Universidad de Concepción
Dirección de Postgrado
Facultad de Ingeniería - Programa de Magister en Ciencias de la Ingeniería con mención en Ingeniería Civil

Flow in a nature-like fishway and its relation to fish behaviour

FELIPE JUSTO BRETON ANEX-DIT-CHENAUD
CONCEPCIÓN-CHILE
2012

Profesor Guía: Oscar Link Lazo
Dpto. de Ingeniería Civil, Facultad de Ingeniería
Universidad de Concepción

ABSTRACT

Nature-like fishways are hydraulic structures built in order to allow fish to negotiate river obstructions. Being different than common fishways designs, nature-like fishways imitate natural rivers characteristics as they are built using simple materials that are usually present in rivers (such as, rocks, boulders, gravel and wood). Even though there is some experience about the efficiency of this type of fishways, there is a lack of knowledge about the hydraulic conditions found by fish during its migration. The flow may be characterized by applying spatial and point analysis techniques. Point analysis describes the temporal behaviour of hydraulic variables measured at a specific location, and includes autocorrelation, spectrum and quadrant analysis. Spatial analysis assesses the spatial distribution of flow variables averaged in time, including main flow variables (such as water depth, mean velocity, kinetic energy and vorticity) and turbulent variables (such as Turbulent Kinetic Energy, TKE; turbulent intensity, asymmetry, kurtosis and Reynolds shear stresses). In this study, experimental results on the flow field induced by a nature-like fishway are presented, and its relation to fish behaviour is discussed. A rocky-ramp with 5% slope following DVWK (2002) design guidelines was built along a 8.9 x 0.9 x 0.6 m laboratory flume. Acoustic Doppler velocity measurements were taken at 186 locations on a regular grid, at a low, middle, and high discharge. Point analysis consistently shows that the boulder to boulder distance is small enough to disrupt turbulent coherent structures. At boulder wakes the flow showed no predominance of sweep and ejection events, evidencing a good resting place for fish migration. The nature-like rocky-ramp offers a diversity of flow conditions controlled by the geometry of the boulders. This might allow a variety of fishes to develop their own preferred paths which may have different magnitudes of hydraulic variables depending on each particular species. Results compare well with values reported for other standard fishways.

ACKNOWLEDGEMENTS

The author thanks Dr. Christos Katopodis and Dr. Claudio Meier for promoting this collaborative work between University of Alberta and University of Concepción. The author also thanks Dr. Mehran Parsheh for providing the mPST code. This work was partially supported by the Chilean research council CONICYT through grant Fondecyt 1110441 and the Canadian Bureau of International Education through an ELAP scholarship.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Context of this work

Several human impacts threaten the conservation of certain fish species due a decrease or an alteration of the available habitat in rivers. To understand how physical habitat may impact fish conservation it is crucial to recognize its hydraulic properties. Pioneer research has linked ecological variables with different mean hydraulic properties, such as discharge, depth, vertically-averaged velocity, temperature and turbidity. Even though turbulence might be also an important factor explaining fish presence or habitat preferences, it has not been widely included in the analysis yet.

The author started research on this topic during a stay in Canada where he took a course on experimental fluid mechanics and did guided research. There he learned Acoustic Doppler Velocimetry (ADV) theory and practice and was also directed on research about fishways design and its flow field characterization. In Chile he takes part in Fondecyt project 1110441 titled “The riverine floodplain ecosystem: high-resolution spatio-temporal insight of the habitat use dynamics of a fish assemblage”. In this project a high-resolution map of various micro-habitat patches available for native fish was created by topography and remote imaginary. Hydraulic properties of the individual patches were also characterized using two Vectrino ADVs field probes. This valuable information is now being compared with results from the fish and benthos organisms sampling campaigns with an emphasis on turbulence.

As a first step, the author did his bachelor thesis on the analysis of ADV series for flow characterization, including data treatment and filtering, as well as a review of various techniques for flow characterization and analysis.

This Thesis deals with the turbulent flow field over a nature-like fishway. The obtained results were sent for possible publication in the Canadian Journal of Civil Engineering on July the 19th.

1.2 Turbulent flow in fishways

Fishways are hydraulic structures enabling fish to negotiate river obstructions such as dams, weirs and under-road culverts. According to their design, one can distinguish standard and nature-like fishways. Standard fishways are built with so-called traditional materials such as concrete, steel or wood, and thus exhibit flat surfaces. They are useful only for a limited number of species. Standard fishways include pool type, vertical slots, Denil passes, eel ladders, fish locks, fish lifts and culverts (DVWK, 2002). Nature-like fishways (see e.g.: Cowx and Robin 1998, Wang and Katopodis 1999) are built with diverse materials like large wood debris, boulders, and riparian vegetation, imitating the local stream conditions (Parasiewicz et al. 1998). Thus, they create more diverse flow conditions within a cross section than standard fishways, being amenable to many species of fish and even also benthic organisms. DVWK (2002) and USBR (2007) provide design guidelines for this type of fishway. The effectiveness of nature-like fishways is well documented. Eberstaller et al. (1998) reported a successful European grayling (*Thymallus thymallus*) migration, just prior to their spawning season, through two bypass channels in Austria (see also the experience of Schmutz et al. 1998 with pike perch, *Stizostedion lucioperca*). Aarestrup et al. (2003) monitored sea trout (*Salmo trutta*) movement through a 130 m long, 1.6% slope nature-like bypass in Denmark. They report that 50% of the fish could negotiate the fishramp. Calles and Greenberg (2005) demonstrated the efficiency of a fishway consisting of a ramp of boulders (rocky-ramp) with a slope up to 2.5%. They observed migration of various species reaching a combined efficiency of 74% (see also Calles and Greenberg 2007). Santos et al. (2005) were able to measure more than 7,500 individual passages of striped mullet and other species (all with different life stages) in another nature-like bypass in Portugal. These examples confirm that this 'nature-mimicking' concept is both environmentally friendly and good performing.

According to several researchers (Cada and Odeh 2001; Nikora et al. 2003; Cotel et al. 2006) the properties of turbulence in a fishway might correlate with fish behaviour. Fish swimming performance within a fish ramp may depend on the intensity of turbulence (turbulent kinetic energy, Reynolds shear stress and vorticity), its periodicity (time scale and dominant frequencies), its orientation (direction of vorticity and resultant forces) and its length scale (eddy and vortex sizes), as discussed by Lacey et al. (2012). Recognizing that turbulence characteristics should be important for fish passage, some studies on standard fish ramp hydraulics have well described the turbulent flow field, including the analysis of distribution and quantification of turbulent properties. For example, Turbulent Kinetic Energy (TKE) is the most common variable to represent turbulence intensity. Guiny et al. (2005) reported maximum TKE values around 0.4 to 1.2 m^2/s^2, in pool-type fishways (depending on orifice sizes), while Silva et al. (2010) only found 0.02 m^2/s^2 in the same kind of fish ramp. Liu et al. (2006) found 0.2 m^2/s^2 in a vertical slot fishramp and Morrison et al. (2008) measure 0.6 m^2/s^2 in culverts. Although there is some expertise on nature-like fishways, at the knowledge of the author, nature-like fishway turbulent properties has not been reported yet. Even though, this information is crucial for a better understanding of fish behaviour and design optimization.

Turbulence in open-channel flows can be studied with the acoustic Doppler velocimeter (Lane et al. 1998). Spatial analysis of turbulence includes determination of Reynolds' shear stresses, higher order velocity moments and vorticity fields (e.g., Tritico and Hotchkiss 2005, Buffin-Belanger et al. 2006, Marchildon et al. 2011), while point analysis of turbulent properties includes quadrant (Lu and Willmarth 1973), autocorrelation (Bendat and Pierson, 1993) and spectral (Welch, 1967) analysis of velocity time-series. These techniques are useful to recognize coherent structures, and to identify predominant coherent mechanisms (e.g., Yossef and Vriend 2010, Sarkar and Dey 2010).

In this study, the flow in a nature-like fishway is characterized using point and spatial analysis of velocity time-series measured with an ADV. These results are linked with the expected fish behaviour in order to provide an insight into the complex relation between ecohydraulics variables. The paper is organized as follows: First the experimental setup and measuring techniques are described. Next, experimental results are presented, and their relation to fish behaviour is discussed. The paper concludes with final remarks.

CHAPTER 2 EXPERIMENTAL WORK

2.1 Experimental setup

Experiments were conducted in a rocky-ramp fishway built in a flume at the Hydraulics Laboratory of the University of Alberta. The length, width, and height of the flume were 8.89 m, 0.91 m, and 0.61 m, respectively. The longitudinal slope was adjusted at 5%. The rocky-ramp consisted of a staggered arrangement of isolated boulders placed along the whole flume extension. A total of 58 boulders with a 14 cm regular diameter (varying between 10 and 20 cm) were arranged in 23 rows alternating between two and three boulders in each row (see Figure 1). Boulders were glued to the ramp bottom with silicon. The centre to centre distance between boulders along longitudinal (Δx) and lateral (Δy) directions was about 38 cm, i.e. around 2.5 times the rock diameter, as recommended by DVWK (2002).

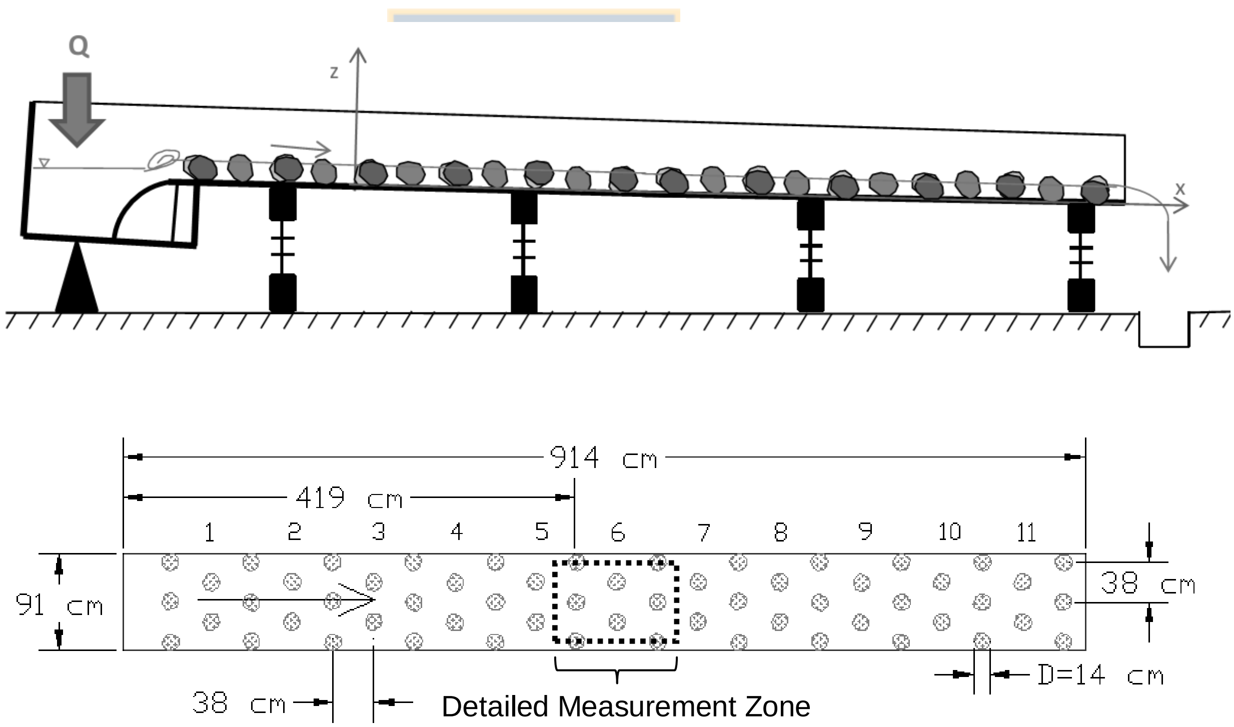

Figure 1. Sketch of the experimental flume: lateral view (top) and plan view (bottom) with dimensions of the boulders arrangement. Dashed line shows the detailed measurement zone. Not to scale.

2.2 Equipment

The discharge was measured using a magnetic flow meter installed on the supply line. Flow visualization was made by dye injection in order to observe flow lines within the fishramp for selection of measuring points. Water depth was measured with a point gauge with accuracy of 0.1 mm. Velocity was measured with an ADV (MicroADV Sontek) with an accuracy of 1%. An aluminium frame was used to support the ADV to avoid the vibration effect of the flume. Measurements were taken in zone number six as shown in Figure 1, at a distance of 4.19 m from the upstream end of the flume. The flow was fully developed in this zone. Neither upstream nor downstream conditions affected the flow between isolated boulders.

2.3 Experimental conditions

Three sets of experiments with discharges of 25, 45, and 60 l/s were conducted. Table 1 shows the experimental conditions. In series S1 it was not possible to measure with the ADV due to low water depth. Thus a Pitot-Prandtl tube was used instead, measuring 73 points over a grid. The probe was located 2.5 cm above the bottom surface. Two types of data were taken with ADV: short velocity time series (two minutes long) for spatial analysis and long velocity time series (30 minutes long) for point analysis. Sampling frequency was set at 50 Hz and sampling volume was located at 3 cm from the flume bottom.

Table 1. Experimental conditions of the three data sets for low, middle and high discharge

Set	Discharge (l/s)	Flow depth (cm)	Mean velocity (cm/s)	Froude number	Reynolds number
S1	25	6.9	39.6	0.48	$2.73*10^4$
S2	45	10.5	46.9	0.46	$4.92*10^4$
S3	60	11.9	55.0	0.51	$6.56*10^4$

For spatial analysis, velocity was measured at 186 well distributed locations within zone number six. Velocity time series were noisy because the flow was highly turbulent and contained significant air bubbles (average correlation and signal-to-noise ratio was about 50 and 30, respectively). Hence, the data were filtered with the Phase-Space Thresholding (PST) method proposed by Goring and Nikora (2002), using Win ADV as recommended by Wahl (2003). Around 16% of instantaneous velocity data were removed by this filter.

For point analysis, velocity was measured at three locations determined by flow visualisation using dye injection as shown in Figure 2: (1) in between two boulders, (2) upstream of a boulder and (3) within a boulder wake. In order to compute spectral and autocorrelation functions, these data were filtered with a modified PST technique (mPST) proposed by Parsheh et al. (2010). Threshold parameters used for this method were estimated for each velocity time series in the way that the spectrum slope fit the Kolmogorov -5/3 law. About 14% of instantaneous velocity values were filtered and filled with the last valid data point after applying this filter.

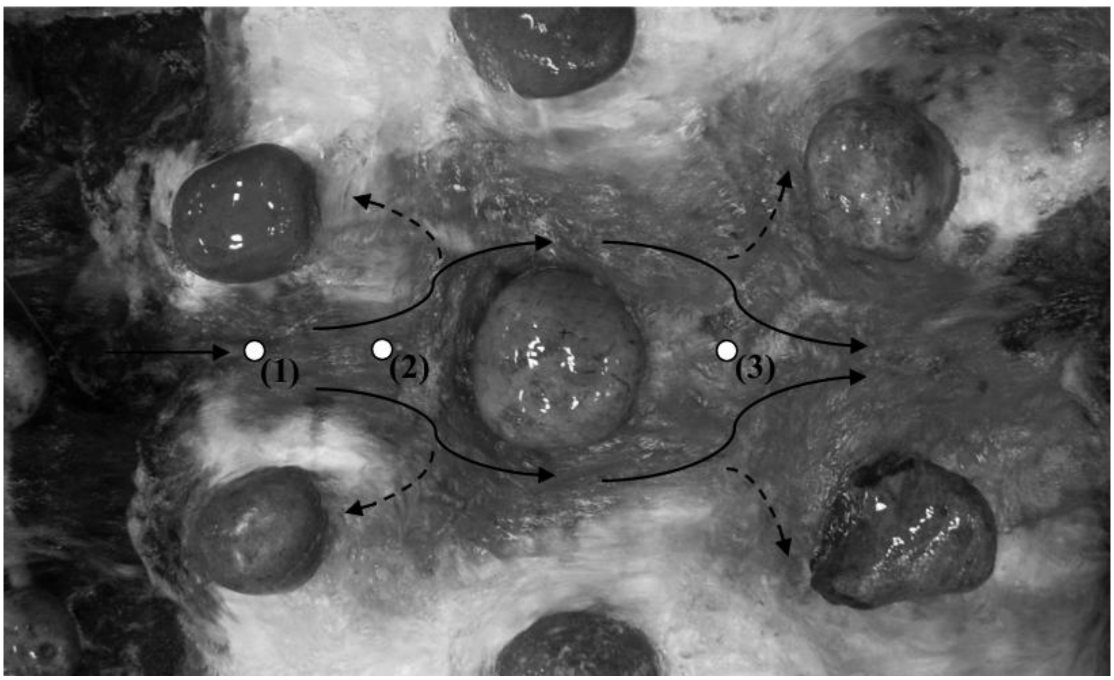

Figure 2. Dye injection image. Measuring locations for point analysis: (1) in between the boulders, (2) upstream of a boulder and (3) at a boulder wake.

CHAPTER 3 RESULTS

In the following, results for S3 are presented and differences with S1 and S2 are discussed. When possible, results are linked with fish behaviour and compared with similar ones reported in literature for other fishways.

3.1 Turbulent flow field

In order to analyze the physical characteristics of potential habitat used by fish, the distribution of flow properties was plotted in contour maps. These were generated by Kriging interpolation of mean properties determined over the measuring grid. Assuming that overbar means average in time of the variable below it, Figure 3 shows the spatial distribution of main velocity, $\sqrt{\overline{u}^2+\overline{v}^2+\overline{w}^2}$, with u, v, w being the longitudinal, lateral and vertical instantaneous velocities, respectively; plane Reynolds shear stress, $-\rho\overline{u'v'}$, where ρ is water density; normalized main kurtosis, $\overline{V^4}/\overline{V^2}-3$, with V the fluctuating velocity in the main flow direction of each measuring point; predominance of sweep and ejection events (presented as the vertical Reynolds' shear stresses, $-\rho\overline{u'w'}$, of series with predominance of quadrants Q4 y Q2), turbulent kinetic energy, $TKE=0.5*\left(\overline{u^2}+\overline{v^2}+\overline{w^2}\right)$, and vertical vorticity, $\frac{\delta\overline{v}}{\delta x}-\frac{\delta\overline{u}}{\delta y}$. Arrow position, size and direction correspond to measuring location, magnitude and direction of mean plane velocity. Color scale is shown at the right side of each plot.

Main velocity map is preferred instead of longitudinal velocity map because we expect that fish care more about the magnitude of flow rather than its direction. Velocity was measured at around 25% of flow depth. Velocity distribution shows a high spatial variability controlled by the geometry of the arrangement of boulders. In general, low velocity magnitudes were found at a boulder wake while upstream of a boulder velocity was high. Maximum main velocity was 85 cm/s while minimum was 0.5 cm/s. A recirculating area located downstream B1 was identified. Some preferred paths (with velocities ranging from 20 to 50 cm/s) and resting areas (with velocities less than 20 cm/s) may be found by fish. Reynolds shear stress ranged from -20 to +20 Pa with the exception of a few isolated points where maxima were ±40 Pa. A preferential path for fish due to low values of turbulent stress starts from the left side of B7, passing between B4 and B5 in a diagonal direction until crossing between B1 and B2.

Magnitudes of main kurtosis and its distribution show a predominance of negative values, i.e. a low intermittency of flow (Balachandar and Bhuiyan 2007). Intermittent turbulent flow (represented by positive values) is only developed in some points. Upstream of boulders B2, B5, B7 and B8 flow is intermittent in time arising from the fact that, as flow is being diverted at this location, direction might be changing in time intermittently. High kurtosis is also observed between B6 & B7 and B7 & B8. As kurtosis at the wake of boulders is low, this place might constitute a good shelter for fish migration.

Predominance map shows the distribution of the vertical Reynolds shear stress, $-\rho\overline{uv}$, for those locations where sweeps and ejection events are predominant. Only zones with shear stresses greater than 5 Pa are highlighted (coloured). By analysing asymmetries in velocity distribution, predominance of sweeps or ejection events was identified. Velocity time series with a negative $\overline{u'^3}$ and a positive $\overline{w'^3}$ (Q2) were associated to ejection events. When velocity time series had a positive $\overline{u'^3}$ and a negative $\overline{w'^3}$ (Q4), predominance of sweep events was identified. Ejection events are more frequently observed than sweeps. The most intense shear stress tends to occur close to the boulders where ejection zones are not spread to the whole cross section. This pattern allows fish to pass through the fishramp avoiding ejection zones, as they can choose to swim between boulders.

In order to compare the results with field data the TKE magnitudes were plotted in the dimensional way as recommended by Lacey et al. (2012). TKE values ranged from 0.005 up to 0.25 m^2/s^2. Zones with low TKE (less than 0.125 m^2/s^2) are plotted in blue tones while zones with high turbulent energy (more than 0.150 m^2/s^2) are plotted in red tones. Spatial differences are related to the shape of each boulder surface, e.g. low TKE values were found in boulder wakes excepting B4 which exhibit a particular shape facing the flow. Fish may find their way through the fishway whether they prefer high or low turbulent intensities, which depend on fish swimming capability (Cotel el al 2006) as high variability of TKE distribution was found. TKE magnitudes compare well with values reported both in other standard fishways (Guiny et al. 2005, Liu et al. 2006, Silva et al. 2010) and *in situ* measurements (see various in situ reports of TKE in Lacey et al. 2012).

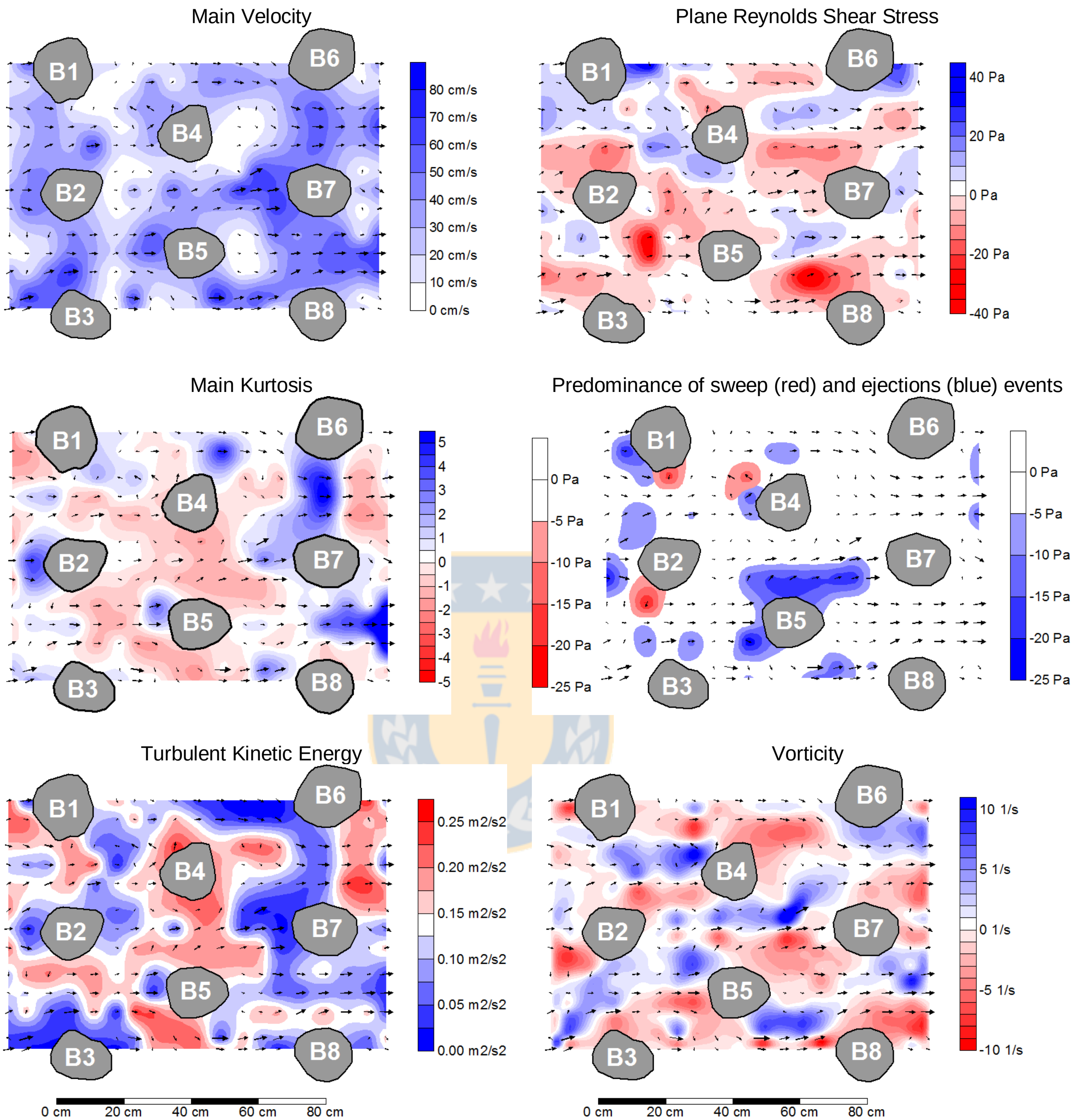

Figure 3. Contour maps of main velocity, $\sqrt{\overline{u}^2+\overline{v}^2+\overline{w}^2}$; plane Reynolds shear stress, $-\rho\overline{u'v'}$; normalized main kurtosis, $\overline{V^4}/\overline{V^2}-3$; predominance of sweep and ejection events (presented as the vertical Reynolds' shear stresses, $-\rho\overline{u'w'}$, of series with predominance of quadrants Q4 y Q2), turbulent kinetic energy, $TKE=0.5*\left(\overline{u^2}+\overline{v^2}+\overline{w^2}\right)$, and vertical vorticity, $\frac{\delta\overline{v}}{\delta x}-\frac{\delta\overline{u}}{\delta y}$. Arrow position, size and direction correspond to measuring location, magnitude and direction of mean plane velocity. Flow rate was 60 l/s.

Vorticity is related to eddy size and distribution. Negative (red) and positive (blue) vorticity values correspond to clockwise and counter clockwise flow spin, respectively. Eddy sizes range from about 1 to 30 cm. Fish might choose places with low vorticity (less than 5 s^{-1}) or zones with eddies that are small related to their body size (Cada and Odeh 2001, Nikora et al. 2003). As vorticity is low at boulder wakes, this might be a good place to rest.

3.2 Quadrant analysis

Figure 4 shows plane versus vertical fluctuating velocities plots made for quadrant analysis. All velocities were normalized by Mean Velocity shown in Table 1 (55 cm/s). A detection function was used to filter out more energetic events (as suggested by Lu and Willmarth 1973) with a hyperbole threshold parameter H=4. These stronger events are highlighted in the figure.

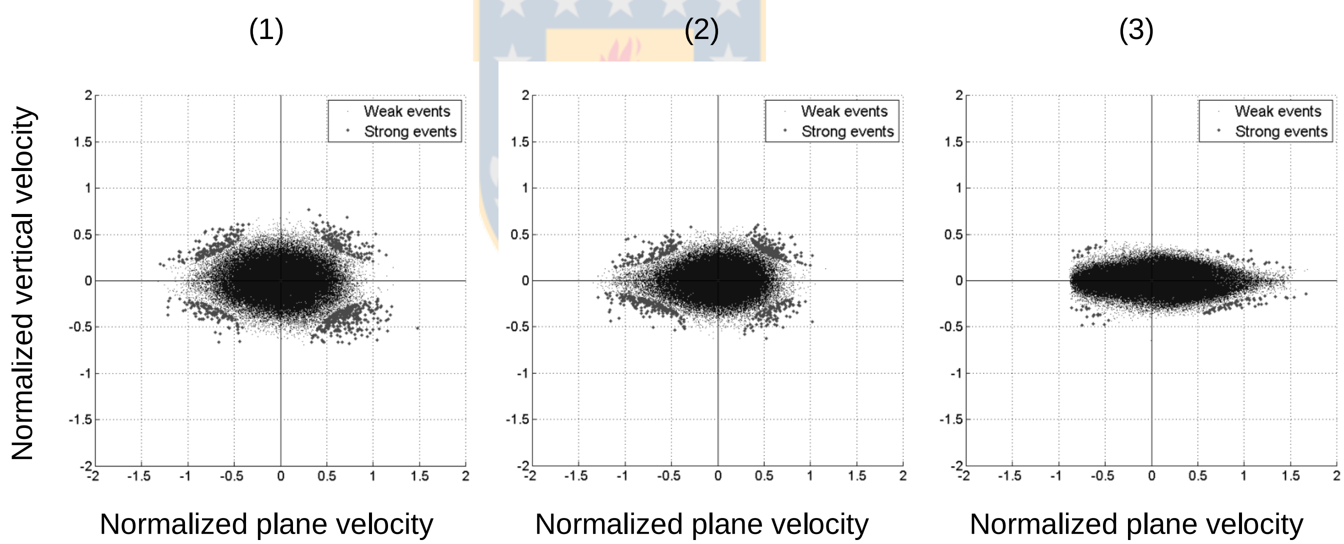

Figure 4. Quadrant plots of vertical versus plane normalized velocity measured at locations (1), (2) and (3), from left to right. Flow rate was 60 l/s.

Plots are not isotropic, as fluctuating plane velocity distribution is not symmetric. Negative fluctuations that are higher in magnitude than mean velocity were observed at locations (1) and (2). At location (3) positive fluctuations reach greater values than mean velocity. High level energy events are observed in all quadrants, but there is no evidence that events from a specific quadrant are predominant. Fish may be more affected by ejections and sweep events in locations (1) and (2) rather than (3), as additional high energy events were filtered at (1) and (2), compared to (3).

3.3 Autocorrelation analysis

Figure 5 shows normalized autocorrelation, $r_{VV}(\tau)=\dfrac{\overline{V(t)V(t+\tau)}}{\overline{V^2}}$, plots for the three locations at each flow direction: $r_{uu}(\tau)$, $r_{vv}(\tau)$, and $r_{ww}(\tau)$; with τ being the time lag.

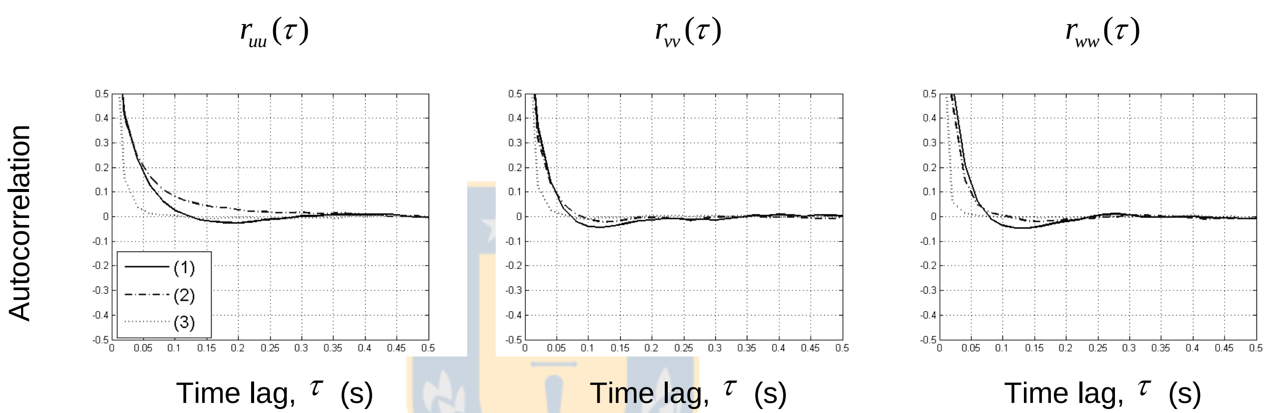

Figure 5. Autocorrelation curves for directions u, v and w, measured at locations (1), (2) and (3) at a flow rate of 60 l/s. Integral time scale, $\Im$, was about 0.005s.

Autocorrelation values were significantly low and no turbulent coherent structures were recognized. The integral time scale, $\Im=\int_0^\infty r(\tau)d\tau$, was about 0.005 s at locations (1) and (2), and much smaller at (3). Autocorrelation plots do not reveal any highly correlated coherent structure that could stress fish within the fish ramp. This probably arises from the fact that the boulder to boulder distance is close enough to disrupt any eddy or von Kármán vortex developed at the boulder wake.

3.4 Spectral analysis

Power spectral density functions of velocity were estimated as proposed by Welch (1967) using a Blackman window with 50% of overlapping. A 512 window size was chosen so that random error of spectrum estimation was less than 8%. Figure 6 shows normalized spectra for the three experiment locations and flow directions: $G_u(f)/\overline{u^2}$, $G_v(f)/\overline{v^2}$, and $G_w(f)/\overline{w^2}$, with f being the frequency.

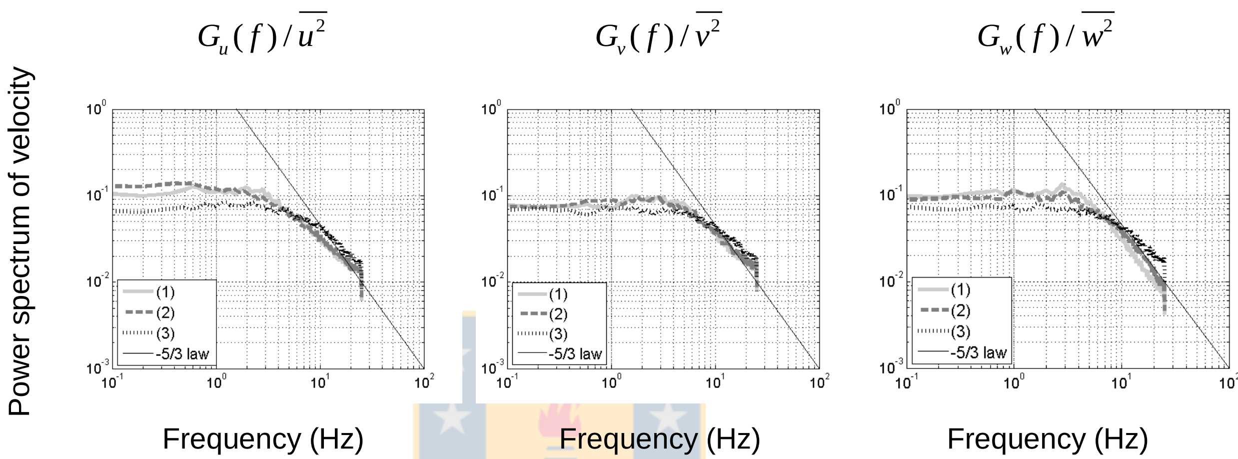

Figure 6. Power spectra of velocity: $G_u(f)/\overline{u^2}$, $G_v(f)/\overline{v^2}$, and $G_w(f)/\overline{w^2}$ for locations (1), (2) and (3); at a flow rate of 60 l/s.

Spectrum slopes fit relatively well with Kolmogorov's law, enclosing the inertial sub-range up to approximately 10^1 Hz. Normalized spectra show magnitudes around 0.1 at the most energetic part, being one order smaller than findings of Liu et al. (2006) within a vertical slope fishway. For the lower frequency range (less than 6 Hz), higher stored energy at locations (1) and (2) is observed compared to (3). At frequencies higher than 6 Hz, the turbulence at the wake of the boulder showed the highest energy magnitude for each direction. Probably these phenomena arise from vortex stretching, the main mechanism of energy transfer. A peak was observed in the spectrum of vertical velocity at around 3 Hz only for locations (1) and (2). This might be associated with the effect of the boulder obstruction located downstream, which causes a water level fluctuation in upstream direction. Considering the mean velocity of 55 cm/s, the peak at 3 Hz is related to a dominant length scale of about 18 cm.

3.5 Discharge effect

Experimental series S1 and S2 were conducted with discharges of 25 and 45 l/s. Mean velocity, turbulent intensities, asymmetry, kurtosis, Reynolds shear stresses, kinetic energy, and vorticity field presented similar patterns as those reported for S3. Only plane Reynolds shear stress presented significant change with discharge in its spatial distribution but the potential preference paths are also present. Variable intensities do not increased more than 20% with discharge. Autocorrelation, quadrant and spectral analysis of S2 data also gave similar results than S3.

CHAPTER 4 CONCLUSION

Results of laboratory measurements of the flow field in a nature-like fishway using an ADV have been presented. The turbulent flow field was characterized applying spatial and point analysis techniques and its relation to fish behaviour was discussed.

The flow field showed a high spatial variability controlled by the geometry of the boulders arrangement. Main velocity ranged from 0.5 to 80 cm/s, exhibiting paths with rapid currents (>20 cm/s) that may be followed by fish, and resting areas (with velocities less than 20 cm/s) that may be used during fish passage. Eddy sizes ranged from about 1 to 30 cm. A wide range of TKE values, from 0.005 to 0.25 m^2/s^2 with differences in space related to the shape of each boulder surface, was also observed. The most intense shear stress tends to occur close to the boulders where ejection zones are not spread to the whole cross section. This pattern allows fish to pass through the fishramp avoiding ejection zones, as they can choose to swim between boulders. At boulder wakes velocity, kurtosis, and vorticity were low, and thus this place might constitute a good place to rest during passage.

Point analysis showed that the boulder to boulder distance in the ramp was small enough to disrupt turbulent coherent structures. At boulder wakes no predominance of sweep and ejection events was observed indicating that wakes constitute good resting place for fish during their migration. Turbulent kinetic energy and Reynolds shear stress distributions presented a high spatial variation in the ramp, showing that a nature-like rocky-ramp offers a diversity of flow conditions that might allow a variety of fishes to develop their preferred paths characterized by flow properties with different magnitudes depending on the particular species. In general, no significant change of hydraulic variable intensities and its spatial distribution with discharge was observed. Obtained results compare well with similar ones reported for standard fishways.

In this work different fluid mechanics techniques for analysis of velocity time series measured with ADV were successfully applied to a laboratory study case. The results showed that the methodology is a promising approach for a better understanding of turbulent flows in open channels. In the near future, open questions like the characterization of turbulence in a river flow will be explored and linked to the particular Chilean native fish behaviour. From the ecohydraulics perspective, this work partially achieves the complex linking between hydraulics and fish ecology.

REFERENCES

Aarestrup, K., Lucas, M.C., and Hansen, J.A. 2003. Efficiency of a nature-like bypass channel for sea trout (*Salmo trutta*) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish **12**: 160–168.

Balachandar, R. and Bhuiyan, F. 2007. Higher-order moments of velocity fluctuations in an open-channel flow with large bottom roughness. Journal of Hydraulic Engineering, **133**(1), 77-87.

Bendat, J., and Pierson, A. 1993. Engineering applications of correlation and spectral analysis, Wiley, New York.

Buffin-Bélanger, T., Rice, S., Reid I., and Lancaster J. 2006. Spatial heterogeneity of near-bed hydraulics above a patch of river gravel, Water Resources Research, **42**, W04413, DOI: 10.1029/2005WR004070.

Cada, G.F., and Odeh, M. 2001. Turbulence at hydroelectric power plants and its potential effects on fish, Report to Bonneville Power Administration, Contract No. 2000AI26531, Project No. 200005700, 37 electronic pages (BPA Report DOE/BP-26531-1). Portland, USA.

Calles, E.O., and Greenberg, L.A. 2005. Evaluation of nature-like fishways for re-establishing connectivity in fragmented salmonid populations in the River Emån. River Research and Applications, **21**: 951–960.

Calles, E.O., and Greenberg, L.A. 2007. The use of nature-like fishways by some fish species in the Swedish River Emån. Ecology of Freshwater Fish, **16**: 183-190.

Chorda, J., Maubourguet, M.M., Roux, H., Larinier, M., Tarrade, L., and David, L. 2010. Two-dimensional free surface flow numerical model for vertical slot fishways. Journal of Hydraulic Research, **48**(2): 141-151.

Cotel, A.J., Webb, P.W., and Tritico, H. 2006. Do brown trout choose locations with reduced turbulence? Transactions of the American Fisheries Society **135**:, 610–619.

Cowx, I.G. and Robin, L.W. (Editors). 1998. Rehabilitation of Rivers for Fish. A study undertaken by the European Inland Fisheries Advisory Commission of FAO. ISBN: 0-85238-247-2 (Fishing news books) and ISBN: 92-5-104018-4 (FAO).

DVWK 2002. Fish Passes - Design, Dimensions and Monitoring. FAO, Rome.

Eberstaller J., Hinterhofer M., Parasiewicz P. 1998. The effectiveness of two nature-like bypass channels in an upland Austrian river. *In* Migration and Fish Bypasses, Jungwirth M., Schmutz S., Weiss S. (eds). Fishing News Books: Oxford; 363–383.

Guiny, E., Ervine D., and Armstrong J. 2005. Hydraulic and biological aspects of fish passes for atlantic salmon. Journal of Hydraulic Engineering, **131**(7): 542-553.

Katopodis, C. 2001. Nature-mimicking fishways: concepts and practical applications. *In* Proceedings of 2nd Nordic International Symposium on Freshwater Fish Migration and Fish Passage, Evaluation and Development, Reykjavik, Iceland, 20-22 September 2001, pp. 87-93.

Katopodis, C., Kells, J.A., and Acharya, M. 2001. Nature-like and conventional fishways: Alternative concepts?. Canadian Water Resources Journal, **26**(2): 211-232.

Lacey, R.W., Neary, V.S., Liao, J.C., Enders E.C., and Tritico H.M. 2012. The IPOS framework: linking fish swimming performance in altered flow from laboratory experiments to rivers. River Research and Applications, **28**: 429-443.

Lancaster, J., Buffin-Bélanger, T., Reid, I. and Rice, S. 2006. Flow- and substratum- mediated movement by a stream insect. Freshwater Biology, **51**: 1053-1069.

Lane, S.N., Biron, P.M., Bradbrook, K.F., Butler, J.B., Chandler, J.H., Crowell, M.D., McLelland, S.J., Richards, K.S., and Roy, A.G. 1998. Three-dimensional measurement of river channel flow processes using acoustic Doppler velocimetry. Earth Surface Processes and Landforms, **23**: 1247-1267.

Liu, M., Zhu, D. and Rajaratnam, N. 2006. Mean flow and turbulence structure in vertical slot fishways. Journal of Hydraulic Engineering, **132**(8), 765-777.

Lu, S. and Willmarth, W. 1973. Measurements of the structure of the Reynolds stresses in a turbulent boundary. Journal of Fluid Mechanics, **60**: 481-571.

Lupandin, A. I. (2005). Effect of flow turbulence on swimming speed of fish. Biology Bulletin, **32**(5), 461-466.

Marchildon, M., Annable W., Imhof J., and Power, M. 2011. A high-resolution hydrodynamic investigation of brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) redds. River Research and Applications, **27**: 345–359.

Morrison, R., Hotchkiss, R., Stone, M., Thurman D., and Horner-Devine, A. 2008. Turbulence characteristics of flow in a spiral corrugated culvert fitted with baffles and implications for fish passage. Ecological Engineering, **35**, 381–392.

Nezu, I., and Nakagawa, H. 1993. Turbulence in open-channel flows. Balkema, Rotterdam NL.

Nikora, V., Aberle J., Biggs B., Jowett I., and Sykes J. (2003). Effects of fish size, time-to-fatigue and turbulence on swimming performance: a case study of *Galaxias maculatus*. Journal of Fish Biology, **63**, 1365-1382.

Parasiewicz, P., Eberstaller, J., Weiss, S., and Schmutz, S. 1998. Conceptual guidelines for nature-like bypass channels. Fish Migration and Fish Bypasses. pp. 348-362.

Santos, J.M., Ferreira, M.T., Godinho, F.N., and Bochechas, J. 2005. Efficacy of a nature-like bypass channel in a Portuguese lowland river. Journal of Applied Ichthyology, **21**(5), 381-388.

Sarkar, S. and Dey, S. 2010. Double-averaging turbulence characteristics in flows over a gravel bed. Journal of Hydraulic Engineering, 48(6): 801-809.

Schmutz S., Giefing C., and Wiesner C. 1998. The efficiency of a nature-like bypass channel for pike-perch (*Stizostedion lucioperca*) in the Marchfeldkanal system. Hydrobiologia **372**: 355–360.

Silva, A., Santos J., Ferreira M., Pinheiro A., and Katopodis, C. 2010. Effects of water velocity and turbulence on the behaviour of Iberian barbel (*Luciobarbus bocagei*, Steindachner, 1864) in an experimental pool-type fishway. River Research and Applications, **27**(3): 360-373.

Tachie, M.F., Paul, S.S. and Katopodis, C. 2009. Flow characteristics around various bluff body geometries in shallow water flow. 33rd IAHR Congress: Water Engineering for a Sustainable Environment.

Tritico, H.M., and Hotchkiss, R.H. 2005. Unobstructed and obstructed turbulent flow in gravel bed rivers. Journal of Hydraulic Engineering **131**(8), 635-645.

USBR 2007. Rock Ramp Design Guidelines. U.S. Department of the Interior Bureau of Reclamation Technical Service Center Denver, Colorado, USA.

Vokoun, J.C., and Watrous D. 2009. Determining swim speed performance characteristics for fish passage of burbot using an experimental flume and nature-like fishway. Completion Report submitted to Connecticut Department of Environmental Protection. University of Connecticut, Storrs. 27pp.

Wang, P. and Katopodis, C. 1999. Fishway studies for the lower Churchill River water-level enhancement project in Manitoba. In Proceedings, 3rd International Symposium on Ecohydraulics, Salt Lake City, UT, 13-16 July 1999.

Welch, P. 1967. The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms, IEEE Transactions on Audio and Electroacoustics, **15**(2), 70-73.

Yossef, M. and de Vriend, H. 2010. Flow details near river groynes – experimental investigation. Journal of Hydraulic Engineering, **137**(5): 504-516.

LIST OF SYMBOLS

f	=	Frequency
u	=	Longitudinal component of instantaneous velocity
v	=	Lateral component of instantaneous velocity
w	=	Longitudinal component of instantaneous velocity
u'	=	Longitudinal component of fluctuating velocity
v'	=	Lateral component of fluctuating velocity
w'	=	Longitudinal component of fluctuating velocity
V	=	Main flow component of fluctuating velocity
TKE	=	Turbulent kinetic energy
$G_u(f)/\overline{u'^2}$	=	Power spectrum of longitudinal velocity
$G_v(f)/\overline{v'^2}$	=	Power spectrum of lateral velocity
$G_w(f)/\overline{w'^2}$	=	Power spectrum of vertical velocity
$r_{uu}(\tau)$	=	Autocorrelation function of u
$r_{vv}(\tau)$	=	Autocorrelation function of v
$r_{ww}(\tau)$	=	Autocorrelation function of w
ρ	=	Water density
τ	=	Time lag
$\mathfrak{I}$	=	Integral time scale