of the population is required to achieve conservation goals (e.g. facilitating the movement of potamodromous species to maintain gene flow). CBCs could also be a valuable mitigation tool when passage of multiple small-bodied fish that have often been ignored during fish passage development is required, such as those found in parts of the Southern Hemisphere (Wilkes et al., 2017), including Chile (Laborde et al., 2020) and New Zealand (Franklin and Gee, 2019). In this scenario, design optimisation might involve reducing the space between bristle clusters (the opposite of what was tested in this study) to selectively facilitate passage for native small-bodied species while limiting the dispersal of larger-bodied non-native ones. When the primary conservation goal is to fully reconnect habitat for fishes, the removal of river infrastructure should be utilised as the primary restoration technique whenever possible.

CRediT authorship contribution statement

Andrew S. Vowles: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Daniella Montali-Ashworth:** Methodology, Formal analysis, Writing – review & editing. **Perikles Karageorgopoulos:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Paul S. Kemp:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Andrew Vowles reports financial support was provided by Environment Agency.

Data availability

Data published in this article are available from the University of Southampton online repository (the DOI for the data is included in the manuscript)

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