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## Numerical Comparison of RANS, URANS and LES Simulations of Turbulent Flow in Vertical Double Slot Fishways

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### Abstract

Numerous actions have been undertaken to achieve a good ecological status or potential of the European Union members water bodies. Vertical Double Slot Fishways (VDSF) have been implemented to bypass obstacles on rivers, however few studies have been made on their design or efficiency. This paper proposes a numerical comparison of three methods: RANS, URANS and LES simulations to model the turbulent flow occurring in VDSFs. All three methods present a coherent average global dynamic of the system. The velocities displayed are of the same order of magnitude as the ones recorded experimentally. The LES simulation additionally presented instantaneous data. The jets coming from the slots are wavering, one taking dominance at one point in time, only to be over-taken by the other later on. The flow inside the pools is thus much more chaotic than average trajectories implied. The access to this instantaneous information is useful since it is the flow faced by the fish, unlike the average flow. If fish reactions to a given unsteady flow were recorded, fish behaviour towards unfamiliar unsteady flows could be predicted. From these predictions, future fish structures could be designed with the theoretical reaction from the fish inside it.

**Keywords:** Vertical double slot fishway; Ecohydraulics; Turbulent flow; Unsteady flow; Numerical simulations

### 1. INTRODUCTION

The Water Framework Directive, adopted in 2000, states that all European Union members must achieve a good ecological status or potential of their water bodies. Amongst the numerous actions undertaken, the removal of obstacles or the implementation of fish passages to bypass those, has been applied to reconnect rivers in order to insure ecological continuity of watershed. Several types of fish passages have been used, such as artificial rivers, baffle fishways or pool fishways (Larinier et al., 1998), which divides the total fall in several successive smaller falls. A specific kind of pool fishways is the vertical slot kind, mostly used in its single slot form (Vertical Slot Fishway) but with an increasing development of its double slots configuration (Vertical Double Slot Fishway). However, while the single slot version is well known and has been the subject of numerous studies (Ballu et al., 2017, 2016; Klein & Oertel, 2016; Marriner et al., 2014; Rajaratnam et al., 1986), only few studies exist on the double slot type.

The Vertical Double Slot Fishway was initially designed in 1943 for the Hell's Gate Canyon, on the Fraser river in Canada (Clay, 1995), but the study was not published. In 2003, Fujihara et al. have published a numerical study comparing a configuration of a VDSF to three different configurations of VSFs. A more recent preliminary experimental study assesses the flow inside three slot-type fishways: a one-side VSF, an alternating side VSF and a VDSF (Huang, 2020).

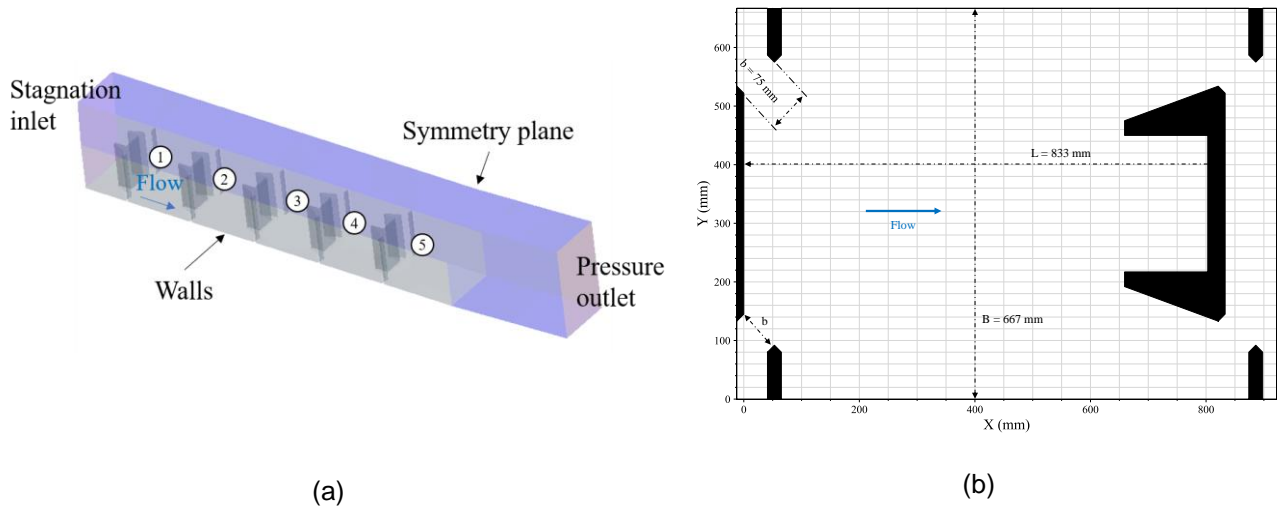
In this paper, a study on the turbulent flow inside a VDSF using Star-CCM+ software is proposed. A comparison of the RANS, URANS and LES models was carried out in a scale model, to determine the most realistic method to simulate the flow inside VDSFs.

### 2. NUMERICAL SIMULATIONS

#### 2.1. Domain

A 1:6 scale VDSF is modelled. The dimensions of this fishway is linked to a VDSF on a Garonne river, located at the Malause dam. The domain and dimensions of the simulated model are presented in **Figure 1**. Water enters the system upstream, then moves through the five simulated pools (numbered 1 to 5 in the **Figure 1**) by gravity. The domain is extended beyond the five pools in order to model the influence of the river on the fishway. The length of a pool is  $L = 0.833$  m and the width of the channel is  $B = 0.667$  m. The width of the slots is  $b = 0.075$  m, resulting in a  $L/b$  ratio of 11.1, and a  $B/b$  ratio of 8.89. The study was carried out for a slope of

$s = 4 \%$  and a flow discharge of  $Q = 0.034 \text{ m}^3 \cdot \text{s}^{-1}$ , which imposes a depth in the middle of the pools of  $h = 0.311 \text{ m}$ .



**Figure 1.** (a) Fishway modelled in Star-CCM+; (b) Dimensions of the pools of modelled VDSF

Numerical values were recorded in the third pool of the scale model to insure the full development of the flow and avoid downstream disruption since the flow is subcritical.

## 2.2. Model descriptions

Numerical simulations have several advantages, since measures difficult to record using experimental means can be extracted and parameter studies can be made. The experimental setup was simulated using Star-CCM+ for three methods: RANS (stationary simulation), URANS and LES (unsteady simulations). The five pools were simulated with a slope of  $s = 4 \%$  and an average depth of  $h = 0.3 \text{ m}$ .

RANS and URANS methods ((Unsteady) Reynolds-Averaged Navier-Stokes) are based on the same principle of the decomposition of Reynolds, which divide the instantaneous measures into a sum of a mean and a fluctuating value. Since the averaging involves a loss of information, models to close the system of equations are implemented. A previous study on the use of turbulence models in vertical slot fishways was undertaken (Ballu, 2017) and presented the Low Reynolds  $k - \epsilon$  model as the best one, using experimental data as reference. Thus, the RANS and URANS simulations of the VDSF used this turbulence closure model. The URANS method takes the unsteady of the flow in account, while the RANS method does not.

The LES method (Large Eddy Simulation) however, has a different approach. It uses a spatial filter to solve the large eddies (coming from the geometry of the domain) and only model the smaller ones. The Smagorinsky model was used in this simulation.

On all three numerical calculations, the Volume of Fluid (VOF) method was implemented to emulate the free surface, which associate the values of volume fraction of both the air and water present in the simulation to each cell.

The RANS simulation tries to converge to a steady state on each iteration; however, for the unsteady simulations, a system of two loops intertwined is applied. The first one is the physical time simulated and therefore relates the unsteady behaviour of the flow. The second one lies within the first, and tries to converge towards a provisional steady state. In order to break free from the second loop and start on the following time step, convergence velocity criteria on several points are employed.

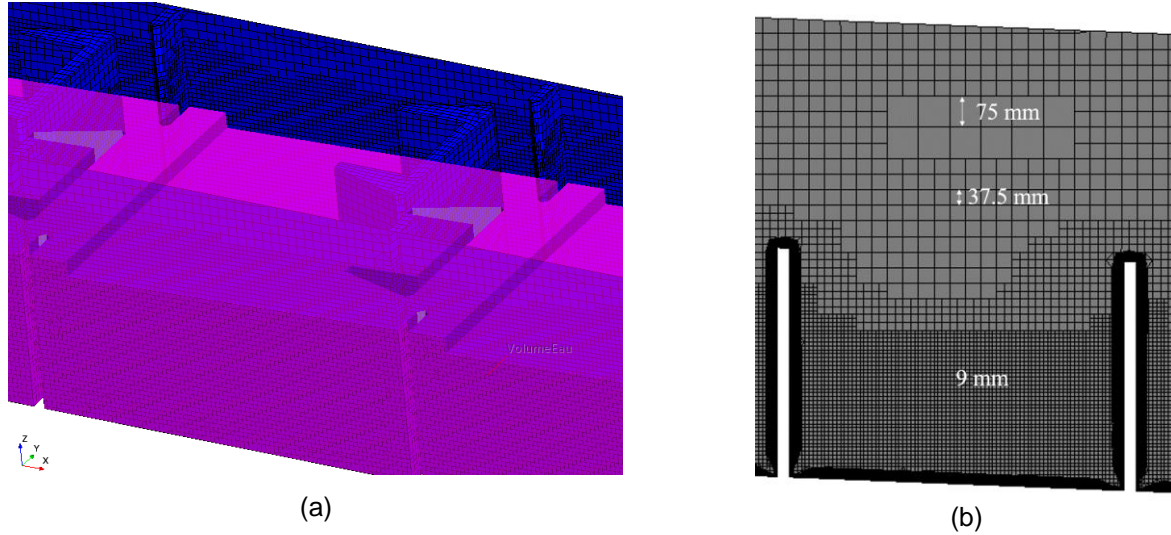
## 2.3. Boundary conditions

The boundary conditions for the simulations are presented in **Figure 1 (a)**. The VDSF floor, side and deflectors are considered walls, with no-slip conditions. Upstream, a stagnation inlet is inputted, so that the water entering the fishway is motionless at the beginning, and the only movement comes by gravity. Throughout the simulations, the hydrostatic pressure and the water level ( $h = 0.3 \text{ m}$ ) are imposed. There is a volume on top of the fishway, in order to distance the border of the domain from the free surface. The boundary condition on that volume is that of a symmetry plane. Downstream, after the extended volume, there is a pressure outlet, thus controlling once again the hydrostatic pressure and the water level.

## 2.4. Mesh

The simulation domain was subdivided in a structured hexahedron mesh of ~10,500,000 cells of smaller size. Each value is constant within the cell, thus a coarse mesh will give a distant estimation of the flow, while a too refined mesh will significantly prolong the calculation time.

As a preliminary study, the mesh was the same for the three simulations, and the size was retrieved from simulations made in previous studies (Ballu, 2017; Ballu et al., 2017) in a Vertical (single) Slot Fishway but which had similar dimensions (same width of slots and similar width of pools). The mesh is presented in **Figure 2**. The larger cells are cubes of 75 mm in length, width and height, and are located in the air volume on top of the fishway. The volume of water (in pink in **Figure 2 (a)**) is refined to cells of 9x9x9 mm<sup>3</sup>. The cells progressively swell from the water volume to the air (**Figure 2 (b)**).



**Figure 2.** (a) Refined mesh water volume for all three simulations; (b) Longitudinal cross-section of the mesh

The size of the boundary layer was estimated to 2.6 cm using the thickening of the turbulent boundary layer on a flat plane formula (Chassaing, 2000), with  $\delta_x$  the thickness of the boundary layer (m),  $L$  the length of a pool (m),  $\eta$  the kinematic viscosity (m<sup>2</sup>·s<sup>-1</sup>) and  $U_\infty$  the velocity beyond the boundary layer (m·s<sup>-1</sup>).

$$\delta_x \cong 0.37 \times \left( \frac{L^4 \times \eta}{U_\infty} \right)^{\frac{1}{5}} \quad [1]$$

In all simulations, the first inner node of the boundary layer mesh is located at  $y^+ = 1$  (where  $y^+$  is the non-dimensional wall-distance), in the viscous sublayer.

$$y^+ = \sqrt{\frac{\tau_w}{\rho}} \times \frac{y}{\nu} \quad [2]$$

with  $\tau_w$  being the wall shear stress (Pa),  $\rho$  the specific mass (kg·m<sup>-3</sup>),  $y$  the normal distance to the wall (m) and  $\nu$  the kinematic viscosity (m<sup>2</sup>·s<sup>-1</sup>).

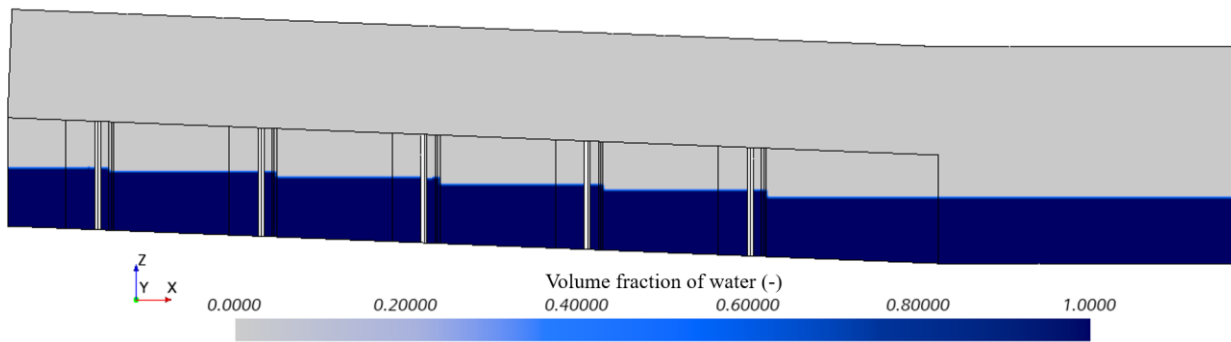
The wall shear stress can be estimated using the Schultz-Grunow relation for the friction coefficient:

$$C_f = \frac{0.37}{\log\left(\frac{U_\infty \cdot x}{\nu}\right)^{2.584}} \quad [3]$$

Using the normal distance to the wall deduced from  $y^+ = 1$ , the thickness of the boundary layer mesh and an expansion ratio of  $r = 1.1$ , the number of cells in the boundary is estimated to 62 cells.

## 2.5. Initial conditions

In order to start the simulations, an initial condition on volume fraction was implemented and can be seen below in **Figure 3**. They initially start with still water inside the fishway and in the volume behind it and the flow starts by gravity.



**Figure 3.** Initial conditions of the volume fraction of water (blue) for all three simulations

The selected time step was of  $\Delta t = 7.5$  ms, so as to observe the Courant-Friedrichs-Lewy criteria;  $CFL \leq 1$ .

$$CFL = \frac{u \times \Delta t}{\Delta x} \quad [4]$$

with  $u$  the velocity of the fluid ( $\text{m}\cdot\text{s}^{-1}$ ),  $\Delta t$  the time step of the unsteady simulation(s) and  $\Delta x$  the size of the discretization of the domain (m).

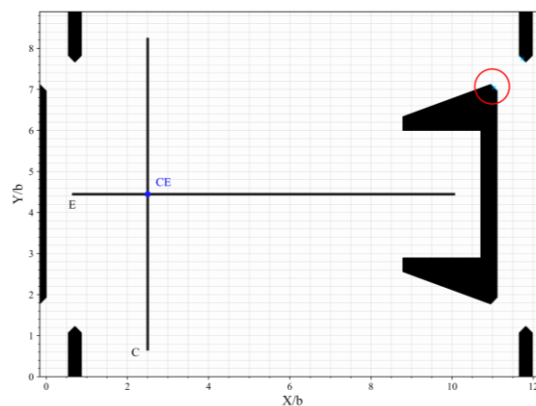
The RANS simulation converges after 4,000 iterations. The mean velocity in several locations converge after 40 seconds of simulated flow in the URANS simulation and after 60 seconds in the LES simulation. The overall simulation time for the URANS simulation is of 120 seconds and of 170 seconds for the LES.

### 3. RESULTS

Velocity magnitude results will be presented here. Mean and instantaneous velocity magnitude will be depicted on a plane parallel to the bottom of the channel. Mean values on two specific profiles will also be presented for all three methods.

#### 3.1. Profiles description

Experiments were carried out to provide a base of comparison to the numerical study. They were undertaken in a similar 1:6 laboratory scale model, located in the Pprime Institute of the University of Poitiers (France). The scale model was a replica of the simulated one, with one difference. Due to an misunderstanding in the conception time, one dimension of the centre baffles (circled in red in **Figure 4**) is slightly bigger in the experimental model than it is in the simulated one, where this dimension is equal to the opposing one in the side baffle. This slim alteration might explain small differences between experimental and numerical models. The data was also collected in the third pool in the experimental model. Flow velocity components were recorded using an Acoustic Doppler Velocimetry probe (ADV) to obtain average velocity on specific profiles. The sampling rate of the probe was 50 Hz and the acquisition time was 300 s for each point. The sampling interval between points for a profile was 20 mm. The profiles can be seen in **Figure 4**. Both profiles were defined in a plane parallel to the bottom of the channel (located at  $h = 0.15$  m from the bottom); one of them (C) was transversal ( $X/b = 2.5$ ), and the other was longitudinal (E) ( $Y/b = 4.45$ , the middle of the pool).



**Figure 4.** Location of the profiles on the plane parallel to the bottom ( $h = 0.15$  m)

The measures were normalized using the width of the slots ( $b$ ) for length measurements and the maximum theoretical velocity in a pool ( $V_d$ ), given by:

$$V_d = \sqrt{2 \times g \times L \times s} \quad [5]$$

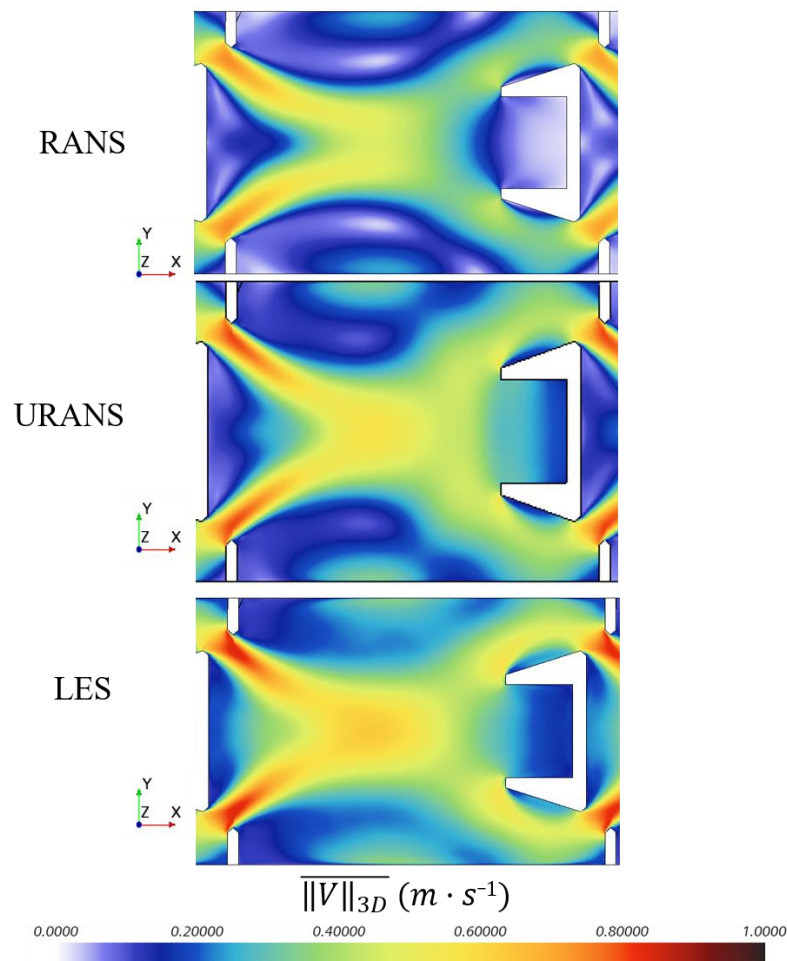
where  $g$  is gravity acceleration ( $m \cdot s^{-2}$ ),  $s$  the slope of the VDSF (-) and  $L$  the length of the pools (m).

### 3.2. Average values

The purpose of this study is to determine the most appropriate method to simulate the turbulent flow inside a VDSF. Thus, the global dynamic inside the third pool is assessed. The mean velocity magnitude in the plane parallel to the bottom ( $h = 0.15$  m) can be seen below, in **Figure 5**.

The dynamic is similar in all three simulations: water comes through the upstream slots (left-hand side) into the pool. The highest velocity can be found in the slots. Both jets reach the middle of the pool and separate again towards the following slots. Several recirculation zones result from the trajectories of the jets. Two are located to the side of the fishway: the one at the top is in a counter clockwise direction while the one at the bottom of the figure is in a clockwise direction. The other two recirculation zones are located behind the central baffle and between the deflectors of the following central baffle.

However, there are some differences between the simulations, foremost the velocity in the slots. The RANS simulation presents a velocity of  $0.7 \text{ m} \cdot \text{s}^{-1}$  while the URANS and LES simulations show one of  $0.8 \text{ m} \cdot \text{s}^{-1}$ . Furthermore, the two trajectories seem to stay rather separate in RANS simulation, while they seem to fully merge together in URANS and LES. The flow also appears to be more 3D-dimensional in LES simulation since there are several locations where the velocity has a rather distinctive gap. Throughout the pool, the velocity is higher in LES than it is in RANS and URANS.

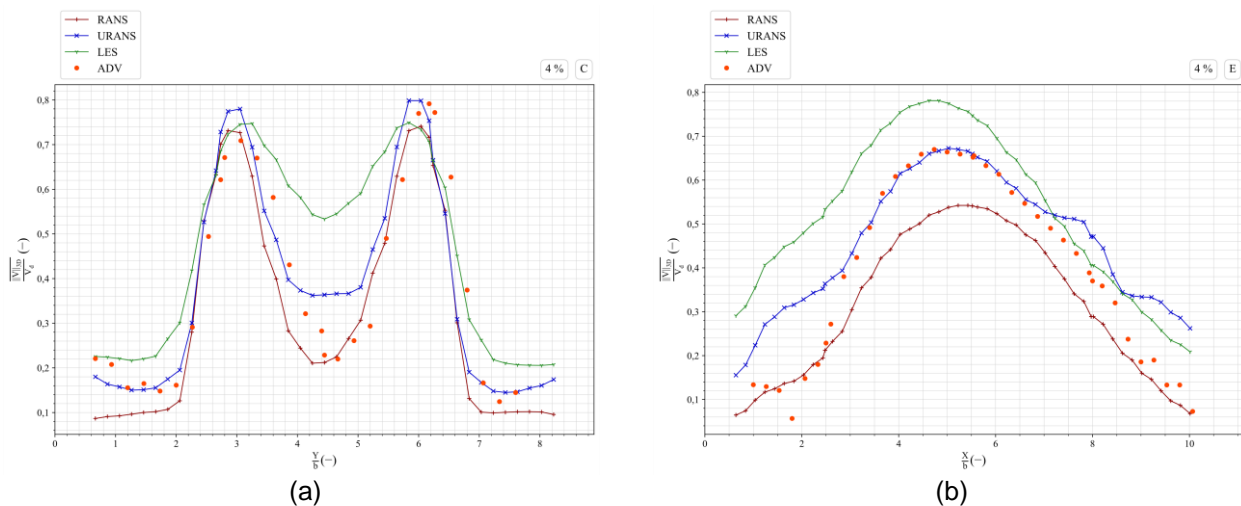


**Figure 5.** Mean velocity magnitude in a plane parallel to the bottom ( $h = 0.15$  m) in the third pool for each method

Since the simulations returned different values, a comparison was drawn from numerical and experimental data. The normalized mean velocity magnitude for the profiles C and E (see **Figure 4**) have been represented in **Figure 6 (a)** and **Figure 6 (b)** respectively.

For the profile C, experimental data exhibits two peaks in velocity magnitude when crossing the two jets coming from the slots. The velocity in the middle however, drastically drops, almost as low as it is on the sides. On the first peak, the three simulations give similar results to the experiments. RANS and URANS continue to be alike to experiments on the fall towards the middle ( $Y/b = 4.45$ ), although URANS mean velocity magnitude does not fall as low as the RANS and experimental ones. However, the LES velocity does not present the same evolution in the middle of the profile. This might be explained by the difference in geometry between experimental and numerical models, since the profiles are not precisely located at the same position (10 mm difference) and the fact that the length of this side of the baffle might influence the range of the wavering of the jets and thus whether the velocity drops in the middle of the profile. On the second peak, only the URANS simulation displays velocities high enough compared to the experiments.

For the profile E, experimental data shows one peak in the middle of the pool, where both jets rejoin. LES velocity is higher than RANS and URANS velocities and overestimate experimental data. Close to the central baffles (for  $X/b < 2.5$  and  $X > 9$ ), RANS simulation is similar to experiments, however, in the middle, the URANS simulation displays a higher and better representation of mean velocity magnitude. Still, after the mixing of the jets, the URANS simulation starts to overestimate the velocity.



**Figure 6.** Normalized mean velocity magnitude for all three simulation methods and experiments for (a) profile C and (b) profile E

The simulations, even if the values of the velocity magnitude are different from the experimental ones, seem to be able to represent the velocity dynamics of the average flow taking place in VDSFs. RANS and URANS appear to be closer to experimental values than LES, which is surprising, given the findings of a previous study (Ballu, 2017). However, it is important to underline that the simulations were launched with a preliminary mesh, which was the same for all three simulations. LES require much finer mesh to present more accurate results. Future studies will thus focus on refining the mesh to a more appropriate size for the LES simulation, to observe the influence on velocity values and on the same geometry as the experimental model to allow more definitive comparison.

### 3.3. Instantaneous values

If LES seems to overestimate the velocity values with the coarse mesh, it still solves and displays coherent instantaneous values, which is not the case of the RANS and URANS simulations. Since RANS is a steady simulation, thus only average data will be extracted from it. However, although URANS is an unsteady method, the unsteady flow was not properly grasped. The instantaneous values were really similar to the average ones. The URANS simulation will be subject to further work on the method and mesh in the future.

The velocity magnitude of the plane parallel to the bottom of the channel, located at  $h = 0.15$  m, in the third pool for different time in LES simulation is presented in **Figure 7**. These snapshots are successive and useful to understand the temporal evolution of the jets, which are not a smooth as the mean trajectories.

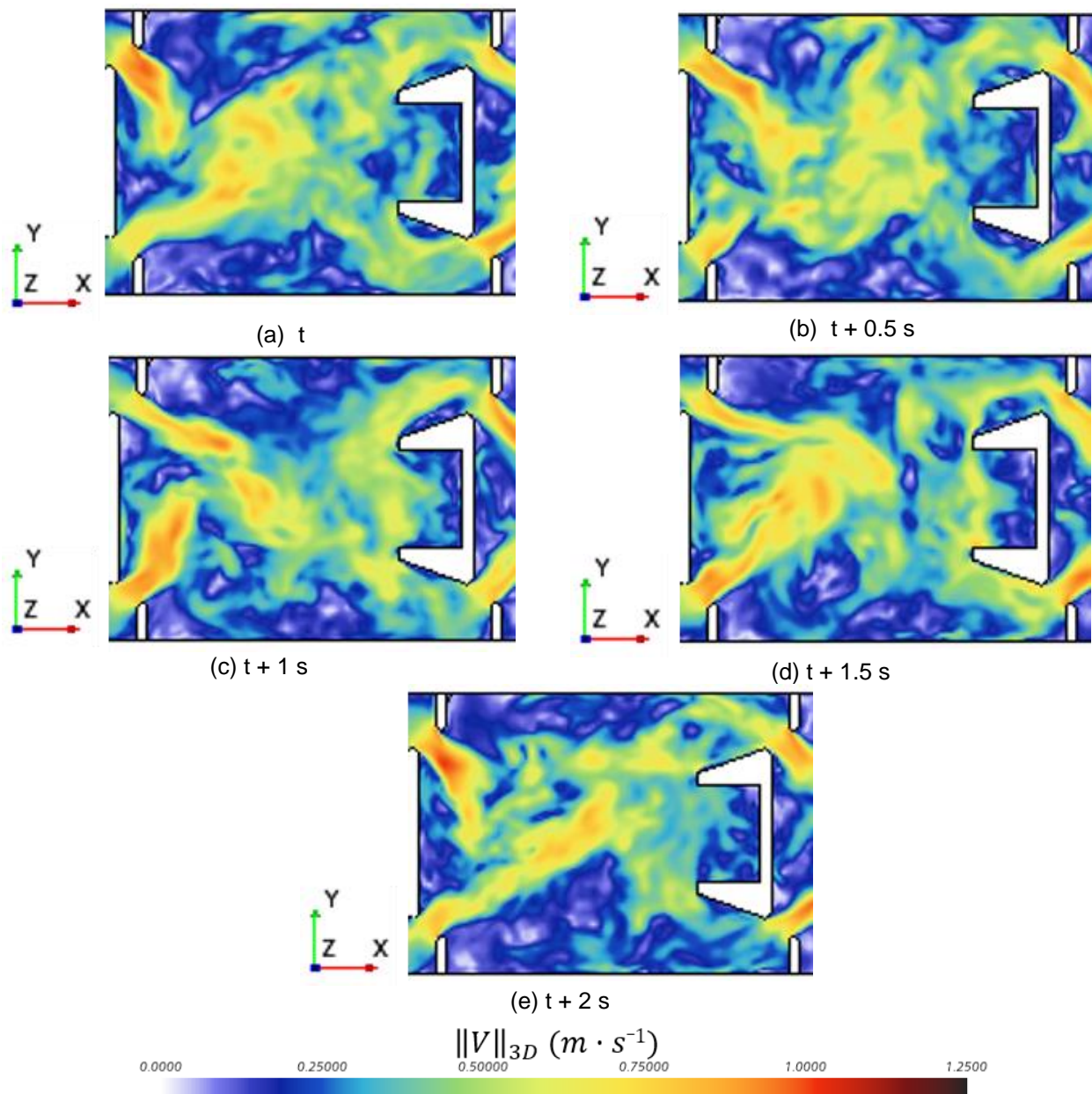
The first snapshot (a) was taken at a moment where the jet coming from the lowest slot of the picture is dominant. It goes from the slot to the middle of the pool uninterrupted, towards the opposite slot (the slot of the

other side for the next pool). The jet coming from the upper slot is rather small but building force and directed towards the dominant slot and adjacent central baffle.

The second snapshot (b) shows the disruption of the thus-far dominant jet by the other one. The jet is broken close to the slot, and the rest of the stream is continuing towards the opposite slot. The jet from the top of the picture is now the stronger one.

In the third snapshot (c), the bottom jet has gotten stronger and is breaking the one from the top. In the fourth snapshot (d), the bottom-jet has significantly strengthened and is now pushing the top-jet towards the right-hand top side slot, thus taking dominance.

In the final snapshot (e), the bottom-jet is still dominant and heading towards the opposite slot. The top-jet is building strength and is directed towards the adjacent central baffle and its twin slot, thus returning to the original state.



**Figure 7.** Velocity magnitude in the third pool at different time for LES simulation

The jets coming from the slots are wavering back and forth in the LES simulation, which is a result that can also be observed experimentally. The LES simulation therefore presents instantaneous data which is interesting not only for the understanding of turbulent flow happening inside a VDSF, but for real life hindrances that occur for fish species as well. LES simulation is consequently more appropriate to simulate turbulent flow occurring inside VDSFs.



#### 4. CONCLUSIONS

The purpose of this study was to determine the best method to numerically simulate the turbulent flow inside Vertical Double Slot Fishways. Three methods were used: RANS, URANS and LES simulations for a scale model of a VDSF. Two specific profiles were studied in addition to a plane in the third pool, parallel to the bottom of the channel. It appeared that all three simulations returned coherent results for the average dynamic of the flow inside the domain. Mean velocity magnitude from the RANS method appears to be rather underestimated while the LES simulation seems to overestimate velocity values, compared to experimental data. However, the LES model presents turbulent kinetic energy similar to experimental one, unlike RANS and URANS simulations. This finding tends to favour LES simulation since it properly represents the dynamic of the flow, even though, for now, it seems to overestimate velocity.

Further studies with a finer mesh for LES simulation will be required. Still, with this preliminary mesh, the unsteady flow and the oscillation of the jets coming from the two slots were detected from the LES simulation. The access to instantaneous data is appealing since it will embody the current truly faced by the fish, as opposed to average values. From those instantaneous data, fish reactions and behaviours could be depicted, and optimized designs of fishways could be drawn from the understandings of these studies.

#### 5. ACKNOWLEDGEMENTS

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