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FISH PASSAGE HYDRODYNAMICS: VALIDATION OF AN AT-SCALE EXPERIMENTAL FACILITY FOR ETHOHYDRAULIC STUDIES OF SMALL-BODIED FISH IN CULVERTS

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ABSTRACT

This paper introduces a new experimental setup for ethohydraulic research at the University of Auckland, specifically studying the interaction between hydrodynamics and fish behavior. Many countries, particularly island nations, are home to diadromous fish species that migrate from marine into riverine ecosystems at an early life stage. On their journey upstream fish can encounter various man-made obstacles, of which culverts are one of the most prevalent. As the number of existing culverts is too high to afford reconstruction of all barriers in the short term, remediation presents itself as a more efficient alternative. However, reconciling remediation with the passage requirements for small-bodied fish is challenging. Current best practices focus on averaged parameters, such as fish swimming endurance or average water velocities in the culvert cross-section. This approach disregards the individual capabilities of fish to deal with turbulence. To understand the interplay of fish locomotion with small-scale flow features in a controlled and replicable manner, an experimental facility to simulate culverts with various design features and discharge rates is presented. We describe the experimental design, validation methods and measurement techniques to be applied. The at-scale design is aimed at complementing field studies, ensuring comparability to large-scale prototypes. Use of parallel setups of, for example, culvert designs within the same flume, is discussed with respect to entrance efficiency as an important aspect of fish passage. Results obtained will inform passage guidelines for small-bodied fish, giving consideration to turbulence effects that can benefit or destabilize fish swimming, and utilization of small-scale low-velocity zones.

Keywords: Particle image velocimetry; inanga (*Galaxias maculatus*); ethohydraulics; culvert remediation

1 INTRODUCTION

Freshwater migration of fish species is largely dependent on longitudinal connectivity, to provide unhindered up- and downstream passage. In regards to river connectivity, potamodromous and diadromous species, that migrate through freshwater once during their life, are of primary concern. Blocking fish migration can have severe effects on the respective ecosystem, as well as on human society that relies on fish as a food source.

Structures that have been built in and along rivers in the past often impede, or completely prevent, the migration of fish species up and down rivers. While river structures are a necessary component of water infrastructure, the importance of enabling fish passage at these structures has received broader attention in recent decades. This has resulted not only in an increased scientific interest in understanding how and why fish migrate and what measures we can take to enable their unhindered ascent and descent, but also the implementation of said measures into nationally and even internationally binding regulations, such as the Water Framework Directive 2000/60/EC of the European Union (EU). However, it has also been recognized that measures that work effectively for one species, or family of fish, may be entirely ineffective for another (Silva et al. 2018). Because of this, national or regional approaches often have to be developed that are distinct from broadly used industry standards.

1.1 New Zealand context

In New Zealand, thousands of structures exist that impede or prevent fish migration, which presents a problem, as New Zealand is also home to dozens of diadromous fish species. It has been found that international research, which often focuses on members of the family Salmonidae, is not always applicable to New Zealand species (Baker and Boubee 2006; Noonan et al. 2012). Because of this observation, increasing efforts have been made in research and regulation to ensure the re-establishment and maintenance of river continuity for native species. This effort is probably most evident in the recent release of the first national guidelines on fish passage (Franklin et al. 2018).

The purpose of the research facility described here is to better understand fish behavior during fish-passage in order to improve remediation of culverts. This research is of particular significance for New Zealand, as in recent years a decline of the majority of New Zealand freshwater fish has been observed (Dunn et al. 2018), among them several members of diadromous species, e.g. of the genus Galaxias. The juveniles of these diadromous Galaxias species are commonly known as whitebait in New Zealand, and of these *G. maculatus* (colloquially called by their Maori name īnanga or īnaka in New Zealand) is the most widespread and common. *G. maculatus* is also relevant to Australia, where the juveniles are known as whitebait as well, and to coastal regions of Southern America, where they are known as 'puyen-chico' or 'puye' (adults) and 'cristalinos' (juveniles), which refers to the translucent appearance of the juveniles (Vega et al. 2018).

Culverts, particularly at road crossings, are among the most prominent migration barriers, not just in New Zealand, but globally. It is therefore crucial to gain more insight into the swimming habits of *G. maculatus* concerning complex flow fields that they can encounter within these culverts. A testing facility in the Water Engineering Laboratory of the University of Auckland has been explicitly designed to address this knowledge gap. The testing facility provides enough room and sufficient flow rate to study fish swimming during migration and is also capable of emulating culverts typically found in the field.

From the insight gained from the experiments it is intended to derive design principles, which can tie into and improve upon the current understanding of fish pass design in New Zealand, not just for *G. maculatus*, but ideally for other small-bodied fish species as well.

This paper's aims are:

- To describe the configuration of a research facility at the Water Engineering Laboratory at the University of Auckland, fit for the purpose of ethohydraulic research into small-bodied fish when navigating individual flow features and during passage through culverts;
- To discuss the various requirements for culvert remediation approaches within the requirements for fish passage design;
- To provide an overview of suitable turbulence measurement techniques.

2 EXPERIMENTAL SET-UP

2.1 Configuration

An acrylic-glass recirculating flume with a length of L_f = 18.61 m, width of w = 540 mm and height of h = 580 mm is used. The central staging area, for observation of flow features and fish, has a length of L_t = 7 m, allowing not only observation of fish swimming in response to isolated flow features, but to implement lengths of culverts commonly found at road crossings (e.g. Kelly and Collier 2007) for holistic ethohydraulic studies. Choosing this length enables results that are transferable to practical application without having to consider scale effects. The substructure of the flume is hinged on a central bearing and, using electro-mechanic lift jacks installed underneath, the overall slope is adjustable between 0 and 1 %. While a flume slope of 1 % covers most slopes of natural river beds that are relevant to fish migration, fixtures in the staging area allow for further adjustment of the slope to account for culverts that are not aligned with the naturally occurring slope.

Recirculation is required for the use of particle image velocimetry (PIV) – a measurement technique for flow field capture that is discussed later – as otherwise continuous seeding of the required particles would be required. The return channel consists of a DN250 tube, with an integrated electromagnetic flow meter (Krohne optiflux 2000 DN250). The magflow meter exhibits a measurement error δ = 0.5% provided the water velocity is larger than v = 0.5m/s (Q = 0.0245 m^3/s) and a measurement error δ ≈ 1% at a water velocity of v = 0.25 m/s (Q = 0.0123 m^3/s). A variable-speed axial-flow pump, with a rated power of P = 5500 W and a maximum flow rate of Q ≈ 85 l/s, allows for fine adjustment of flow rates. This fine adjustment is necessary to adapt conditions in the flume to the individual requirements of the fish, as they cannot be determined in detail a priori and will change depending on the used culvert designs. In order to provide mobility of the sensor equipment, the implementation of a sleigh, moving along rails straddled on top of the flume is planned. The sleigh houses both the camera sensors for fish tracking and velocimetry, as well as part of the illumination for both. Additional backlighting is required below the flume, which is moved separately. The configuration of the experimental flume is shown in Figure 1.

While initial hydrodynamic testing to establish the conditions and workflow for the operation of the flume and sensor equipment can occur with any cross-section, for actual fish passage testing a circular culvert configuration is preferred. It can be safely assumed that the majority of existing culverts are circular culverts, since the construction costs for pipe culverts can be expected to be lower than for reinforced-concrete boxed culverts (New England Environmental Finance Center 2010). Particularly for short stretches that require no bends, as is typical at river crossings, circular culverts are the more cost-efficient solution and would be selected in the majority of construction cases, where fish passage has not been a major consideration. Overall, circular culverts would pose a far greater threat to fish migration than box culverts and therefore are of considerable interest to research.

Acrylic glass half-pipe or, should larger diameters be required, quarter-pipe inlays can be used to emulate circular culverts at low to medium flow rates. Should higher flow rates be required, e.g. estimation of the effect of individual culvert designs on discharge capacity in a filled culvert (pressurized flow), full-pipes are necessary. However, such a configuration may impede observation inside the culvert and will in most cases not be suitable for observing fish traversal, as passage in the field does not need to be provided at all times, i.e. not during high discharge events. The flume allows for the parallel setup of two culverts, via a centrally mounted separator. This has the added benefit of being able to let fish choose between their preferred design and directly compare the designs in regards to ascension rate and time, similar to the procedure detailed by (Enders et al. 2017). In order to determine discharge rates for both separated channels, two v-notch weirs can be installed upstream of the staging area. An overview of several previous experiments focused on hydraulic performance of culverts, fish passage rates, fish swimming performance and fish traversal through a culvert is provided in Table 1. The parameters of the research facilities used in these experiments provided a broad guideline on the configuration of the flume setup presented here.

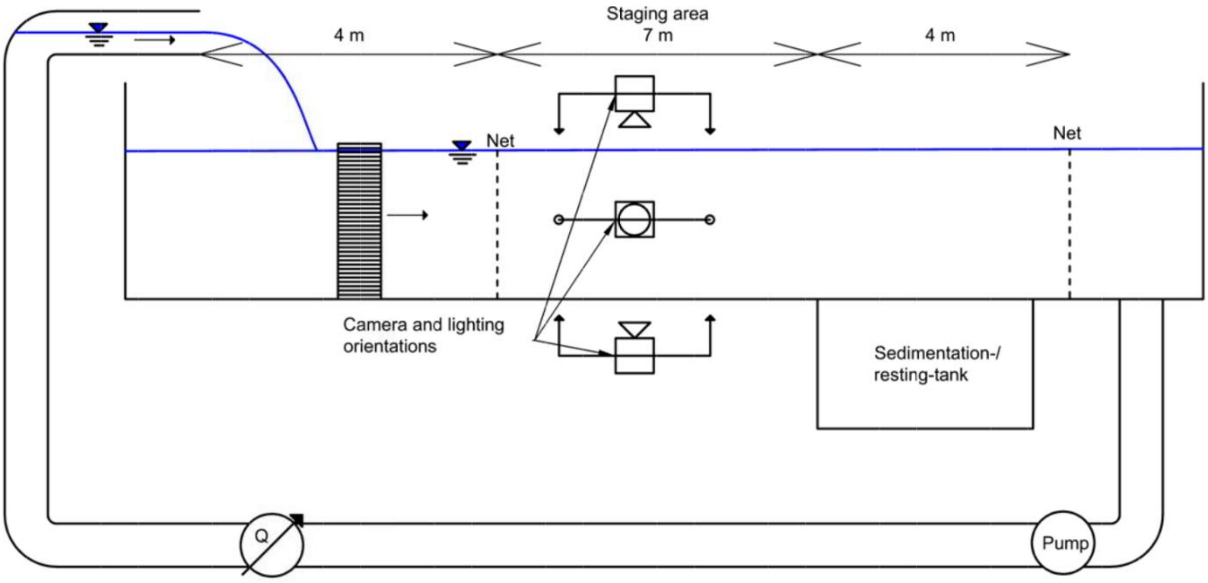

Figure 1. Flume setup.

Table 1. Overview of fish passage experiments. Step sizes indicated in parentheses where applicable.

Experiment type	shape	diameter or width w	length L_t	baffle types	flow rate Q or mean velocity ū	specimen used
	[–]	[m]	[m]	[–]	[dm³/s], [m/s]	[–]
(Ead et al. 2002) culvert hydraulics	round	0.29 to 0.57	~6.20	offset, (slotted) weir, spoiler, alberta fishweir and fish baffle	N/S	none
(Nikora et al. 2003) swimming performance, traversal	box	0.19	0,8	none	ū = 0.1; ū = 1.0	*G. maculatus*
(Lupandin 2005) swimming performance	box	0.08	1,2	none	Q_{max} = 3.7	*Perca fluviatilis*
(Baker and Boubee 2006) culvert hydraulics, passage, traversal	box	0.20	1,5	gravel, sand, nylon brush, Miradrain and Cordrain (core)	Q = 0.26; 1.1	*G. maculatus, Gobiomorphus huttoni*
(Plew et al. 2007) culvert hydraulics, swimming performance, traversal	box	0.405	0,83	none	ū = 0.4; 0.48; 0.6	*G. maculatus*
(Tonkin et al. 2012) passage	round	0.35	3; 6	mussel spat rope	Q = 0.9 to 1.04	*G. huttoni*
(Olsen and Tullis 2013) culvert hydraulics, passage	round	0.61	18	weir and corner baffles	Q = 18 to 131	*Salmo trutta fario/ lacustris*
(Baker 2014) culvert hydraulics, passage, traversal	box	0.20	3 to 6 (1.5)	Miradrain (core)	Q = 1.1	*G. maculatus, G. huttoni*
(Goettel et al. 2014) passage, traversal	box	0.50	3,3	alternating brick groups	Q = 2.9; 3.4; 4.3	*Rhinichthys obtusus*
(Duguay and Lacey 2015) culvert hydraulics	round	0.254	4,11	(slotted) weir and spoiler baffles	Q = 25 to 45 (2.5)	none
(Enders et al. 2017) culvert hydraulics, passage	box	0.80 x 2	18	vertical baffles and horizontal baffles	Q = 630	*Alosa pseudoharengus, Salvelinus fontinalis*
(Khodier and Tullis 2017) culvert hydraulics	round	0.57	18,3	horizontal baffles	Q = 28.3; 56.5; 85	none
(Link et al. 2017) swimming performance, traversal	box	0.40	0,65	none	ū = 0.49	*Basilichthys microlepidotus, Cheirodon galusdae*

2.2 Design approaches for minimally invasive remediation

Culvert designs streamlined for discharge efficiency often lead to high velocities in the culvert, preventing weaker fish from passing upstream during periods of increased discharge. Overall reduction of water velocities, through baffles or other rough linings, on the other hand, is undesirable from an economic point of view, as this also significantly reduces the performance of the chosen culvert cross-section for water conveyance. Culvert remediation must balance these conflicting requirements to satisfy both discharge capability, as well as passability by a particular species or even a range of species. Locally confined low-velocity zones are thought to play a significant part in the successful upstream passage of fish and can have a smaller effect on discharge capacity than an overall reduction of water velocities would have (Zhang and Chanson 2018). Localized low-velocity zones can, for example, be created with the use of isolated roughness elements, that protrude into the flow, i.e. baffles, and elements that cause a distributed increase in wall roughness in a linear or laminary fashion, in order to create a continuous layer (in flow direction) with reduced water velocities.

The previously mentioned observations are relevant for *G. maculatus*, as their upstream climbing/swimming ability in high-velocity streams is usually considered to be poor (Boubee et al. 2000; Richardson and Taylor 2002) as juveniles all of the five whitebait species are comparatively weak swimmers. However, when observing the behavior of young whitebait migrating upstream at St Ronans weir in the Waiwhetu river, which is shown in Figure 2, it was found that they were able to climb an almost vertical incline. For the non-climbing whitebait species this is a considerable challenge to overcome and can most likely be explained by the thick layer of algae on the back of the weir, which provides a permeable layer with much-reduced water velocities. In a highly turbulent flow, such a permeable layer could provide a means for small-bodied fish to migrate while minimizing the effects on the discharge rate and therefore be a useful approach for remediation.

Figure 2. St Ronan's weir at Waiwhetu river (h ≈ 0.80 m) with a thick layer of algae (picture: Friends of Waiwhetu Stream).

3 VALIDATION AND MEASUREMENT METHODOLOGY

3.1 Hydrodynamics

In order to ensure the accuracy of measurements and minimal influence from the inlet and other external factors, validation of the experimental facility is carried out via individual measurements using an acoustic Doppler velocimeter (ADV). The primary method of validation is the comparison of water velocity distribution and fluctuations between similar flow cross sections. In order to be able to compare cross sections, the expected behavior of the flow field within the region in question has to be known. A fully developed uniform velocity profile for an open channel flow is characterized by a constant averaged velocity profile along the length of the flow (Akan 2006) in x-direction (Figure 3). Consequently, individual measurements in different lengthwise (x-axis) locations taken at otherwise identical spanwise (y-axis) and vertical (z-axis) coordinates should result in identical average velocities for each measurement point. Comparing these velocity profiles allows identifying the extent of fully developed open channel flow within the facility. With average velocity unchanging, other flow parameters can be examined and compared between cross sections. For this purpose, the fluctuating velocity component of the flow for each point in time is extracted from the instantaneous velocity, via subtraction of the average flow velocity as shown in Eq. [1]. The obtained turbulent fluctuation component lends itself to further comparison of turbulence between different cross-sections and over different data sources. For an initial source of turbulence, it can be expected that turbulent kinetic energy and turbulence strength would dissipate over time due to the transfer of turbulence energy towards smaller turbulence length scales and subsequent viscous energy dissipation through heat. For an idealized and fully developed open channel flow, turbulence is caused by shear stresses at the walls of the channel and the water-air interface at the open boundary. While disregarding external disturbances, it can for constant channel geometry and wall roughness, therefore, be assumed that turbulence strength u'_{RMS} turbulence intensity T_I and turbulence kinetic energy T_{KE} (Eq. [2] to [4]) remain constant throughout the region of fully developed open channel flow (Figure 4). Statistically steady turbulence can also be assumed for the individual velocity components u v and w, rather than velocity magnitude **v**(x,y,z).

$$u'(t) = u(t) - \overline{u(t)} \quad [1]$$

$$T_{KE} = \frac{1}{2} \cdot \left(\overline{(u'(t))^2} + \overline{(v'(t))^2} + \overline{(w'(t))^2}\right) \quad [2]$$

$$u'_{RMS} = \sqrt{\left(\overline{(u'(t))^2} + \overline{(v'(t))^2} + \overline{(w'(t))^2}\right)} \quad [3]$$

$$T_I = \frac{u'_{RMS}}{\bar{u}} \quad [4]$$

Consequently, the difference of these turbulence metrics between cross sections should be zero for idealized open channel flow and any deviation from it would have to be caused by unwanted effects such as manufacture and assembly tolerances, deformation of the channel geometry, inlet turbulence proliferating downstream through the flume or measurement error.

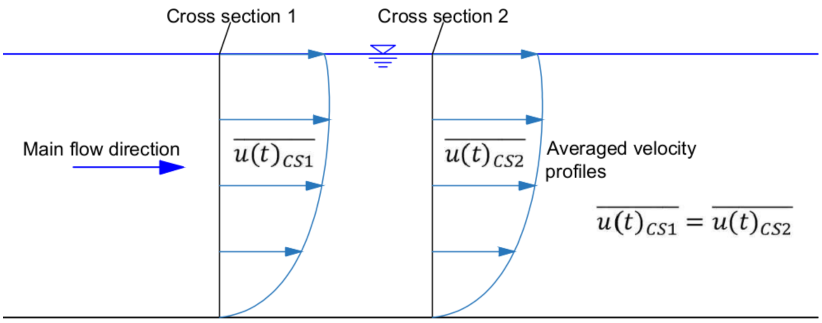

Figure 3. Schematic of constant averaged velocity profiles at different cross sections in a fully developed open channel flow.

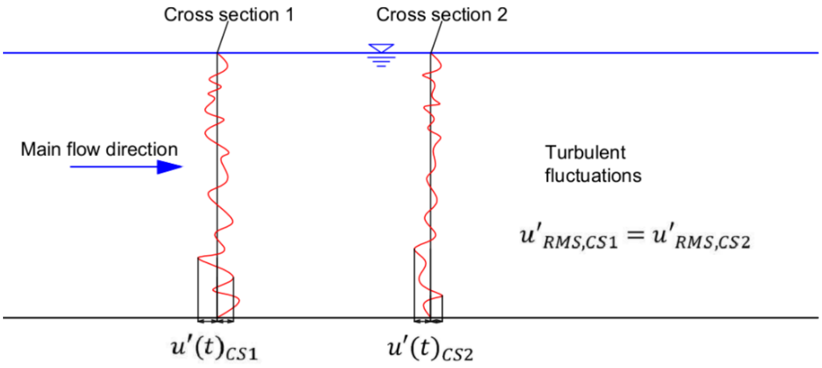

Figure 4. Schematic of instantaneous turbulent velocity fluctuations at different cross sections in a fully developed open channel flow.

3.2 Particle Image Velocimetry

In order to correlate fish swimming behavior with individual flow features, it is required to capture the instantaneous flow field in a vast spatial region. Particle image velocimetry (PIV) and particle tracking velocimetry (PTV) fulfil this requirement and are, apart from the necessary seeding of the flow, nonintrusive, as they are based on optical observation. Both PIV and PTV are closely related, having in common that light from an external source is reflected off particles in the flow and captured by an external camera system. PIV cross-correlates groups of particles between image pairs and calculates a vector field for a pre-determined grid size (Eulerian flow field) from the displacement. PTV, on the other hand, correlates individual particles between image pairs, visualizing the path each particle travelled (Lagrangian flow field). From these paths, a Eulerian flow field can be interpolated.

Initially, the capture of the flow field is achieved in a thin slice vertically aligned with the flow, capturing only the x (aligned with the flow) and z (vertical) components of the flow field (Figure 5). This setup is similar to the one described by Link et al. (2017), which was used to capture the horizontal vortex shedding behind a vertically aligned cylinder. If vertically aligned vortices are to be captured, the orientation of the light sheet has to be vertical as well. The sensor configuration for this is straightforward, with a light sheet generated from above or below the flume and a single camera capturing the light that is bouncing off the seeding particles from the side. This 2-dimensional 2-component (2D-2C) particle image velocimetry is initially used to establish the suitability of the available equipment and set-up for flow field capture and to measure individual flow features that can be reduced to a 2-dimensional problem (Figure 5). To observe the complex flow fields that can be generated in a culvert, eventually, all three spatial components of the flow field have to be captured, known as 3-component particle image velocimetry. Stereoscopic particle image velocimetry is a relatively cost-efficient way of achieving this, while the capture of the three components itself still happens within a thin light shield and is therefore still considered 2-dimensional (2D-3C).

The stereoscopic approach is described by, e.g. (Gaydon et al. 1997) and (Jahanmiri 2011). The technique uses two cameras set up at an angle recording the same observation area, which is illuminated by a light sheet, as in 2D-2C. The images can be used to generate velocity vectors, the perspective distortion of which reveals the third missing vector component. This bears the disadvantage of the either decreased common field of view between the cameras (Figure 6) or the non-aligned depth of field plane between the two cameras (Figure 7). Due to the rapid displacement of the particles in relation to their small diameter, the two cameras require precise synchronization via generator locking (genlock) which ensures that images are captured at the same point in time to enable per-pixel stereo matching of the two images. In addition to providing a third vector component, stereoscopy removes the error of vector components parallel to the light sheet, which is introduced by the out-of-plane motion of the particles. This error becomes more significant the further the particle is away from a single camera axis, due to the shift in perspective.

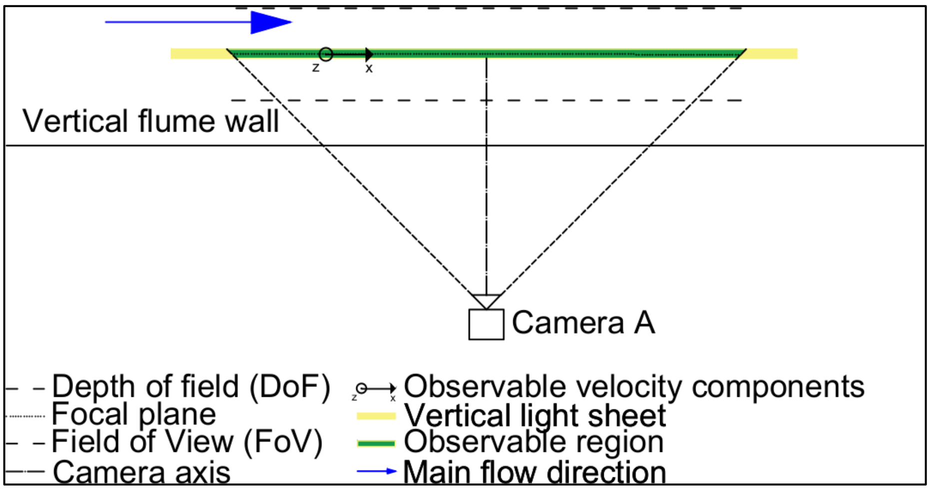

Figure 5. Schematic of the initial set-up for particle image velocimetry with a single camera.

The stereoscopic method represented in Figure 6 is strictly translational, where the optical axes of the cameras are kept parallel. This configuration allows covering a greater observation area within the acceptable depth of field for the camera. The acceptable depth of field is the spatial region in which a captured object creates an airy disc on the image sensor of the camera that is smaller than or equal to the size of one pixel and thus below the resolution capability of the camera. The disadvantage of this is that the size of the common field of view (FoV) of the cameras, in which stereoscopic image capture is possible, needs to be balanced with the distance between the cameras. The distance has an effect on the accuracy of the obtained out-of-plane velocity component, where greater distance results in fewer errors for the obtained vector component. The stereoscopic method represented in Figure 7 combines translation with rotation, this removes the issue with the common FoV at increasing inter-camera distance, but it means that the limiting factor is now the common depth of field (DoF) that is shared by both cameras. As the focal planes are not aligned anymore, this area becomes smaller with increased rotation. The experimental set-up for particle image velocimetry uses a light sheet generated by high-powered LEDs, rather than a laser light sheet, as is typical for particle image velocimetry. The reason for this is the considerable cost of a laser system, as well as the danger the use of high powered lasers poses to both the operator as well as the fish that are to be observed in the flume.

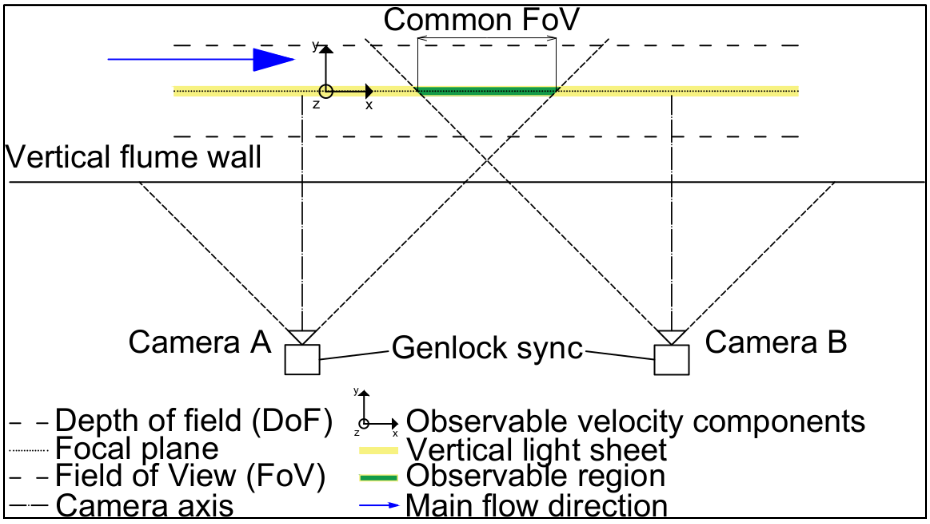

Figure 6. Schematic of stereoscopic particle image velocimetry with pure translation of cameras.

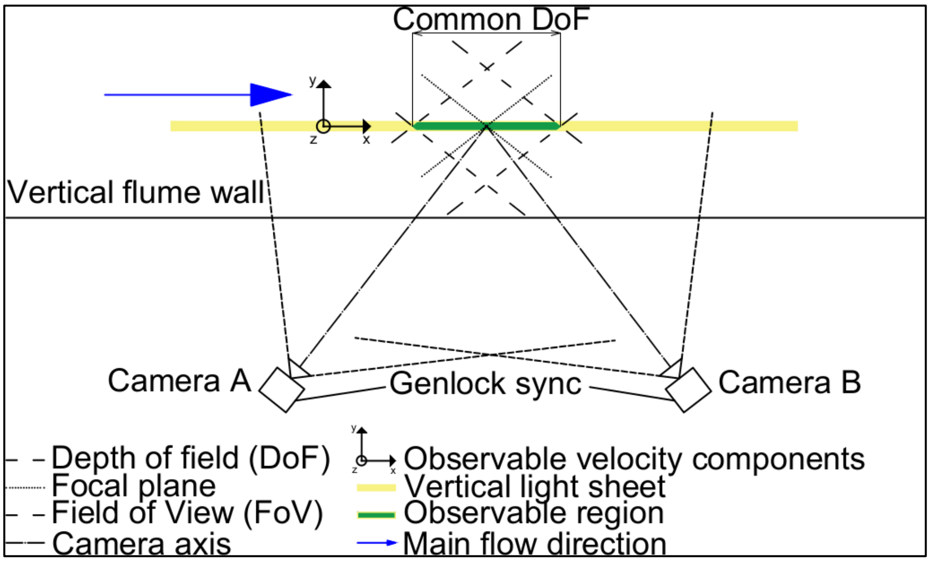

Figure 7. Schematic of stereoscopic particle image velocimetry with rotation and translation of cameras.

To ensure the quality of the PIV results, calibration and systemic errors should be eliminated as far as possible and the results obtained with PIV must be validated. For PIV this is outlined by (Raffel et al. 2018). While erroneous vectors in the dataset are often easily identified by manual analysis of the results, with large datasets, this is no longer practical. For automatic validation several validation algorithms such as standard deviation, velocity limit, or (normalized) median filters are available. These algorithms can filter erroneous vectors based on the overall characteristics of the flow (e.g. anticipated water velocity limits in x, y and z-direction) or the assumption that within a localized flow region changes from one flow vector to the next can be expected to be within specified limits. Filtering criteria have to be adapted to the flow in question, e.g. in compressible flows, where the divergence does not equal zero, larger changes between neighboring vectors may be possible than within incompressible flows, due to changes in volume caused by pressure differences.

4 CONCLUSIONS AND OUTLOOK

A research facility at the Water Engineering Laboratory at the University of Auckland, suitable for conducting ethohydraulic studies correlating fish swimming behavior and small-scale flow features, is described. Validation of the facility by cross-section comparison with the assistance of an ADV is discussed. The implementation of measurement techniques for the capture of instantaneous flow features in high resolution particle image velocimetry is outlined. The flume is used to evaluate *G. maculatus* during swimming, together with the flow field surrounding them, both for individually selected flow features, as well as during traversal through a culvert, as close as possible to how they would encounter them during their migration in the wild.

The objectives of the facility and the methods described in this study include the following:

- Investigate the interaction of small-bodied fish, namely *G. maculatus* with isolated flow features, in particular, turbulence, to further the understanding of the behavior of the species
- Observe and quantify the traversal of *G. maculatus* in an at scale culvert model to obtain data that can directly be applied to culvert design
- Observe and quantify the swimming behavior of *G. maculatus* when schooling in larger groups
- Apply the gained insight to help inform fish passage guidelines for the passage of small-bodied fish and to assist in minimal intrusive remediation techniques for culverts

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