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RESEARCH ARTICLE

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Experiments on the hydraulics and swimming responses of juvenile Chinook Salmon encountering a floating guidance structure

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Abstract

Floating guidance structures are intended to promote safe passage for juvenile salmon migrating downstream through reservoirs. However, the ability of an engineered structure to guide fish to safe passage has been primarily tested through large-scale implementation in reservoirs or in laboratory studies and computer simulations without live fish. Research is needed that integrates fluid mechanics with fish behaviour to study how hydraulic conditions around a guidance structure trigger swimming behaviours. In this study, an outdoor experimental channel was used to identify: (a) the hydraulic signature of a floating guidance structure and (b) changes in fish swim behaviour in relation to channel hydraulics. The flow field surrounding a guidance structure at two deployment angles was characterized using acoustic Doppler velocimeters. Swimming behaviours of juvenile Chinook salmon were recorded using underwater videogrammetry. A statistical method for behaviour change detection identified the most likely locations of swimming behaviour changes in fish as they first encountered the guidance structure. Finally, the locations of behaviour changes were compared to the hydraulics surrounding each guidance structure. Taken together, results indicated the fish did respond to the guide wall with behaviour changes, but did not distinguish between the two guide wall angles. While the two guide wall angles did produce statistically different distributions of hydraulic variables, the differences were small, potentially too small for the fish to produce a behavioural response. To inform the design of guidance structures, further work may clarify if swim responses vary with more aggressive wall angles and/or higher approach velocities, or if any contraction of flow and/or visual cue will produce similar behaviour responses.

KEYWORDS

environmental fluid mechanics, fish behaviour, fish passage, floating guidance structure, guide wall, hydraulics, reservoirs

1 | INTRODUCTION

A smolt (seaward migrating juvenile salmonid) often has several routes for passing a dam, each with its own limitations. Of all passage routes at hydroelectric projects, turbines produce the highest rates of injury and mortality, which can be caused by high shear stress, turbulence, cavitation, decompression, blade strike, and mechanical wounding (Brown et al., 2012; Čada, 2001; Pracheil, DeRolph, Schramm, &

Bevelhimer, 2016). Furthermore, the disorientation of fish exiting turbine draft tubes increases vulnerability to predation, both avian and aquatic (Rieman, Beamesderfer, Vigg, & Poe, 1991). At run-of-river (roughly 30 m head) dams on the mainstem Snake and Columbia rivers, the survival of downstream migrant fish, such as juvenile salmonids, is generally highest at spillways and surface flow outlets (e.g., ice and trash sluiceways [Muir, Smith, Williams, & Sandford, 2001; Ploskey et al., 2013]). Although spills during springtime migrations often coincide with high flows that exceed water needed for hydropower generation, involuntary summer and fall spills are economically expensive. For example, spill operations at federal dams in the Columbia River basin resulted in large energy (250 MW) and economic ($38.6 M) losses in 2018 alone (BPA, 2018).

Methods to safely pass downstream migrants are important subjects of research. In addition to fish-friendly turbines (Hogan, Čada, & Amaral, 2014), there are two other general approaches for downstream fish passage at hydroelectric projects: out-of-river passage via collection and transportation, and in-river passage via non-turbine routes. For migrants to be transported out-of-river, floating surface collectors first capture emigrants from the forebay of a dam (Coutant, Mann, & Sale, 2006). Guidance structures, nets, or reservoir hydraulics alone can help juvenile fish to the entrances of floating surface collectors. In addition, turbine intake screen systems can be used to collect emigrants for out-of-river transportation. Captured migrants are transferred to a barge or a truck for out-of-river passage. In-river passage may occur via juvenile bypass systems involving upward-angled mesh, screens, or louvers that bypass fish via the pipes or ice and trash sluiceways that empty into tailwaters (Schilt, 2007). However, fish guidance efficiencies of screens for yearling Chinook salmon (*Oncorhynchus tshawytscha*) often do not meet fish guidance efficiency goals (Johnson, Beeman, Duran, & Puls, 2007). Alternatively, surface passage can be constructed or retrofitted via small sluiceways that draw fish near the water surface and pass them into the tailrace via a long, mildly sloping open channel. Surface passage is cost-effective and produces high survival rates for emigrating fish (Ploskey et al., 2013). Structures that effectively guide emigrating juvenile fish to safe passage routes without the need for spilling large volumes of water, such as surface flow outlets, are necessary to improve collection efficiencies for both out-of-river transportation and in-river passage systems.

Floating guidance structures (also called guide walls) are long, partially submerged panels that alter channel hydraulics to promote safe passage through man-made barriers (Schilt, 2007). Their application ranges from improving entrance discovery of floating surface collectors and surface outlets to exclusion from diversion channels (Adams, Johnson, Rondorf, Anglea, & Wik, 2001; Romine et al., 2016; Scott, 2014). However, their ability to successfully divert individuals towards specific passage route or locations, and ultimately improve passage survival at dams, is highly dependent on site-specific characteristics of design and location (Faber et al., 2010; Johnson & Dauble, 2006).

Previous work has demonstrated that juvenile salmonids modify swimming behaviours in response to turbulent flows, particularly hydraulic gradients (Haro, Odeh, Noreika, & Castro-Santos, 1998). For example, smolts tend to migrate in the thalweg near the water surface (Andrew & Green, 1960; Li et al., 2015). In a laboratory flume setting, Enders, Gessel, Anderson, and Williams (2012) found that juvenile salmon migrants tend to avoid areas of both accelerating and decelerating flows near spatial gradients of 1 m/s/m (also denoted s^{-1}) or greater. The same year, Vowles and Kemp (2012) observed brown trout reacting to spatial velocity gradients at slightly lower thresholds (0.2–0.4 s^{-1}) in a constricted channel. In addition, migrating juvenile salmon may use turbulence to seek regions of relatively high velocity that enhance downstream progress and promote bypass entrance discovery (Coutant, 1998; Darland et al., 2000; Odeh et al., 2002). Furthermore, constrictions have been shown to trigger a halting or pause in movement for juvenile salmon (Kemp, Gessel, & Williams, 2005). The tendency of smolts to react to velocity gradients, particularly at constrictions, has implications for the design of guide walls regarding their orientation and angle to the downstream velocity vector.

Research on fish swimming behaviour has led to both theories and experiments to improve downstream fish passage. Haro et al. (1998) theorized that guidance structures should produce uniformly accelerating, low-turbulence hydraulics while minimizing visual cues to best promote low-flow bypass structures. In addition, normal (perpendicular to the barrier face) and sweeping (parallel to the barrier face) velocity vector components were expected to play key roles in fish guidance (Cuchet, 2014). Barriers at low angles (smaller than 45°) have been shown to increase the sweeping velocity of a barrier relative to high angles, potentially increasing guidance of target species (Scruton, McKinley, Kouwen, Eddy, & Booth, 2003). Mulligan, Towler, Haro, and Ahlfeld (2018) hypothesized that a guide wall at 15° would produce hydraulic conditions potentially favourable for efficient guidance. However, the ability of an engineered structure to guide fish to safe passage has been primarily tested either (a) after large-scale implementation in existing reservoirs or (b) in laboratory studies or computer simulations without live subjects (Kock, Liedtke, Ekstrom, Tomka, & Rondorf, 2012; Mulligan, Towler, Haro, & Ahlfeld, 2017; Scott, 2014). Research directly linking fish and fluid behaviour around guidance structures may reveal relationships can be used to inform the design of guidance structures.

The objectives of the research presented here were to: (a) identify the hydraulic signature upstream of a floating guidance structure placed at two angles to the flow (20 and 30°); and (b) identify responses in fish swim behaviour in relation to hydraulics in an experimental channel. A hydraulic signature is the unique set of fluid dynamics (water speed [m/s], turbulent kinetic energy [TKE, in m^2/s^2], TKE gradient [$m^2/s^2/m$], water acceleration [m/s^2], and/or velocity gradient [m/s/m or s^{-1}]) produced by a guidance structure. We hypothesized that changes in fish swimming behaviour would be related to changes in the hydraulic signature produced by the guidance structure. We also hypothesized that a threshold response to those characteristics may exist, whereby fish response was not triggered until a biologically detectable hydraulic signature was produced by the guide wall. The results are applicable to bioengineering guidance structures to help increase downstream passage survival rates.

2 | METHODS

2.1 | Structure design

An outdoor experimental channel at the Oregon Hatchery Research Center in Alsea, OR, was operated as a closed system using water from nearby Falls Creek and a diesel engine pump to recirculate flow. A screen installed in the upstream end of the experimental section dissipated turbulence from the pump and restricted fish from swimming upstream of the experimental section. The channel (1.22 m deep × 1.22 m wide × 61 m long) was constructed with a 1% slope. A 10 m long section in the downstream end of the 61-m channel was operated for trials. In the interest of identifying the effect of guide wall angle on its hydraulic signature, a constant discharge of approximately 0.13 m^3/s was maintained in the channel for all trials. At a water depth of approximately 61 cm, the water velocity of approximately 0.17 m/s represented those in reservoirs near dam forebays with relatively low velocities (Goodwin et al., 2014; Goodwin, Nestler, Anderson, Weber, & Loucks, 2006). The water within the channel was refreshed daily before each trial, and the temperature of the water was maintained not to exceed 21°C (15.6–20.3°C), in accordance with swimming behaviour thresholds for juvenile Chinook salmon (Lehman, Huff, Hayes, & Lindley, 2017). An adjustable guidance structure (guide wall) was attached by a hinge to the river-left channel wall and attached 6.75 cm (± 0.75 cm) above the channel bottom (Figure 1). The height of the guide wall was 79 cm. Its length was 1.67 and 1.14 m at 20 and 30° angles, respectively, so that the proportion of total channel width (50%) did not change between trials. These angles were chosen to test fish behaviour in response to the hydraulics surrounding practical deployments of guidance structures similar to those that have previously been studied (Mulligan et al., 2017, 2018). The guide wall was painted to match the grey colour of the concrete channel.

FIGURE 1 Experimental channel (de-watered and looking downstream) with the adjustable floating guidance structure attached to the left channel wall. During trials, a diesel engine pump (background in blue) suctioned 0.13 m^3/s from the channel (average water speed of 0.17 m/s) and discharged it upstream of this photograph in a closed loop. The mesh screen kept debris and fish from reaching the suction end of the pump [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | Hydraulic data collection and analysis

2.2.1 | ADV measurements

Water velocities were measured using an array of three acoustic Doppler velocimeters (ADVs; Sontek 16 MHz MicroADV) that were suspended from a truss above the channel. Three-dimensional water velocities were measured at seven cross-sections and four depths (5, 15, 35, and 55 cm above the channel bottom) near the experimental guidance structure, with horizontal point measurements spaced 10 cm apart (Figure 2). Operating at 25 Hz for 5 min at each of 243 locations for a single guide wall configuration, velocity measurements were collected for 486 total locations. Velocity measurements were post-processed using WinADV (Wahl, 2017). Measurements within each 5-minute sampling period with less than 70% correlation or a signal-to-noise ratio of less than 5 dB were removed. Spikes in each time series were filtered using phase-space threshold despiking. Coordinates of each measurement were converted to a universal coordinate system, which included the channel and guidance structure geometry, using a total station (Nikon DTM 352).

2.2.2 | Calculation of hydraulic variables and interpolation

Two deployment angles (20 and 30° relative to the flow) of a guidance structure were assessed for water speed (m/s), turbulent kinetic energy (TKE, in m^2/s^2), TKE gradient (m^2/s^2/m), water acceleration (m/s^2), and velocity gradient (m/s/m or s^{-1}). All hydraulic variables considered in this analysis were calculated from time-averaged velocities in the lateral (u), longitudinal (v), and vertical (w) directions. The magnitude of the spatially averaged velocity components, u, v, and w, referred to as water speed (m/s), was calculated using Equation 1:

$$\text{Water Speed} = \sqrt{u^2 + v^2 + w^2} \tag{1}$$

as the square root of the sum of u^2, v^2, and w^2. Turbulent kinetic energy was calculated using Equation 2:

$$\text{TKE} = \tfrac{1}{2} * \left(u'^2 + v'^2 + w'^2\right), \tag{2}$$

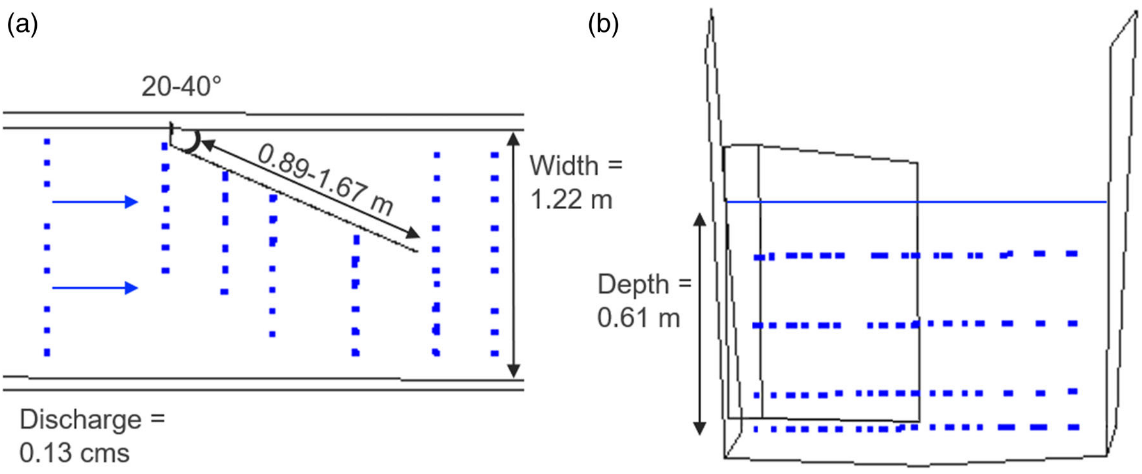

FIGURE 2 Plan view (a) and cross-sectional view (b) of the experimental channel. Blue dots mark locations of ADV measurements at seven cross-sections and four depths at 30°. Blue arrows indicate the direction of flow [Color figure can be viewed at wileyonlinelibrary.com]

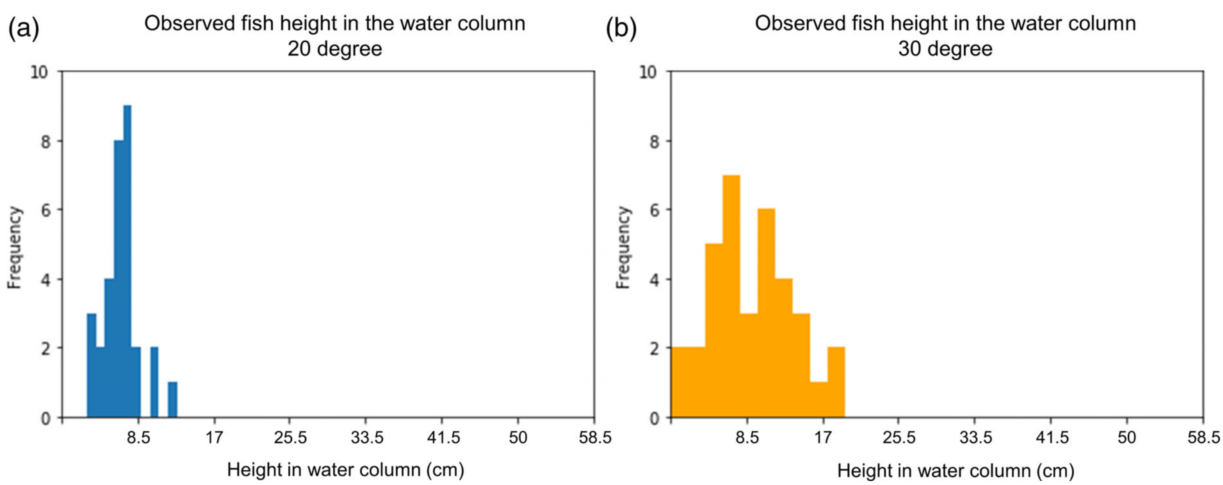

FIGURE 3 Observed height of fish above the channel bottom at 20 and 30° guide wall angles. The median height between both angles was approximately 5 cm [Color figure can be viewed at wileyonlinelibrary.com]

where u', v', and w' are fluctuations from the velocity components. Spatial gradients of water speed and TKE were calculated as the difference in magnitude of the hydraulic variable divided by the distance between points to produce measurements of velocity gradient (m/s/m, or s^{-1}) and TKE gradient ($m^2/s^2/m$). Finally, acceleration (m/s^2) was calculated as a product of velocity gradient and water speed. These five hydraulic variables (water speed, TKE, TKE gradient, velocity gradient, and acceleration) were interpolated using the average of 10 nearest neighbours onto a three-dimensional high-density mesh. Assuming that fish swim behaviour occurred in response to the hydraulics they experienced, a planar slice of each of the interpolated hydraulic meshes was extracted from the height of the water column at which the median number of fish observations were recorded (5 cm from the channel bottom, Figure 3) for analysing relationships between hydraulics and fish swim behaviour.

2.3 | Fish behaviour data collection and analysis

2.3.1 | Source and tagging of test fish

A total of 183 juvenile salmon, raised in Oregon State University's Fish Genetics and Performance Laboratory were individually using one or two 1-cm long Floy Tags (Floy Tag,, & Mfg., Inc., 2018). Tags were implanted along either side of the fish's spine behind the dorsal fin. Each fish was given a unique number and tag colour that could be identified in underwater videos. Each fish was also weighed, photographed, and its tail fork length was measured at the time of tagging. The sample (n = 183) contained a mean tail fork length of 10 cm (*SD*, 0.6 cm) and a mean weight of 8.6 g (± 1.7 g).

2.3.2 | Experimental design

Twenty trials were conducted at each guide wall angle, for a total of 40 trials. Trials at 20° were conducted first, the experimental structure was modified, and trials at 30° were conducted subsequently. Twenty trials were chosen to maximize statistical power and provide replication while balancing resources and time. Groups of five fish were placed in the upstream end of the experimental section at the beginning of each 30-minute trial. The trial length was limited by the battery life of the cameras. Groups of five were chosen because behaviours of isolated individuals may differ in a social environment, while identifying the trajectories of more than five individuals per trial was problematic experimentally. Trials were conducted at twilight between 17:00 and 21:00 hrs to maximize fish movement (Li et al., 2015).

2.3.3 | Videography

The swimming behaviour, indicated by the direction, speed, and path of juvenile spring Chinook salmon, was recorded and analysed as they first encountered guidance structures at 20 and 30°. One pair of GoPro Hero 3 cameras recorded fish movement at 1080p resolution in 30 frames per second (GoPro, Inc., 2018). Because it was assumed that key behaviour changes would occur upstream of the far tip of the guidance structure, the cameras were placed against the left channel wall at the start of testing and aligned with the guide wall (Figure 4). After 30 min, fish were collected from the downstream end of the channel, where they tended to congregate, and returned to a recovery tank. After all fish had undergone one trial, the recovery tank became

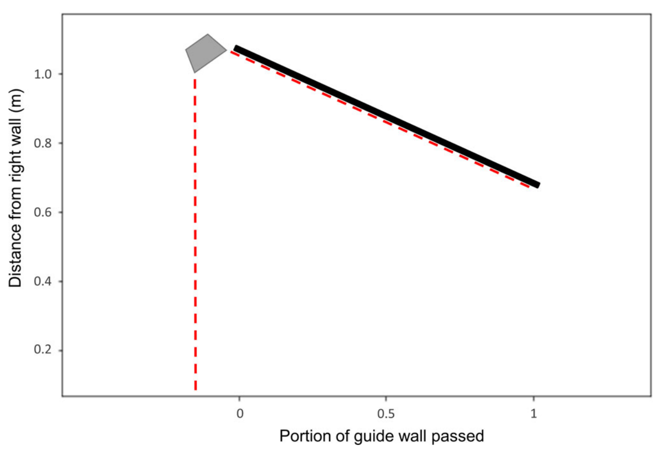

FIGURE 4 Plan view of the observational cameras (outlined between dashed red lines). The grey polygon represents the stereo-paired GoPros. The black line represents the floating guidance structure [Color figure can be viewed at wileyonlinelibrary.com]

the tank from which groups were drawn. Thus, it was possible for a fish to be observed in multiple trials.

Video observations of fish movement were processed in VidSync v1.661 (Neuswanger, Wipfli, Rosenberger, & Hughes, 2016). Researchers manually marked fish paths in three-dimensional space to document an individual fish's entire first encounter with the guidance structure as it passed into the view of the cameras. Because initial reactions to the guide wall (rather than habituated behaviour) were of interest in this study, only the swim paths of fish when first entering the field of view of the cameras were recorded. Furthermore, fish that exhibited schooling behaviour (swimming within one body-length and behind another fish) were excluded from the analysis. The coordinate system of the fish paths was translated to the coordinate system of the hydraulic measurements for comparison.

2.3.4 | Analysis of behaviour

A statistical model was used to identify the likely locations of changes in swimming behaviour within the trajectory of each individual swim path. Changes in velocity, such as slowing down or speeding up, and/or turning angle constitute a behaviour change. Using a behavioural change point analysis, the single most likely location for changes in fish swim behaviour was estimated using autocorrelated functions of fish velocity and/or turning angle developed by Gurarie et al. (2017) in R (R Core Team, 2018). Change-point analysis was selected due to its ability to deal with the statistical features of this dataset (Swanson, Tullos, & Goodwin, 2020) (i.e., highly autocorrelated, high temporal resolution from videography, and irregularly sampled) that challenge assumptions of correlative approaches. By conducting sequential scans of fish locations within an observation window over time, behavioural change points across a swim path were identified. A potential change point was selected within each scan as the time at which the likelihood of fitting two continuous velocity models (CVMs) on either side of the observation window was maximized. The complete set of possible change points across all scans were then analysed for statistical significance by comparing the Bayesian Information Criterion (BIC) of fitted CVMs on either side of the window to a null model with no change point. Thus, the single most likely change point was estimated as the observation with the highest relative log likelihood of a behaviour change of all observations in a swim path. Next, behavioural change points were classified as either "passing" (preceding downstream movement) or halting (paused movement or preceding upstream movement). Finally, behavioural change points were compared spatially between guide wall angles and statistically against the hydraulics at the location of the change point. Based on this algorithm, individual swim velocities were not directly used to identify locations where fish behaviour changed. Instead, the locations of a swim behaviour change in the CVM were identified, and then hydraulic characteristics were overlaid with the location of behaviour change.

The distribution of hydraulic characteristics present in the channel was compared to the characteristics at the location of a behaviour change. Kolmogorov–Smirnov tests were used to determine if two distributions of hydraulics were significantly different. Only the hydraulics within view of the camera was used in this analysis. Significant differences (p value < .05) in the distributions of available and change-point hydraulics across both guide wall angles were used to establish associations between the hydraulic produced by the guide wall and fish swim behaviours.

3 | RESULTS

3.1 | Channel hydraulics across guidance structure angles

Although the magnitude of hydraulic variables varied only slightly with the guide wall angle (Table 1), the distribution of hydraulic characteristics at 20 and 30° angles varied significantly for all variables (Figure 5). Two-sample Kolmogorov–Smirnov tests for independent distributions produced p values less than .001 between all distributions for all variables (Figure 5). All distributions were right-skewed.

At the 30° guide wall angle, slow-moving water, upstream of the guide wall (at 0.25 times the length of the guide wall), created heterogeneity in the spatial distribution of hydraulic variables in the vicinity of the face of the guide wall (Figure 6). Because the guide walls all occupied the same width of the channel (0.5 width), the degree of contraction was the same between the guide walls, but the longitudinal distance over which the flow was contracted varied. As a result, the 30° wall produced a more abrupt contraction over a shorter distance (1.06 m) than the 20° wall (1.3 m). For this reason, velocities decreased upstream of the guide wall with increasing guide angle

TABLE 1 Ranges (maximums and minimums) and median values of hydraulic variables at 20 and 30° guide wall angles

Guide wall angle	Water speed (m/s)	TKE (m^2/s^2)	TKE gradient ($m^2/s^2/m$)	Velocity gradient (s^{-1})	Acceleration (m/s^2)
20	0.03–0.28	3.1×10^{-4} – 8.5×10^{-3}	2.0×10^{-4} – 1.2×10^{-2}	0.04–0.33	2.5×10^{-3} – 4.3×10^{-2}
Median	0.17	7.1×10^{-4}	5.8×10^{-4}	0.10	1.2×10^{-2}
30	0.03–0.30	2.6×10^{-4} – 1.2×10^{-2}	9.4×10^{-5} – 1.4×10^{-2}	0.03–0.27	2.5×10^{-3} – 5.5×10^{-2}
Median	0.16	5.2×10^{-4}	8.1×10^{-4}	0.10	9.9×10^{-3}

Note: Ranges and median values encompass configuration's entire hydraulic mesh.

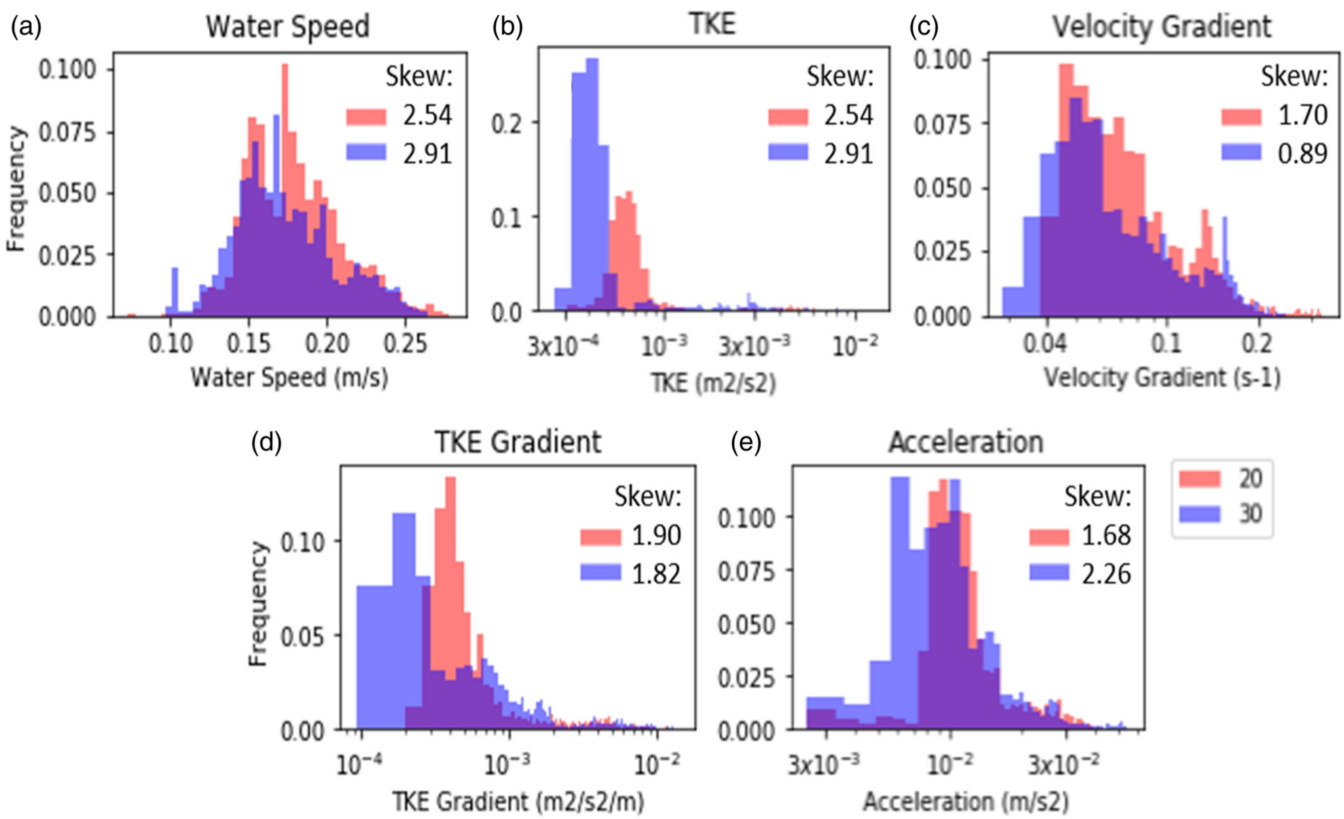

FIGURE 5 Histogram distributions of hydraulic variables across the entire interpolated mesh at 20 and 30° guide wall angles. Frequencies were normalized by the total number of observations for each angle. Kolmogorov–Smirnov tests for independent distributions gave p values less than .05 for every variable [Color figure can be viewed at wileyonlinelibrary.com]

(x = −0.5 to 0.5; Figure 6a,b). Similarly, low magnitudes of TKE, TKE and velocity gradients, and acceleration developed from x = −0.5 to 0.5 with increasing guide wall angle. Furthermore, water speed, TKE, TKE gradient, velocity gradient, and acceleration were more uniformly distributed at 20° than for the 30° wall (Figure 6).

3.2 | Behaviour changes upstream of the guidance structure

Upon entering the view of the cameras, fish either drifted slowly downstream by swimming against the current (positive rheotaxis) or

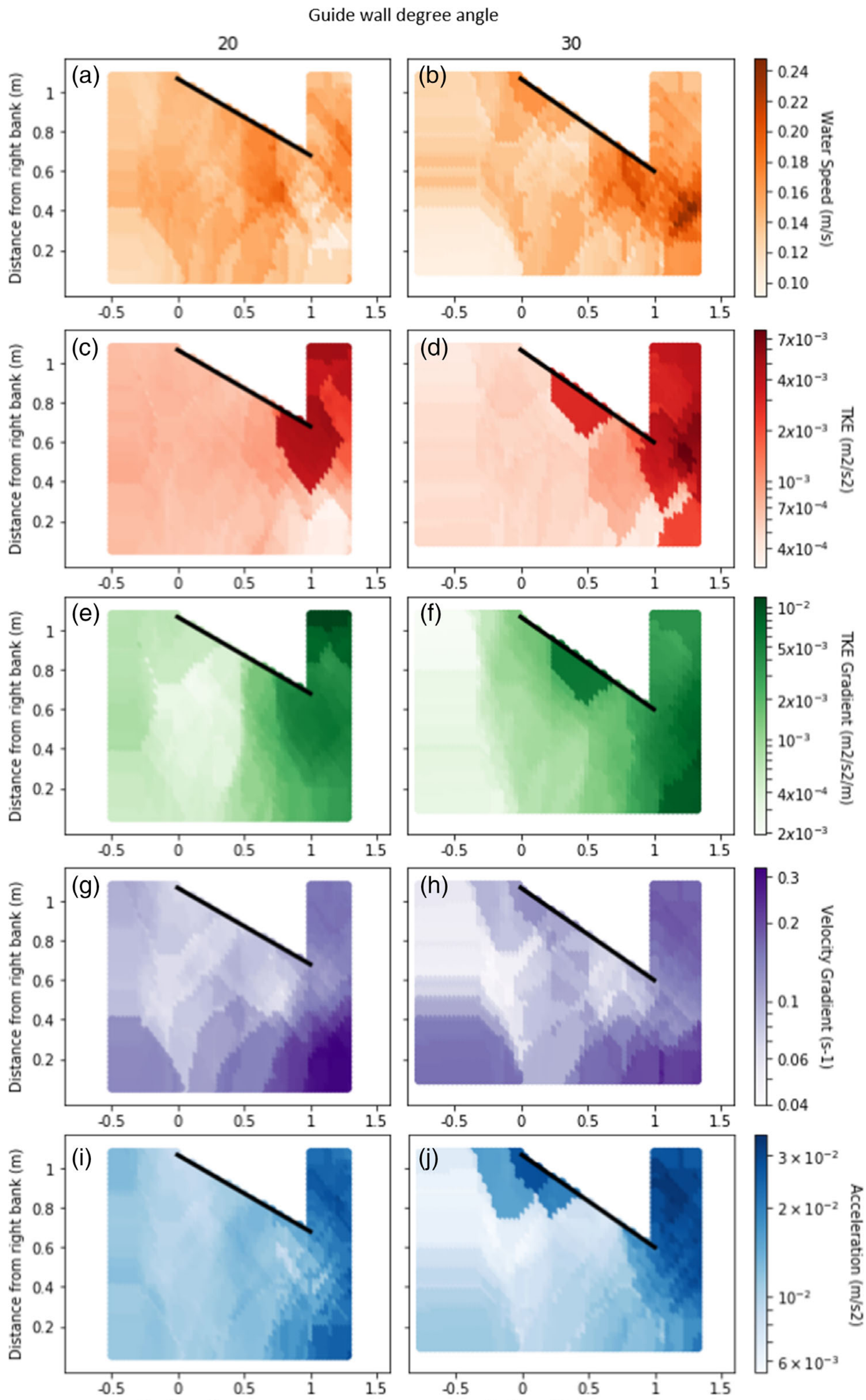

FIGURE 6 Spatial distribution of water speed, TKE, TKE gradient, velocity gradient, and acceleration at 20 and 30° guide wall angles. Water in the channel flows from left to right. The x-axis is normalized by the length of the guide wall for comparison of hydraulic zones. The black line represents the guidance structure. Hydraulic measurements were not taken immediately behind the guidance structure. Height of planar slice through hydraulic mesh (z = 5 cm) was chosen by the height at which the medial number of fish observations were recorded over both angles [Color figure can be viewed at wileyonlinelibrary.com]

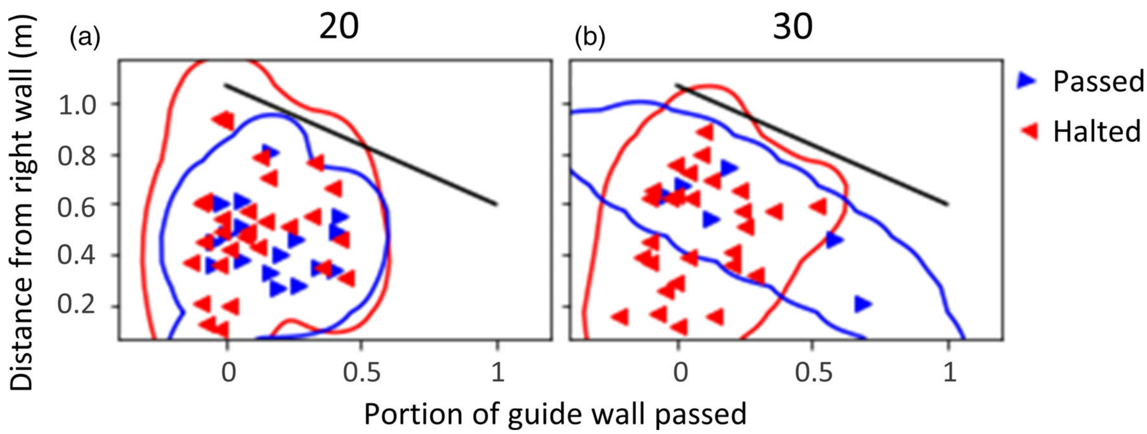

FIGURE 7 Location of passing and halting behaviours at 20 and 30° angles, normalized by guide wall length for comparison with one another. The black line represents the guidance structure, normalized by length. Red and blue contour lines represent two-dimensional, 95% confidence intervals (CI). Overlap of confidence intervals implies a lack of significant difference between the spatial distribution of passing and halting behaviours at all angles. Water flow is from left to right [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 Location of behaviour changes (both passing and halting) at 20 and 30° angles. The guide wall (black line) is normalized by its length for comparison between angles. Flow is from left to right [Color figure can be viewed at wileyonlinelibrary.com]

moved quickly downstream by swimming with the current (negative rheotaxis). Halting behaviour under positive rheotaxis was demonstrated by swimming side to side in the channel rather than continuing downstream, or by returning upstream and out of view of the cameras. Passing behaviour under positive rheotaxis included turning downstream to quickly pass the guide wall. Halting behaviour under negative rheotaxis was characterized by abrupt changes in the direction or speed away from the guide wall, or turning upstream. Passing behaviour under negative rheotaxis was characterized by accelerated swimming past the guide wall. Although the median depth at which fish were observed was 5 cm above the channel bottom, very few fish swam underneath the guidance structure.

The proportion, type, and location of behaviours did not vary significantly within or across guide wall angles. Forty-seven fish demonstrated behaviour changes at 20° and 34 demonstrated behaviour changes at 30°, out of 100 tested at each angle. Of fish that exhibited behaviour changes (see Section 2.3.4), seven out of 81 fish (9%) were observed in two trials over two guide wall angles over a period of weeks.

Most behaviour changes near the guidance structure at both angles were halting in nature. Differences in the proportion of fish that exhibited halting behaviours were observed, although these differences were not statistically significant. Results indicate that halting occurred for 62% (95% confidence interval (CI), 0.48–0.76) and 82% (0.70–0.95) of fish for 20 and 30° angles, respectively. In addition, the location of behaviour type (halting or passing) did not vary spatially within either angle. Instead, 95% CI showed substantial overlap in the spatial distribution of halting and passing behaviours at 20 and 30° (Figure 7). Lastly, the location of behaviour changes did not vary significantly between angles, as indicated by overlap of 95% CI (Figure 8).

3.3 | Hydraulic drivers of changes in swimming behaviour

For all hydraulic variables under both guide wall angles, the distributions of hydraulic conditions throughout the channel and those at the locations of fish behaviour changes were significantly different (Figure 9). This result suggested that any of the five, or a combination of, hydraulic variables could cue a behaviour change, as the distribution of hydraulics associated with behaviour changes was significantly different than those available in the view of the camera. However, velocity gradient was the only hydraulic variable that demonstrated a consistent threshold associated with behaviour changes (Figure 10). The distribution of velocity gradient was statistically similar at both 20 and 30° angles, indicating a velocity gradient of 0.08 m/s/m (standard deviation 0.02 m/s/m) consistently incited behaviour changes at both guide wall angles.

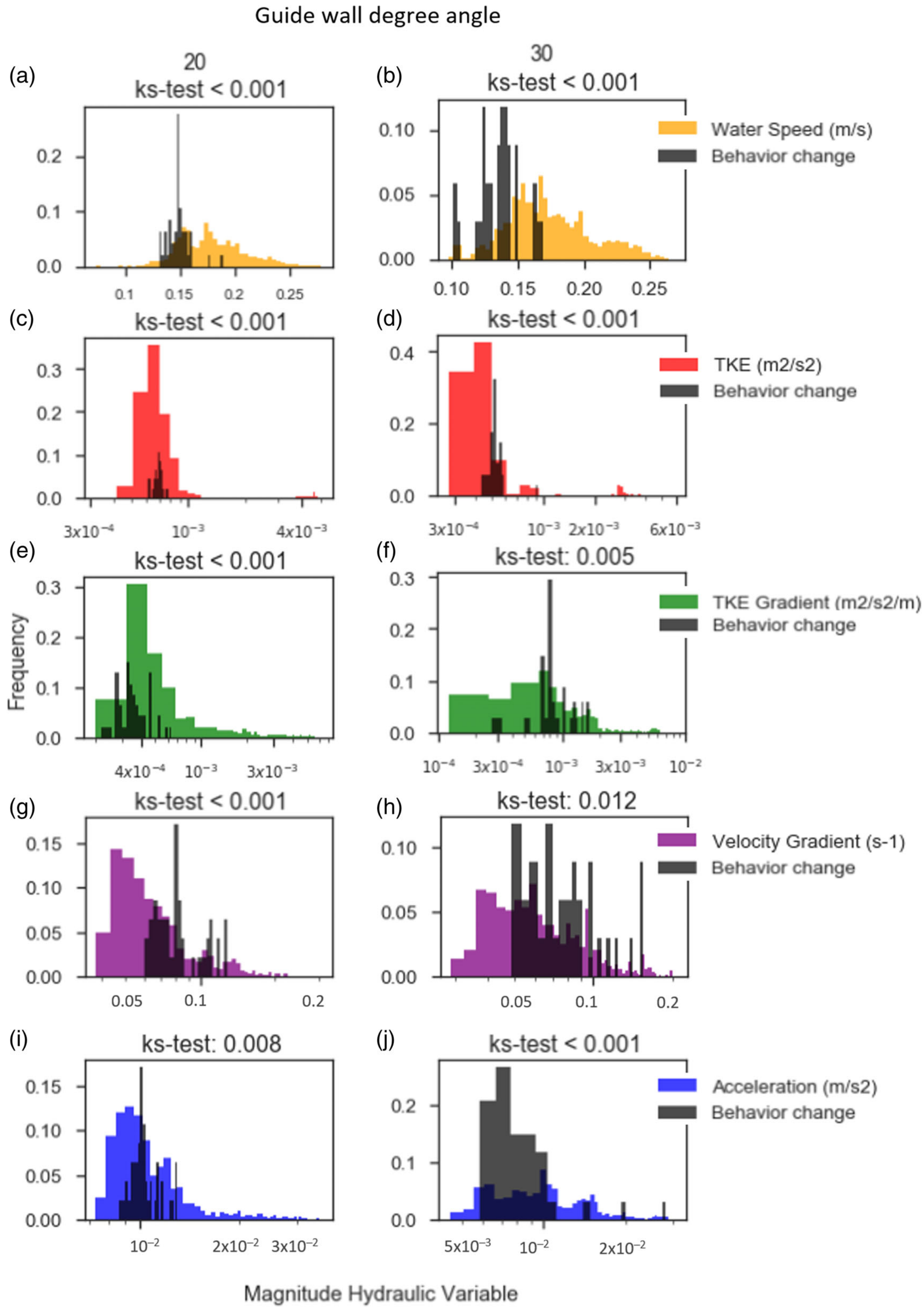

FIGURE 9 Histograms depicting the distribution of the hydraulics present in the channel (colours) and the distribution of the hydraulics at which a behaviour change was observed (grey). Channel hydraulics outside of the camera view has been removed. Note that axis extents vary across guide wall angle for some hydraulic metrics to emphasize differences between distributions of hydraulics and swim behaviour [Color figure can be viewed at wileyonlinelibrary.com]

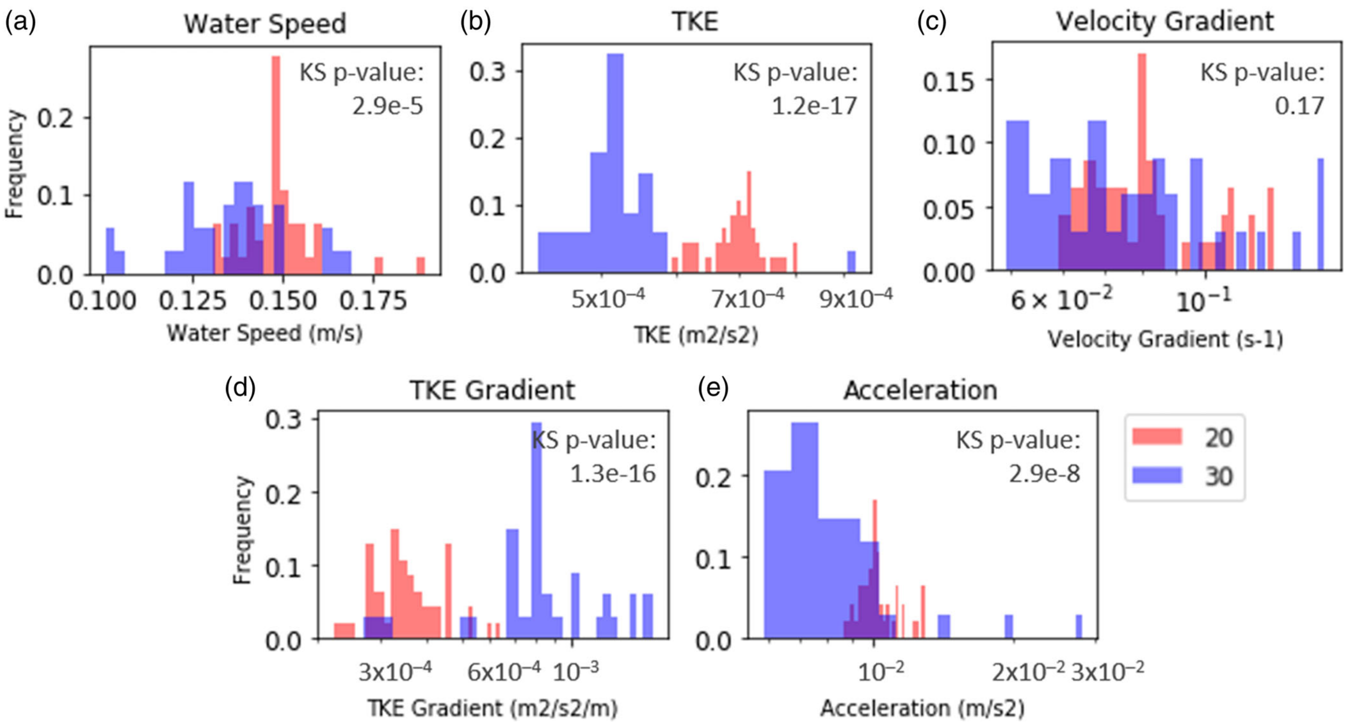

FIGURE 10 Histograms depicting the hydraulics at which behaviour changes occurred at 20 and 30°. The results of Kolmogorov–Smirnov two-sample tests for independent distributions between all guide wall angles are indicated by text [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

4.1 | Factors driving swimming behaviour

The hydraulic impacts of the guidance structures in this study confirmed and elaborated on previous findings (Mulligan et al., 2018). Two guide wall angles produced small but statistically significant differences in the distributions of hydraulics throughout the experimental channel. A guidance structure oriented 20° to the direction of bulk flow produced the most uniformly distributed hydraulics, and heterogeneity of the flow field increased at 30°. Higher approach velocities would likely exacerbate differences in the hydraulics upstream and downstream of the guide wall, as well as between guide wall angles.

The constriction of the channel and/or the visual recognition of the guide wall likely accounted for the relatively high proportion of halting behaviours observed. The proportion of halting to passing behaviours was not statistically different between angles, suggesting that the fish did not interpret the hydraulics of the guide walls as being fundamentally different. An experimental control to observe fish behaviour in the absence of the guidance structure was not conducted, because a similar flume experiment by Enders et al. (2012) with no barrier and rectilinear flow observed fish movement downstream without halting behaviour. Other studies of fish behaviour at constrictions (Kemp et al., 2005; Vowles & Kemp, 2012) have reported halting (rejecting) behaviours in between 6 and 40% of subjects, albeit much lower than observed in this study (62–82%).

If behaviour changes were purely mediated by hydraulics and angles produce biologically significant hydraulic conditions, the location of behaviour changes was hypothesized to vary between angles. The area of reduced velocity upstream of the guidance structure (x = −0.5 to 0.5 in Figure 6) became better defined as the guide wall angle increased. As a result, the locations of potential hydraulic thresholds shifted down the length of the guidance structure. For example, the magnitude of turbulent kinetic energy at x = 0 for 20° was not present until x = 0.75 at 30°. Thus, when normalized by guide wall length, behaviour changes were expected to have occurred at increasing distances downstream with angle, assuming (a) behaviour changes were hydraulically mediated and (b) the differences in hydraulics between guide wall angles were biologically significant. No significant difference existed in the location of behaviour changes between guide wall angles, leading us to conclude that the angle of the guide wall did not influence the location of behaviour changes. This may be because there are no biologically based turbulence thresholds for triggering behaviour changes, or that there are biological thresholds but that the wall angles did not produce them. Biological thresholds in previous experiments were found under hydraulic conditions of higher velocity (Enders et al., 2012; Haro et al., 1998; Vowles & Kemp, 2012), greater acceleration (Vowles & Kemp, 2012), and/or a wider range of velocity gradient (Enders et al., 2012). Further experimentation with guidance walls at more aggressive angles to the flow (up to 45° as suggested by Mulligan et al., 2018) or a higher approach velocity may accentuate flow heterogeneity, and thus the location of behaviour changes between angles, if hydraulic conditions do indeed induce behaviour changes.

Although the distribution of each hydraulic variable within view of the camera differed significantly from the distributions where behaviour changes were observed (Figure 9), only velocity gradient's behaviour change distribution was similar across angles. These results suggest that the locations of behaviour changes were discriminant within the range of hydraulics they experienced. Only the distributions of velocity gradient at the location of behaviour changes were similar between 20 and 30° angles (Figure 10), with a median magnitude of 0.08 m/s/m. This result is lower than the findings of behaviour changes in Vowles and Kemp (0.2 to 0.4 m/s/m; 2012), Enders et al. (1 m/s/m; 2012), and Haro et al. (1 m/s/m, 1998). However, the approach velocities of the latter two studies (the approach velocity of Vowles and Kemp was not given) were both larger than those in this experiment, so larger spatial velocity gradients may have been necessary to incite a behaviour change. From this and previous experiments, guidance structures that limit spatial velocity gradients may limit behaviour changes and promote passage near engineered structures.

4.2 | Assumptions and limitations

Several assumptions were adopted in this study. First, because of the limited scope of underwater cameras, key behavioural changes were assumed to occur within view of the cameras upstream of the floating guidance structure. Behaviour changes may have occurred upstream or downstream of the view of the cameras that were not recorded. Second, by observing only the first encounter with the guidance structure, a bias existed for halting behaviour, as avoidance and rejection of the guidance structure were often a fish's first reaction to it. Fish on subsequent encounters often exhibited passing behaviour. While this study focused on first encounters, future research should consider behaviours in the fish's entire swim path upstream of the guidance wall. Third, despite approach velocities similar to those of low-velocity reservoirs, the experimental channel was not representative of reservoir hydraulics overall. The narrow channel width can affect the turbulent flow characteristics and may also influence fish's swimming behaviour. In addition, while guide walls are designed to capitalize on emigrating juvenile salmonids' tendency to swim in the upper portion of the water column, the depths available for fish to swim were not possible to represent in a flume. The results thus reflect preliminary evidence of the effect of guide wall angle into the longitudinal flow, but should be replicated at full scale in a reservoir over a range of discharges.

5 | CONCLUSION

Guidance structures can address the pressing problem of downstream passage for juvenile salmon migrating past dams or other obstructions in their migration pathway. However, the ability of an engineered structure to guide fish to safe passage would benefit from further research to directly link fluid and fish behaviour.

These results indicate the fish did respond to the guide wall with behaviour changes, but the results were not statistically significant for distinguishing between the two guide wall angles. While the two guide wall angles did produce statistically different distributions of hydraulic variables, the differences were small, potentially too small for the fish to detect. Furthermore, the wall angles did not appear to produce thresholds that impacted fish's behaviour, except potentially for velocity gradient.

Further work is required to determine if more severe wall angles or higher approach velocities produce biologically significant hydraulic thresholds that may inform the design of floating guidance structures, or if the fundamental driver of behaviour changes is simply flow contraction, the visual obstruction of the guide wall or some combination of these factors. Design of guidance structures is relevant for a wide range of applications, including exclusion nets, which promote fish movement to floating surface collectors, and inclined screens, bars, and louvers, but it remains unclear what aspect of the guide wall is most effective at triggering behaviour changes. With current technologies like three-dimensional positioning using acoustic telemetry, detailed investigations of the hydraulic and behavioural impacts of guidance techniques in reservoirs are possible (Darland et al., 2000; Scruton et al., 2003). Reservoir-scale models of floating guidance structures could be deployed during migrations of Pacific salmon and other anadromous fish in subsequent years to evaluate their effectiveness.

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DATA AVAILABILITY STATEMENT

The data used to perform these analyses are publicly available online at ScholarsArchive@OSU, https://ir.library.oregonstate.edu/concern/datasets/h989r8272.

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