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Remediation design to improve culvert passage for small-bodied fish

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ABSTRACT: Culverts that impede or inhibit fish migration are, among other river structures, a growing concern in habitat conservation efforts globally. Small-bodied fish species, which are often weaker swimmers than larger specimen, can be impacted by shallow depths and high water velocities encountered in culverts. Retrofitting of culverts is commonly used to enable fish migration. Here, we present a fish friendly remediation design, imitating filamentous algae, and discuss the suitability for fish passage. We describe how instantaneous turbulent flow structures can be assessed for the remediation design. The studied remediation design is a dense layer of filamentous algae that has been observed to provide small-bodied whitebait with a means to overcome an almost vertical weir. We describe a laboratory model that is used for flow field quantification.

1 INTRODUCTION

Culverts and other channel-like structures in natural river flows are capable of interrupting the migration patterns of fish. While unimpeded fish passage is not generally expected during high-flow events (i.e. floods), such river structures can make even low- to medium-flow regimes impassable for fish. As they are streamlined for discharge, culverts typically feature smooth inverts, with no provisions in place to slow down or diversify the flow of water. The resulting flow causes high water velocities that are relatively uniform throughout the cross-section. At the same time, this also reduces water depth, preventing fish with deeper bodies from propelling themselves upstream.

Culverts can also be slightly raised from the riverbed, constricting the available cross-section, resulting in a significantly sped-up flow (O'Shaughnessy et al., 2016). Therefore, flow requirements for fish are often not met inside culverts, preventing upstream migration. Additionally, perched entryways can also prevent upstream migration, yet are not discussed herewith.

Culverts are primarily designed to provide a specific discharge. Changing the roughness of the culvert by improving the flow inside the culvert to accommodate fish will invariably lead to reduced discharge capacity during high-flow events, increasing the risk of floods. Additionally, during high-flow events, fish passage is naturally impeded (NIWA, 2015), and the roughening likely is not beneficial.

Increased shear forces introduced by increased roughness can also cause turbulence in the flow that fish cannot cope with (Goodrich et al., 2018). Introducing increased roughness elements that have not been thoroughly tested on target species should be avoided. More recently, studies have taken to investigate ethohydraulics, the interaction of fish swimming with the flow field that surrounds them (e.g. Trinci et al., 2017, Romao et al., 2017).

Here we introduce an alternative remediation design than conventional roughness elements. Observations of fish swimming in nature have shown that a dense layer of filamentous algae can provide small-bodied fish to overcome steep obstacles. We describe how such an observation can be transferred into a laboratory model and how flow fields can be obtained and studied. Quantifying flow information is essential to relate to observed fish swimming for the study of ethohydraulics.

2 REMEDIATION DESIGN

The design tested in the flume is a recreation of a dense layer of filamentous algae (unknown species), which has been observed to help īnanga/common galaxias (*Galaxias maculatus*), a widespread diadromous Southern Hemisphere species, to overcome an almost vertical weir (h ≈ 0.8 m) at the Waiwhetū Stream near Wellington, New Zealand (from personal correspondence with Grant Webby of Friends of Waiwhetū Stream). We see the main advantage in filamentous algae in their capacity to slow down the flow in a small permeable region of the stream, which can then be utilised by fish, limited by their body sizes depending on the thickness of the algae layer. A filamentous algae species that can provide these benefits is, e.g. *Chlorophyta Microsporales*. However, for experimental and remediation purposes, growing and using natural algae was not seen as practical, due to the growth duration and requirements, as well as their susceptibility to mechanical damage. An algae analogue is required to satisfy the needs of experimental and practical applications. For example, a human hair is of a comparable thickness (~50μm) and flexibility as filamentous algae, but of higher density than water and more resilient to mechanical stresses. For reasons of simplicity, a polyester-based hair imitation was chosen, with thickness and flexibility similar to human hair, however with a mass density closer to algae ($\rho \approx 0.9$ g/cm^3). For practical applications, a biodegradable/natural solution should be preferred.

In experimental testing, the polyester fibres with a thickness of $t \approx 40$ μm are arranged in rows of bunches of ~900 fibres each, with a length of approximately $l \approx 150$ mm. Rows are spaced apart at $a = 100$ mm axis to axis in the downstream direction. The overlap of ~50 mm ensures a continuous layer of fibres. Fibre bunches are held in place by tube mounts, embedded in an 18 mm thick baseplate. In total, eight rows with 15 bunches each are used, resulting in a length of $L = 85$ cm. The width of the design is $W = 54$ cm, which puts fibre density at an average of ~235 000 fibres/m^2. With the present design, the deflected fibre layer protrudes about 40 mm from the bottom of the baseplate, subject to water velocities. A schematic of the set-up is shown in Figure 1, and a side view of the set-up in the flume is shown in Figure 2.

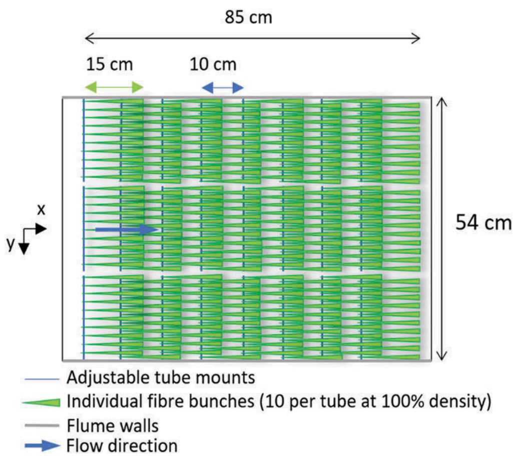

Figure 1. Schematic of experimental design ‘algae analogue’ positioned in a 540 mm wide flume.

Figure 2. Side-view of the remediation design in the flume.

3 METHODOLOGY

Any roughness element, such as the introduced remediation design that is placed into a flow, will increase shear forces and thus turbulence (Liu et al., 2008). As has been pointed out in Knapp et al. (2019), not only does turbulence intensity affect fish swimming, but it is also widely accepted that turbulence length scale has significant effects on destabilisation and displacement in turbulent flows, with larger sized and more energetic eddies being more likely to be detrimental to fish swimming. Investigating and understanding the effects of turbulence structures on fish swimming may, therefore, help develop more efficient remediation designs, that have a lower impact on average water velocities and consequently discharge.

For the investigation of the flow field and turbulent structure that surrounds the algae, a method that allows capture of instantaneous velocities within a large area is required. Particle Image Velocimetry (PIV) has been well established in hydraulic research and is suited for this application (a more accurate account of PIV can be found in Raffel et al. (2018)). For PIV, light is emitted in a thin sheet and reflected off particles of specific size and density suspended in and moving faithfully with the flow. This reflected light is then captured by an onlooking camera and by comparing adjacent frames the displacement of particle groups, and thus the local velocity of the flow within a window of predetermined size (so-called interrogation window), can be calculated. Accurate capturing of fastmoving flows is only possible with short relative exposure times in order to reduce motion blur of the particles, which in turn means a low signal to noise ratio in the captured image. This reduced intensity requires high-intensity light sources, to compensate, and that usually means using light sheets generated by high powered pulsed lasers.

The use of high-powered lasers poses specific challenges, especially when researching fish swimming behaviours, such as the complexity of the set-up, health and safety requirements, costs, or the potential of injury to the fish. Therefore, we opted to use a continuously active LED generated light sheet to ensure compatibility with later live experiments. Adjustments in particle size and composition (HDPE in combination with a non-toxic fluorescent dye with a mean particle diameter of $\emptyset = 340$ μm) helped overcome the challenges this imposes on exposure times and light intensity. In our preliminary testing, we calculate flow fields from the image data obtained using the experimental design using the PIVlab toolbox (Thielicke & Stamhuis, 2014a, 2014b) for MATLAB (v.9.7 R2019b). Images were pre-processed using the built-in options in PIVlab (CLAHE + Highpass filter + denoise filter) and processed in 3 steps, down to an interrogation window size of 2 cm which was deemed enough for initial testing purposes. The chosen interrogation windows size results in a vector distance of 1 cm due to the 50% overlap of interrogation windows. Vector validation was performed using fixed velocity limits and with a standard deviation filter (threshold 7) as well as a local median filter (threshold 2, epsilon 0.1 as per the recommendations given by Westerweel & Scarano (2005)). Filtering resulted in up to 10% of individual vector data being removed from the results on average, which aligns well with the filtering results discussed by Westerweel & Scarano (2005). Results were exported in ASCII format and subsequent filtering, applying a custom MATLAB script, was used to remove any outlier results files in which more than 20% of data had been removed to reduce the likelihood of bad samples in the end-result. For calculation of averaged velocities, no interpolation of vector data was applied.

Preliminary testing occurred at d = 10 cm water depth (measured at the downstream edge of the canopy at x = 850 mm from the leading tube mount) at a flow rate of Q = 15 l/s, resulting in averaged streamwise water velocities of u_m = 0.28 m/s for the given cross section creating a deflected vegetation canopy height of h ≈ 4 cm. The chosen parameters are similar to other studies that investigate vegetation canopy flows, as listed in Table 1. Data was captured for 180 seconds at a constant interval of Δt ≈ 6.66 ms (equivalent to 150 frames per second) to ensure enough samples remain (> 120 seconds) for statistical averaging after filtering was applied.

4 RESULTS AND DISCUSSION

Initial results for an averaged velocity profile obtained for y = 100 mm and x = 850 mm are displayed in Figure 3. The velocity profile is compared with data obtained by Poggi et al. (2004), for both a low density as well as a high-density canopy consisting of rigid cylindrical rods.

The obtained data aligns well with the high-density case in the region of the canopy interface (0.75 < z/h < 1.5) and a velocity inflexion is observable just below the limit of the canopy (0.75 > z/h > 1) suggesting a mixing layer flow rather than a pure boundary layer flow (Raupach et al., 1996). Within the canopy, significant velocity differences can be observed, with a steeper velocity drop off towards the bottom boundary than in the comparison data. This difference can be explained with the configuration used by Poggi et al. (2004) which provides more spacing in between roughness elements and therefore likely a lower overall roughness within the canopy.

Quadrant analysis on the obtained turbulence data can provide more insight into the incidence of ejection and sweeping events inside and outside of the canopy layer, which in turn may inform design decisions focused on the improvement of fish swimming.

5 OUTLOOK AND CONCLUSIONS

The remediation design under investigation shows some resemblance to results for high-density canopies (Poggi et al., 2004), studying velocity inflexion between the canopy layer and

Table 1. List of studies investigating vegetation canopy flow.

Publication	Flow depth [m]	Average water velocity [m/s]	Canopy type [-]	Canopy height [m]
(Biggs et al., 2019)	0.35–0.4	~ 0.1–0.2	Natural filamentous algae	~0.1–0.4
(Marjoribanks et al., 2017)	0.32	0.3	Flexible cylindrical stems	0.15
(Poggi et al., 2004)	0.6	0.3	Rigid cylinders	0.12
(Jalonen et al., 2013)	0.23	0.1–0.9	Artificial poplars (foliated elements)	0.23
(Nikora et al., 2013)	~0.05–0.4	0.05-0.6	Artificial flexible grass	~0.04

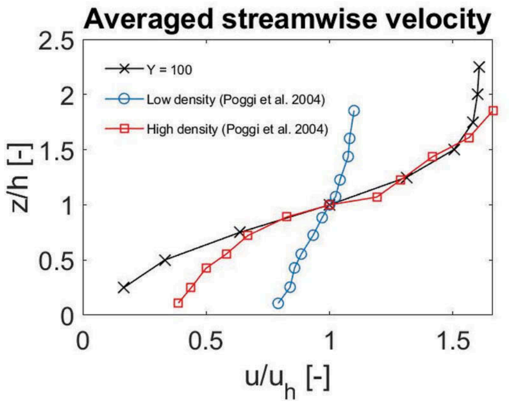

Figure 3. Averaged streamwise velocity with Q = 15 l/s obtained at y = 100 mm and x = 850 mm; Compared to low and high-density canopy data obtained by Poggi et al. (2004); Results normalised by canopy height h and streamwise velocity at canopy height u_h.

the free stream layer for a rigid design and observed spikes of turbulence and shear stress at canopy level. The observations would suggest a less pronounced occurrence of Kelvin-Helmholtz instabilities at canopy level, due to the reduced velocity inflexion. The occurrences of turbulence which are relevant for fish swimming, created by these Kelvin-Helmholtz instabilities at canopy level, will receive more attention in the ongoing experiments. Furthermore, as this is a design intended for remediation, the effects on hydraulic discharge efficiency for a culvert or culvert-like structures need to be investigated. Our flexible design provides challenges for flow data collection and averaging of flow field information, which we described in our methodology. Further testing is required to improve the introduced methodology, and further research is required to determine the effect of fibre density on a non-continuous canopy layer.

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