Flow structure and fish passage performance of a brush-type fishway: a field study in the İyidere River, Turkey

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Abstract. The fish passage performance and flow structure of a brush fish pass were investigated at the İncirli Small Hydropower Plant on the İyidere River, located in the East Black Sea region of Turkey. The spatial distributions of velocity vectors, power velocity, Froude number and turbulent kinetic energy are presented. The flow is quasi-uniform and subcritical, which provides different migration corridors with favourable hydraulic conditions; importantly for the fish, these corridors continue through the complete fish pass. The flow–bristle interaction creates a reduced velocity and low-turbulence resting zones. In addition, the passage efficiency of the brush fish pass was assessed using passive integrated transponder telemetry. The results clearly showed that upstream passage efficiency differs between fish species: \textit{Salmo coruhensis} performed better than \textit{Alburnoides fasciatus} on the same fish passage. The passage efficiency for the target fish species \textit{S. coruhensis} was calculated to be 82.4%. The data revealed that the brush fish passage provides passage for small-bodied fish (total body length <15 cm) in a high-gradient channel with a slope of 10%. The monitoring data revealed that bristles as flexible hydraulic elements are beneficial for migrating fish.

Additional keywords: brush fish passage, fishway hydraulics, turbulence, upstream passage efficiency.

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Introduction

Hydropower plants can block or delay the passage of fish migrating up- and downstream. This block can limit the longitudinal connectivity of streams for fish movement, and this can decrease the population of different fish species (Kubečka \textit{et al.} 1997; Larinier 2008; Couto and Olden 2018). For example, in Turkey there are 382 freshwater fish species, of which approximately one-third are endemic. Some of those endemic fish species have an average body length of 5 cm (Ekmecki \textit{et al.} 2016). Accordingly, it is not possible for these endemic fish species to ascend conventional technical pool fish passes due to the high velocity and turbulent kinetic energy (TKE). In this context, it is necessary to provide passage for small-bodied fish and those with weak swimming capacity through fish pass structures (Santos \textit{et al.} 2016; Kucukali and Hassinger 2018).

Brush elements as absorbers hydraulic energy in fishways were first used in 2002 in Germany (Hassinger 2015), and currently ~60 brush fishways are in operation in Europe. In one study, migration through a brush and a vertical-slot fish pass was monitored daily at a site on the River Spree in Spreewald, south-east of Berlin (Landesumweltamt Brandenburg 2007). In that study, in <1 month after both passes were operational, more than 12,000 individuals of 14 species with no size selection (the size range of fish started at 0.4 m, and was probably limited by the trap mesh size, which was in the order of 0.04 m) had migrated through the brush fish pass, compared with approximately one-tenth this number (1200), representing 12 species, migrating through the vertical-slot fish pass. Moreover, the field study of Schmalz and Thürmer (2012) at the Döbritschen Small Hydropower Plant (SHP) plant showed that, for upstream migration, 76.3% of fish (2189 fish, 16 species) used a brush-type fish passage and 23.7% (679 fish, 9 species) used a vertical-slot fishway at the same run-of-river hydropower plant. It should be noted that all the species that used the vertical-slot fishway also used the brush-type fishway. These monitoring data indicate that the brush fish passage is not size selective. Conversely, several field studies (Schmalz and Thürmer 2012; Alp \textit{et al.} 2015; Peter \textit{et al.} 2017) have shown that the size of the fish in the vertical-slot fishway affects passage efficiency. For example, Alp \textit{ et al.} (2015) reported that only 15.4% of fish tagged with passive integrated...
transponders (PITs) passed through the vertical-slot fish passage, whereas when only individuals >20 cm were considered, passage efficiency increased to 63.3%.

In the brush fish pass, there is effective energy dissipation because of the large number of bristles that are induced to vibrate by flow (Kucukali and Hassinger 2015; Kucukali 2016). Rahn (2011) conducted systemic experiments in a diagonal brush fish pass and found that significant energy dissipation (>50%) takes place in the brush blocks. However, without the bristle field, flow velocity would be excessively high and the flow would be supercritical (Kucukali and Hassinger 2018). Although there extensive literature regarding turbulence in fishways, most of the international standards only take stream-wise velocity into account as a relevant criterion, and the level of turbulence is not considered (Environment Agency 2010; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014). Moreover, several studies have reported on the flow and turbulence characteristics of conventional fish pass structures, such as vertical-slot (Cardoso 2015; Höger 2015; Quintella 2015; Ozcan 2017), pool–weir (Yagci 2010; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014) and nature-like (Baki et al. 2014; Cassan et al. 2014; Czerny et al. 2015) fishways. A common characteristic of these fish pass structures is that the hydraulic energy is mostly dissipated in an energy cascade process: in vertical-slot fishways, the turbulent jets plunge into pools, whereas in nature-like fishways the wake behind the macro-roughness dissipates excess energy. In addition, conventional technical fish passes have usually been designed for species with good swimming ability, and the passage of smaller individuals with weaker swimming ability is not taken into account due to high bed slopes or high discharges (Rodriguez et al. 2006; Mallen-Cooper et al. 2008; Silva et al. 2012; Katopodis and Williams 2012; Weibel and Peter 2013; Romão et al. 2017). For example, Richmond et al. (2007) and Wang et al. (2016) demonstrated that more juvenile fishes migrate through the reduced-velocity zone in a culvert. Accordingly, the proposed brush fish pass differs from conventional fish passage types by providing a nearly optimal migration corridor under quasi-uniform and subcritical flow for smaller and weaker fish. In addition, the brush fish pass attracts stronger rheophilic fish to move upstream in the jet region, where velocities are in the order of 1.3 m s⁻¹. Schneider and Kopecki (2017) reported behaviour-relevant velocity (rheoreactive response velocity) categories for upstream fish migration as follows: (1) flow velocity in stream-wise direction (Vx) ≤ 0.15 m s⁻¹, no clear orientation; (2) 0.15 m s⁻¹ < Vx ≤ 0.30 m s⁻¹, young fish oriented; (3) 0.30 m s⁻¹ < Vc ≤ 1 m s⁻¹, adult fish oriented; (4) 1 m s⁻¹ < Vc ≤ 1.75 m s⁻¹, high swim capacity; and (5) 1.75 m s⁻¹ < Vc, limit of swimming capacity.

No study in the literature has examined the flow structure and fish passage efficiency of a brush fish pass simultaneously at the prototype scale. Although physical models are widely used under controlled conditions, scale effects may exist in physical models (Kucukali and Hassinger 2015) and, accordingly, the actual operational conditions of fish pass structures (i.e. variable headwater and tailwater levels) cannot be well simulated. In this study we focused on the flow structure of a brush fish pass considering the passage performance of fish species endemic to Turkey.

Materials and methods

Study area

The Iyidere River is located in the Eastern Black Sea River Basin in Turkey, has a drainage area of 1053 km² and a length of 53 km. The Iyidere River flows through a mountainous landscape and 55% of the basin area is covered by forested mountains. The locations of SHP weirs on the Iyidere River are shown in Fig. 1; the power plants are situated downstream of weirs. For example, the İncirli power station is located 6 km downstream of the İncirli weir. The discharge of the Iyidere River is measured systematically by State Hydraulics Works of Turkey (DSI) at monthly intervals at gauging station 2218, which was established by the General Directorate of Electrical Resources Survey Administration of Turkey (EIE) in 1955. The annual mean river discharge was calculated as being 27.8 m³ s⁻¹, ranging from 14.38 m³ s⁻¹ in December to 64.92 m³ s⁻¹ in May (Table 1). In the river basin, a cascade-type hydropower system has been developed and the İncirli Weir is situated first downstream from the basin, which is in the barbel zone (Fig. 1). In the river basin, six SHPs are in operation. The attributes of these SHPs are given in Table 2. İncirli SHP is diversion-type plant (tunnel length = 6 km) with a design head of 62 m and installed capacity of 25.2 MW.

Under the scope of the present study, we completely removed the existing orifice pool-type fishway and built a new diagonal brush fish pass at İncirli Weir. Fig. 2 shows the general view of the brush fish pass that was constructed at İncirli Weir in January 2017. The reason for the diagonal arrangement is that in this kind of configuration the flow is cross-exchanged constantly. By grouping brush blocks, pools can be formed between the groups of blocks. Under normal operating conditions, the total level difference between the upstream and downstream of the fish pass structure is 5 m. The bed slope of the fish passage is 10%, and it has a total length of 46 m. The areal density of the brushes is selected according to the result of a design process that is based on an equilibrium of forces. The brush density is a function of slope, discharge, water depth, bristle diameter, bristle length and grouping pattern of brush modules. The design tool used was developed by Hassinger (2002) and is widely used in the design of brush-type fishways. Rounded river stones (maximum diameter 0.16 m) were placed on the bed of the channel to create a microhabitat.

Physical water quality parameters, such as water temperature, pH, electrical conductivity, dissolved solids and dissolved oxygen were analysed on site using a multiwater quality meter (Hach Lange HQ40D, Hach Company, Loveland, CO, USA). International standardised methods were used for sampling and analysis, with the Communique on Methods of Sampling and Analysis of Water Pollution Control Regulation being taken into consideration (American Public Health Association 2017).

Flow and turbulence measurements

An acoustic Doppler velocimeter (ADV; Sontek 50-MHz, Sontek Company, San Diego, CA, USA) was used to measure the three-dimensional instantaneous velocity fields. The ADV used had three sensors and measured flow velocity in a controlled volume of 0.05 m in front of its sensors. The flow velocities measured by the ADV range from 0.1 mm s⁻¹ to 2.5 m s⁻¹, with an accuracy of ±1%. Velocity measurements were taken at each grid point.
The velocity data were collected at a frequency of 50 Hz over a sampling period of 30 s. Preliminary tests showed that a 30-s sampling period was enough and yielded stationary results for all measurement points (Hassinger and Bejranonda 2015; Kucukali and Hassinger 2018). In the present study, the ADV sample size was 1500, which is the same as that in the study of Enders et al. (2017) but smaller than the sample size of 4500 in the study of Quaresma et al. (2017). It would have been better to have a longer sampling duration with the ADV, but in this study it would have been risky to sample for a longer period of time because the discharge may change during the velocity measurements due to the operation conditions of the hydropower plant. Hydraulic conditions tend to have repeating patterns (Fig. 4). Accordingly, a representative basin was selected for flow and turbulence measurements. The lateral and vertical distributions of velocity measurement points for the given cross-section are shown in Fig. 3. In order to enable comparisons of flow and turbulence structures with experimental data, the spacing of the measurement grid in this study is similar to the velocity sampling density of Rahn (2011). Data on instantaneous velocity were filtered with WinADV software (ver. 2.031, Bureau of Reclamation, Washington, DC, USA) using the Goring and Nikora (2002) phase-space threshold despiking method. Signal post-processing included removal of mean signal to noise ratio data <5 dB and the removal of mean correlation values <0.6. The deleted data were not substituted. More than 90% of data remained for each sampling point after filtering.

Table 1. Mean monthly values for the Iyidere River

<table>
<thead>
<tr>
<th>Month</th>
<th>Discharge (m³ s⁻¹)</th>
<th>Water temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.55 ± 2.34</td>
<td>3.5 ± 1.9</td>
</tr>
<tr>
<td>2</td>
<td>12.21 ± 2.78</td>
<td>3.7 ± 2.4</td>
</tr>
<tr>
<td>3</td>
<td>18.58 ± 5.53</td>
<td>7.1 ± 2.2</td>
</tr>
<tr>
<td>4</td>
<td>40.25 ± 13.72</td>
<td>9.8 ± 2.1</td>
</tr>
<tr>
<td>5</td>
<td>64.92 ± 13.42</td>
<td>10.9 ± 1.8</td>
</tr>
<tr>
<td>6</td>
<td>64.08 ± 15.27</td>
<td>15.9 ± 1.8</td>
</tr>
<tr>
<td>7</td>
<td>36.04 ± 10.29</td>
<td>19.7 ± 3.1</td>
</tr>
<tr>
<td>8</td>
<td>19.4 ± 6.2</td>
<td>17.4 ± 3.1</td>
</tr>
<tr>
<td>9</td>
<td>16.71 ± 8.02</td>
<td>20.4 ± 2.5</td>
</tr>
<tr>
<td>10</td>
<td>18.0 ± 6.7</td>
<td>13 ± 2</td>
</tr>
<tr>
<td>11</td>
<td>17.38 ± 5.37</td>
<td>8.1 ± 2.5</td>
</tr>
<tr>
<td>12</td>
<td>14.38 ± 3.32</td>
<td>5.2 ± 2.2</td>
</tr>
</tbody>
</table>

Table 2. Attributes of the small hydropower plants (SHPs) in the Iyidere River basin

<table>
<thead>
<tr>
<th>SHP</th>
<th>Q (m³ s⁻¹)</th>
<th>H (m)</th>
<th>P (MW)</th>
<th>L (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incirli</td>
<td>62</td>
<td>62</td>
<td>25.2</td>
<td>6</td>
</tr>
<tr>
<td>Saray</td>
<td>62</td>
<td>31.4</td>
<td>13.5</td>
<td>3.74</td>
</tr>
<tr>
<td>Cevizlik</td>
<td>50</td>
<td>230</td>
<td>91.4</td>
<td>8</td>
</tr>
<tr>
<td>Kalkandere</td>
<td>50</td>
<td>98</td>
<td>35</td>
<td>7</td>
</tr>
<tr>
<td>Kızılagac</td>
<td>50</td>
<td>16</td>
<td>5.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Zorlu</td>
<td>17</td>
<td>220</td>
<td>24.9</td>
<td>6</td>
</tr>
</tbody>
</table>
From these measurements, the instantaneous local velocity components of \( u \), \( v \) and \( w \) in stream-wise, lateral and vertical directions respectively were obtained. The resulting local velocity, \( V \), can then be calculated using Eqn 1:

\[
V = \sqrt{u^2 + v^2 + w^2}
\]  

Moreover, a local power velocity (\( V_{pm} \)), which is thought to be a useful parameter for understanding fish migration patterns (Kucukali and Hassinger 2018), can be defined as follows:

\[
V_{pm} = \sqrt{\frac{1}{n} \sum V_i^2}
\]  

**Fig. 2.** The existing pool orifice-type fish pass (a) in the Incirli Small Hydropower Plant was replaced with a diagonal brush fish pass (b). The channel has a bed slope of 10% and a width of 1.1 m.

**Fig. 3.** Top view of the brush fishway and the velocity measurement grid (open circles) in a repeating section. Capital letters indicate the longitudinal measurement sections. The drawing is to scale. In the brush blocks, light grey circles represent bristles, whereas dark grey circles represent holes. Continuous holes are left for small migration corridors, whereas single holes are left for the fixing of brush blocks. \( \delta \), channel bed slope.

**Fig. 4.** Flow pattern (‘S’ flow) in the diagonal brush fish pass.
where \( n \) is the number of velocity samples. From the time series of the velocity measurements, the root mean square of the turbulent fluctuation velocities (\( \sqrt{u'^2}, \sqrt{v'^2} \) and \( \sqrt{w'^2} \) in the longitudinal, lateral and vertical directions respectively) were calculated at each measurement point. The turbulence intensities (TIs) in three directions were calculated as follows:

\[
TI_x = \frac{\sqrt{u'^2}}{U} \tag{3a}
\]

\[
TI_y = \frac{\sqrt{v'^2}}{U} \tag{3b}
\]

\[
TI_z = \frac{\sqrt{w'^2}}{U} \tag{3c}
\]

where \( U \) is the uniform velocity. The spatial distribution of TKE in the flow field is important because energy dissipation results from the generation of turbulence (Piquet 2010). Hence, the TKE per unit mass \( (k) \) is calculated as shown in Eqn 4:

\[
k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \tag{4}
\]

In addition, the Prandtl–Kolmogorov formula (Schlichting and Gersten 2000) relates the local rate of energy dissipation with the 1.5 power of the TKE as follows:

\[
\varepsilon = 0.168 \times \frac{k^{3/2}}{L} \tag{5}
\]

where \( \varepsilon \) (\( m^2 \text{ s}^{-3} \)) is the energy dissipation rate per unit mass, \( L \) (m) is the macro-scale turbulent length scale and \( k \) (\( m^2 \text{ s}^{-2} \)) is the TKE per unit mass. The macro-scale turbulent length scale characterises the size of the large vortical structure. In addition, the presence of turbulence in the flow domain plays an important role in the conversion of flow kinetic energy to TKE. Hence, it is suggested that a better understanding of turbulence arising from the geometry of the fish pass will improve our understanding of fish behaviour characteristics. Accordingly, in this study TKE was selected as the relevant parameter for turbulence analysis. Gao et al. (2016) found TKE was the single most important stimulus for fish trajectories. Moreover, the mean energy dissipation rate per unit mass for uniform flow (\( \varepsilon_{un} \), \( m^2 \text{ s}^{-3} \)), can be defined as follows:

\[
\varepsilon_{un} = S_b \times U \times g \tag{6}
\]

where \( S_b \) is the channel bed slope and \( g \) is the acceleration due to gravity. The energy dissipation per unit volume (\( \Delta P, \text{W m}^{-3} \)), is calculated as:

\[
\Delta P = \gamma Q S_b - Bd \tag{7}
\]

where \( Q \) is the discharge, \( \gamma \) is the specific weight of the water, \( d \) is the uniform flow depth and \( B \) is channel width.

The Darcy–Weisbach friction factor, \( f \), is calculated using Eqn 8:

\[
f = \frac{8S_b R_b g}{U^2} \tag{8}
\]

where \( R_b \) is the hydraulic radius (ratio of the cross-sectional area to the wetted perimeter). Thus, Reynolds \( Re \) and the bulk Froude number, \( Fr \), are calculated as follows:

\[
Re = q + v \tag{9a}
\]

\[
Fr = \frac{U}{\sqrt{g d}} \tag{9b}
\]

where \( q \) is the unit discharge and \( v \) is the kinematic viscosity. The Froude number is used as the relevant parameter in river habitat classification systems (Kemp et al. 2000) and fish fatigue (Katopodis and Gervais 2015) studies. In addition, the Froude number has a physical meaning: it is the ratio of flow kinetic energy to potential energy. Thus, the analysis is performed on a physical basis and contains the most important hydraulic parameters of velocity and flow depth for fish passage design.

**Fish monitoring in the diagonal brush fish pass**

The effectiveness of a fish pass is considered a qualitative concept that involves checking whether the system provides satisfactory passage for the target species under the flow conditions observed during the migratory period (Larinier 2008; Makrakis et al. 2011; Wagner et al. 2012). Conversely, passage efficiency takes into account the percentage of fish present on one side of the passage that are able to move through the fish passage (Larinier et al. 2002; Larinier 2008; Wagner et al. 2012). Hence, fish passage efficiency \( (E) \) is defined as the ratio of the number of individuals that passed through the structure \( (FP_{ex}) \) to the number of individuals detected at the fishway entrance \( (FP_{en}) \):

\[
E = (FP_{ex} / FP_{en}) \times 100 \tag{10}
\]

In the context of the present study, a fish monitoring study was undertaken at the Incirli brush fish pass during the periods April–July 2017, November–December 2017 and April–May 2018 considering the spawning seasons for *Salmo coruhensis* (November–January) and Cyprinids (April–July). In order to determine the fish passage efficiency, a PIT telemetry method was used. There is no battery inside tags; therefore, the retention time of the tags is until the fish die. During the field study, fish were caught by electroshock the downstream of the Incirli Weir, anaesthetised with 2-phenoxy ethanol and their body length measured. Using a hypodermic needle, PIT tags were injected into the peritoneal cavity of individuals with a body length >70 mm. All PIT tags used in the study were HPT 12 tags (Biomark, Boise, ID, USA) (length 12 mm, frequency 134.2 kHz). After injection of the tag, fish were transferred to a plastic container (volume 0.5 m³), where they were kept for 30 min (all fish recovered from the procedure within 5–10 min). The fish were then carried in the plastic container 100 m downstream of the fish passage and released. Prior to release, the status of each fish was checked.
This tagging procedure is compatible with previous studies (Thorsteinsson 2002; Gibbons and Andrews 2004; Skov et al. 2005; Thorstad et al. 2013). It was not possible to determine tag mortality after the fish had been released. Accordingly, we can state that no fish died during the 30-min acclimation period in the container, but we do not know whether there was any mortality during the field investigation.

Square antennas (100 × 80 cm) were installed at the entrance and exit of fish passage (Fig. 5) and were connected to a data logger system (Biomark). Two interconnected batteries supplied the system with 24 V direct current power. The data logger recorded the exact date, time and individual PIT tag identity numbers of fish passing the loop antenna. As part of this study, 373 fishes from 6 different species (S. coruhensis, Barbus tauricus, Alburnoides fasciatus, Squalius orientalis, Capoeta banarescui and Ponticola rizeensis) were tagged (Fig. 6). The body length of fish ranged from 70 to 313 mm (mean ± s.d., 145.2 ± 2.0 mm).

Measurement of fish movement is an important task for evaluating fish passage efficiency. Accordingly, we placed two video cameras (GoPro Hero 5, GoPro, San Mateo, CA, USA) underwater in the fish passage. The positions of the cameras and the camera views are shown in Fig. 7. Video recordings were made in July 2017. A similar video recording technique was used by Schweizer (2017) inside a vertical-slot passage. Fish speed and fish tail beat frequency were derived from video recordings made using the GOPRO Hero 5. The video recording frame rate was 60 frames per second with a spatial resolution of 1920 × 1080 pixels over a field of view of ~0.27 m². Video recordings were divided into frames during fish passages (Fig. 8). Then, these frames were studied individually to observe fish movement characteristics. By tracking a point on the fish’s body (i.e. fish eye) from frame to frame, it is possible to generate a trace of the fish’s position through time (Plew et al. 2007; Wang et al. 2016). All frames were analysed, and the eyes of the fish were tracked. Considering our image processing analysis, the uncertainty in the fish trajectory position is expected to be less than 3 cm. Eulerian fish speed was derived from first differentiation calculated using central differences at each time step of the video record trajectory (Wang et al. 2016). The rationale behind this image processing analysis is to gain a better understanding of how fish use and process flow information.

Two-dimensional (2-D) fish trajectories were labelled manually from 12 different video recordings. In all recordings, fish passed between the mid-depth and near the channel bottom. The depth of the flow in the brush fish pass is ~0.4 m. This can be assumed to be shallow water; therefore, we focused on the 2-D fish trajectories of individuals in the plan view in order to better understand how different fish species use and process flow information. In addition, we determined flow velocities at the mid-depth and along the channel bottom. A computer vision-based fish detection and analysis framework was used (Yildirim et al. 2018). Positive samples (fish regions) were extracted from the underwater fishway videos and fish trajectories were quantified using AutoCAD (Autodesk, San Rafael, CA, USA). To evaluate the performance of our system, in addition to actual fish regions that constituted positive samples, we generated 250 × 250-pixel cropped images of background fish passage and other underwater objects that did not contain fish, to form a set of negative samples. More information on this method of image analysis is provided in Yildirim et al. (2018).

In addition to fish detection, fish tail beat frequencies were determined automatically (Yildirim et al. 2018). This was achieved using two alternative image analysis-based frequency estimation methods, namely the average magnitude difference function (AMDF) and the autocorrelation function (ACF; Yildirim et al. 2018). To this end, fish segments recognised using a hybrid approach exploiting adaptive background subtraction and extreme learning machines were cropped and further analysed using AMDF- or ACF-based frequency estimation methods (Yildirim et al. 2018).

Results and discussion

Flow characteristics

The flow conditions in the brush fish pass are summarised in Table 3. For values of Q of 38 and 264 L s⁻¹, flow depth and cross-sectional averaged velocities were in the range 0.15–0.40 m and 0.23–0.60 m s⁻¹. Bulk Froude number ranged from 0.15 to 0.16, whereas Reynolds number varied between
3.45 × 10^4 and 2.4 × 10^5. In the present study, considering the variation in Reynolds number, the results are not likely to be affected by viscous scale effects. However, this issue was not addressed in previous studies (Wu et al. 1999; Yagci 2010; Cardoso 2015; Höger 2015). For example, Wu et al. (1999) reported that Reynolds number has no effect on energy dissipation rate and showed that the dissipated power density is directly proportional to the slope of the vertical-slot fishway. However, in the present study the energy dissipation per unit volume tended to increase with Reynolds number, with values ranging from 226 to 589 W m⁻³ (Table 3). In the brush field, energy is dissipated by the oscillation and bending of bristles resulting from flow separation at each bristle element. In addition, flow-induced vibrations were clearly observed within the brushes during the field measurements (Fig. 4).

Bristles mounted vertically deflect the flow in the basin, and no backflow forms in the middle of the basin and there is no rotational flow (Fig. 9). Immediately behind the brush block, the mean flow velocity is reduced by ~70%, but the flow has not separated and no recirculation zone forms. This flow field in the vicinity of brush blocks with an absence of recirculation regions is consistent with field measurements reported by Mosch (2007) and Nikora et al. (2012) and the laboratory measurements of Rahn (2011). In the brush fish pass, the horizontal velocity distribution creates a transverse exchange of momentum. This flow pattern may have important implications for upstream fish migration. Enders et al. (2017) hypothesised that horizontal turbulent momentum exchange that matches the body undulation of the swimming fish can be more beneficial for fish passage than vertical momentum exchange. Moreover, Wilkes et al. (2017) suggested that fish would occupy positions with energetically hydrodynamic conditions that are likely to minimise swimming costs. Brush blocks have permeability (i.e. they are like a porous medium) and there is flow inside the brush blocks. We calculated that ~50% of the total discharge passes through the brush blocks, which is consistent with the laboratory measurements reported by Rahn (2011) for a diagonal brush fish pass. It was not possible to measure velocity inside the brush blocks due to the presence of bristles. Therefore, we extrapolated our measured velocity data for those regions (Fig. 9). To this end, we established a dense velocity measurement grid considering the site constraints. The spatial distribution of the \( V_{pmd} \) through the fish pass is shown in Fig. 9. The high velocity level in the S flow region (main flow) and reduced velocity zones behind the brush blocks can be clearly seen in Fig. 9. The measured velocity data indicate that the brush fish pass as a whole meets the requirements of threshold velocity values defined for different fish passage types based on different fish regions (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014).

Fig. 10 shows that the velocity distribution is not logarithmic behind the brush blocks related with the flow–bristle interaction.
The vertical velocity profile behind the brush blocks is almost the exact opposite of what would be expected in a free surface channel with bottom friction (i.e. rounded river stones). The maximum flow velocity was measured near the channel bottom and there a deceleration towards the free surface was noted. An inflection point in the mean velocity profile behind and near the top level of the bristles indicates a sink of momentum. This vertical velocity profile is in agreement with the physical model measurements of Kucukali and Hassinger (2015). The finding of higher flow velocities in lower layers of the water-body in the brush zone is in contrast with results reported by others (Maier and Lehmann 2006; Kubrak et al. 2008) that indicate flow velocity is constant over the water depth if the water level does not exceed the brush tips. The reason for this apparent discrepancy is that new and clean brushes in the test provide larger gaps for flow in the lower regions, where the bristles are bundled closely; the bristles are only spread out in the upper layers. Thus, the process of energy dissipation by a large number of small eddies is concentrated in the upper portions because of the larger gaps between the bristle bundles in the lower regions. In real-world practice, the gaps at the bottom will become partly filled with organic debris and the velocity will be uniform over the water column (Kucukali and Hassinger 2015). This organic material within the brush blocks is of minor importance for the function of the fishway as long as the slots remain open. It is recommended that the bristle elements should be combed with a rake at least twice per year (Hassinger 2015).

In this study, the Froude number was used as one a reference parameter to evaluate the migration corridors and resting areas of fishes. As can be seen from Table 3, the flow is subcritical under all hydraulic conditions. The reason for this is that the drag force created by the bristles increases the depth of the flow while reducing flow velocity, ensuring that the flow is subcritical.

### Table 3. Flow conditions in the brush fish pass for different inlet water levels

<table>
<thead>
<tr>
<th>$H$ (m)</th>
<th>$d$ (m)</th>
<th>$Q$ (L s$^{-1}$)</th>
<th>$d/h$</th>
<th>$U$ (m s$^{-1}$)</th>
<th>$f$</th>
<th>$U^*$ (m s$^{-1}$)</th>
<th>Re</th>
<th>Fr</th>
<th>$\Delta P$ (W m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101.70</td>
<td>0.15</td>
<td>38</td>
<td>0.41</td>
<td>0.23</td>
<td>6.98</td>
<td>0.023</td>
<td>3.45 x 10$^4$</td>
<td>0.16</td>
<td>226</td>
</tr>
<tr>
<td>101.85</td>
<td>0.2</td>
<td>66</td>
<td>0.54</td>
<td>0.30</td>
<td>5.12</td>
<td>0.029</td>
<td>6.00 x 10$^4$</td>
<td>0.15</td>
<td>294</td>
</tr>
<tr>
<td>102</td>
<td>0.34</td>
<td>187</td>
<td>0.92</td>
<td>0.50</td>
<td>2.64</td>
<td>0.041</td>
<td>1.70 x 10$^3$</td>
<td>0.15</td>
<td>491</td>
</tr>
<tr>
<td>102.05</td>
<td>0.40</td>
<td>264</td>
<td>1.08</td>
<td>0.60</td>
<td>2.02</td>
<td>0.045</td>
<td>2.40 x 10$^3$</td>
<td>0.15</td>
<td>589</td>
</tr>
</tbody>
</table>

![Fig. 9. Velocity vectors (a) and power velocity distribution (b) around brush blocks at the mid-depth.](image)

![Fig. 10. Vertical velocity profiles behind the large brush block for different bristle relative submergences.](image)
The fact that in the brush zone energy dissipation is related to the mum velocity was reduced by same dissipated power of components were 37 and 17% respectively. Fig. 12 shows the remaining contributions to TKE from the lateral and vertical component was found to be responsible for 46% of the TKE. The brush zone of a baffle–brush fish pass (Kucukali and Hassinger 2018) was spatially averaged and maximum TKE values in the brush fish pass are given in Table 4. The water was mildly alkaline, rich in oxygen and contained low concentrations of dissolved solids. One of the most important parameters for water quality considering fish migration is water temperature. Fish are extremely sensitive to water temperature, and in our field study upstream migrations started when water temperature exceeded 10°C (Table 4).

To determine the attraction efficiency of the fish pass, the number of fish detected at the fish pass entrance was considered: 82 of 373 fishes were detected at the entrance of the fish passage, with a calculated attraction efficiency of 22% for all fish species. The reason for the low attraction efficiency of the fish pass is specifically the excessively strong water current (O = 5–6 m s⁻¹) coming from below the gates of the weir. On a species basis, the attraction efficiency of the fish pass was highest for A. fasciatus (33.33%) and lowest for P. rizeensis (12.31%). It was determined that 55 of the 82 individuals successfully passed through the structure. Passage efficiency was highest for C. bunarescui (100%) and lowest for P. rizeensis.
In the brush fish pass, the length of fish detected at the entrance antenna ranged between 95.0 and 283.0 mm (mean ± s.d., 142.18 ± 2.92 mm), whereas the length of fish detected at the upstream antenna ranged between 95.0 and 218.0 mm (mean ± s.d., 149.2 ± 2.8 mm). Analysis of variance (ANOVA) test results showed that fish size is not significant for brush fish passage efficiency (ANOVA, \( F = 0.541; \) d.f. = 2, 537; \( P = 0.582 \)). The data reveal that the brush fish pass allows the passage of small-bodied fish (total body length, \( 15 \) cm; Fig. 13), which is in agreement with the fish monitoring data of Landesumweltamt Brandenburg (2007) and Schmalz and Thürmer (2012). However, the efficiency of vertical-slot and nature-like fish passages depends on fish size (Peter et al. 2017). Moreover, Weibel and Peter (2013) found that block ramps with slopes of \( .5\% \) are ineffective for small-sized cyprinid species. In this study, the brush fish pass was not size selective even for a bed slope of \( 10\% \). The ascending times of the tagged fish passing through the brush fish passage are provided in Table S1, available as Supplementary Material to this paper. The ascending (passage) times of the fish varied from 15 min to 26 days. It is thought that water temperature, flow rate and fish species have an effect on fish ascending times. However, the sample size in

Table 4. Water quality parameters in the fish passage measured during fish tagging

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature (°C)</th>
<th>TDS (mg L(^{-1}))</th>
<th>EC (µS cm(^{-1}))</th>
<th>pH</th>
<th>DO (mg L(^{-1}))</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 May 2017</td>
<td>17.4</td>
<td>56.5</td>
<td>56.5</td>
<td>7.51</td>
<td>9.53</td>
<td>99.3</td>
</tr>
<tr>
<td>4 June 2017</td>
<td>20.4</td>
<td>63.5</td>
<td>63.5</td>
<td>7.40</td>
<td>9.10</td>
<td>104.5</td>
</tr>
<tr>
<td>3 July 2017</td>
<td>19.8</td>
<td>54.6</td>
<td>54.6</td>
<td>6.52</td>
<td>10.25</td>
<td>107.2</td>
</tr>
<tr>
<td>7 August 2017</td>
<td>20.10</td>
<td>52.7</td>
<td>52.7</td>
<td>6.75</td>
<td>9.65</td>
<td>106.4</td>
</tr>
<tr>
<td>8 September 2017</td>
<td>19.5</td>
<td>49.7</td>
<td>49.7</td>
<td>7.81</td>
<td>9.41</td>
<td>105.5</td>
</tr>
<tr>
<td>5 October 2017</td>
<td>18.7</td>
<td>46.3</td>
<td>46.3</td>
<td>5.86</td>
<td>9.98</td>
<td>106.6</td>
</tr>
<tr>
<td>12 November 2017</td>
<td>16.2</td>
<td>54.5</td>
<td>54.5</td>
<td>6.74</td>
<td>11.58</td>
<td>105.4</td>
</tr>
<tr>
<td>25 December 2017</td>
<td>12.6</td>
<td>49.4</td>
<td>49.4</td>
<td>7.25</td>
<td>11.85</td>
<td>97.5</td>
</tr>
<tr>
<td>17 January 2018</td>
<td>9.7</td>
<td>49.9</td>
<td>49.9</td>
<td>8.01</td>
<td>12.48</td>
<td>103.9</td>
</tr>
<tr>
<td>20 February 2018</td>
<td>7.4</td>
<td>45.7</td>
<td>45.7</td>
<td>7.85</td>
<td>12.16</td>
<td>106.5</td>
</tr>
<tr>
<td>30 March 2018</td>
<td>9.7</td>
<td>43.8</td>
<td>43.8</td>
<td>7.79</td>
<td>12.23</td>
<td>102.9</td>
</tr>
<tr>
<td>16 April 2018</td>
<td>10.9</td>
<td>26.1</td>
<td>26.1</td>
<td>7.56</td>
<td>12.30</td>
<td>109.2</td>
</tr>
<tr>
<td>24 April 2018</td>
<td>11.1</td>
<td>29.6</td>
<td>29.6</td>
<td>7.01</td>
<td>11.91</td>
<td>104.7</td>
</tr>
</tbody>
</table>

Table 5. Passage efficiency for different fish species at the Incirli brush fish pass

<table>
<thead>
<tr>
<th>Fish species</th>
<th>Number of tagged fish</th>
<th>Number of fish detected</th>
<th>Passage efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>55</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>A</td>
<td>96</td>
<td>32</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>99</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>18</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>S</td>
<td>40</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>P</td>
<td>65</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>373</td>
<td>82</td>
<td>55</td>
</tr>
</tbody>
</table>

(50%; Table 5). In the brush fish pass, the length of fish detected at the entrance antenna ranged between 95.0 and 283.0 mm (mean ± s.d., 142.18 ± 2.92 mm), whereas the length of fish detected at the upstream antenna ranged between 95.0 and 218.0 mm (mean ± s.d., 149.2 ± 2.8 mm). Analysis of variance (ANOVA) test results showed that fish size is not significant for brush fish passage efficiency (ANOVA, \( F = 0.541; \) d.f. = 2, 537; \( P = 0.582 \)). The data reveal that the brush fish pass allows the passage of small-bodied fish (total body length <15 cm; Fig. 13), which is in agreement with the fish monitoring data of Landesumweltamt Brandenburg (2007) and Schmalz and Thürmer (2012). However, the efficiency of vertical-slot and nature-like fish passages depends on fish size (Peter et al. 2017). Moreover, Weibel and Peter (2013) found that block ramps with slopes of \( .5\% \) are ineffective for small-sized cyprinid species. In this study, the brush fish pass was not size selective even for a bed slope of \( 10\% \). The ascending times of the tagged fish passing through the brush fish passage are provided in Table S1, available as Supplementary Material to this paper. The ascending (passage) times of the fish varied from 15 min to 26 days. It is thought that water temperature, flow rate and fish species have an effect on fish ascending times. However, the sample size in

Fig. 13. Total body length (\( L_f \)) distribution for tagged fish and fish detected at the downstream and upstream antennas. Boxes indicate the interquartile range, the horizontal lines inside the boxes indicate median values, whiskers indicate maximum and minimum values and symbols indicate outliers. The number of tagged fish per species is given in Fig. 6.
this study is not sufficient to enable statistical tests to be performed investigating the effects of these parameters on fish ascending times. We found that mean ascending times differ for different fish species, and calculated the following mean times to negotiate a single fishway (Table S1) and there are multiple barriers along its path to spawning grounds, the fish may never arrive at the spawning grounds in time to reproduce. Moreover, we found that mean ascending time did not differ between smaller fish, by species, compared with bigger fish. Sample drawings from the labelled fish trajectories in the fishway plan are shown in Fig. 14. Fish motivation was not measured in this study. It was observed that fish use the backs of the brush blocks, regions characterised by reduced velocity and TKE, as resting areas. Fish move through the brush blocks by following the main flow, which is beside the small brush block (Fig. 14a, b). In addition, the bottom macro rough elements were important for P. rizeensis to move through the structure (Fig. 14c). B. tauricus selected a completely different trajectory to traverse the fishway (Fig. 14d), namely beside the side wall, which is characterised by high local velocity due to jet formation. In response to these local flow conditions, the tail beat frequency of the fish increased by a factor of ~3 from 11 to 30 Hz. This finding implies that local flow conditions may have important effects on individual fish movement and fish tail beat frequency (i.e. energy expenditure). The spawning period of Salmo coruhensis is between November and February. Therefore, spawning migration activities are expected to occur between October and March. However, in this study, tagged S. coruhensis individuals were observed in the fish passage in April, May, October and November (Table S1). The movement of S. coruhensis in the fish passage in April and May is not related to spawning migration. Fish in streams and rivers migrate for spawning, feeding or other purposes, such as hiding and finding suitable habitats. Therefore, S. coruhensis may use the fish passage for other purposes in addition to spawning migration. In addition, the main aim of this study was not to investigate spawning migration. We focused on the flow structure of the brush fish pass considering the passage performance of fish species. Fish trajectory data provide important information for understanding the behaviour of a fish inside the fish
pass. Fish trajectories were labelled manually from 12 different videos, are not average values and were selected to show the fish kinematics of different species.

Conclusions
Efficient fishway design has become increasingly important with growing human activity at a global scale in riverine environments. The lack of adequate data and tools for identifying biological, hydraulic, and other physical parameters is the main challenge in fish passage design. In this study, the field measurements reveal that a wide spectrum of different flow characteristics is provided in a diagonal brush fish pass. It is expected that the fish seek convenient corridors and avoid zones not suitable for their migration preferences. The maximum velocity measured (1.5 m s\(^{-1}\)) is well below that set for fish passage (2.0 m s\(^{-1}\)).

Moreover, we compared our results with those of conventional fish passage structures. Most international standards (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014) recommend that \(\Delta P\) should not exceed 200 W m\(^{-3}\). However, the findings of this study reveal that this threshold value is not a relevant criterion for the brush fish pass because a significant amount of energy is dissipated in brush the blocks with the vibration and bending of the bristles, which enables energy transfer from the main flow to the bristles. Hence, in this case energy dissipation cannot be an indicator of turbulence in the same manner as in technical fishways. Moreover, compared with nature-like and vertical-slot fish passes, spatially averaged TKE in the basin was considerably reduced for the same dissipated power. Froude number has also been used as a reference parameter for migration corridors and resting areas of fish. The area behind the brush blocks was characterised by low Froude numbers, and these areas can be used by fish as potential resting zones and refuges. The bristles, as energy absorbers, represent a cost-effective option that can be retrofitted at any time to existing structures to improve the hydraulic conditions for fish passages.

Satisfactory passage efficiencies were found through the brush-type fish pass for fish species endemic to Turkey.

Conflicts of interest
The authors declare that they have no conflicts of interest.

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