Numerical approaches to evaluate the hydraulics of Vertical Slot Fishways

A comparative study of 2D and 3D simulations

Marcelo X. Ruiz-Coello, Ricardo Sandoval, Andrea Bottacin-Busolin, María J. Guerra, Luis Ríos, Patricio Ortega & Andrea Marion

marceloxavier.ruizcoello@unipd.it

26-05-2023

XL International School of Hydraulics
23 - 26 May 2023 • Kąty Rybackie • Poland

European Union Horizon 2020 Research and Innovation Programme: Marie Sklodowska-Curie Actions, Grant Agreement No. 860800

Introduction

(Marriner et al., 2016)

River connectivity has been affected by human development

Grill et al. (2019)

VSFs are the most common and most studied fishways worldwide

Fuentes-Pérez et al. (2017)

VSF design efficiency are still a challenge (54% - 63%).

Bunt et al. (20012

90% efficiency is required to achieve restoration of connectivity

Lucas & Baras (2001)

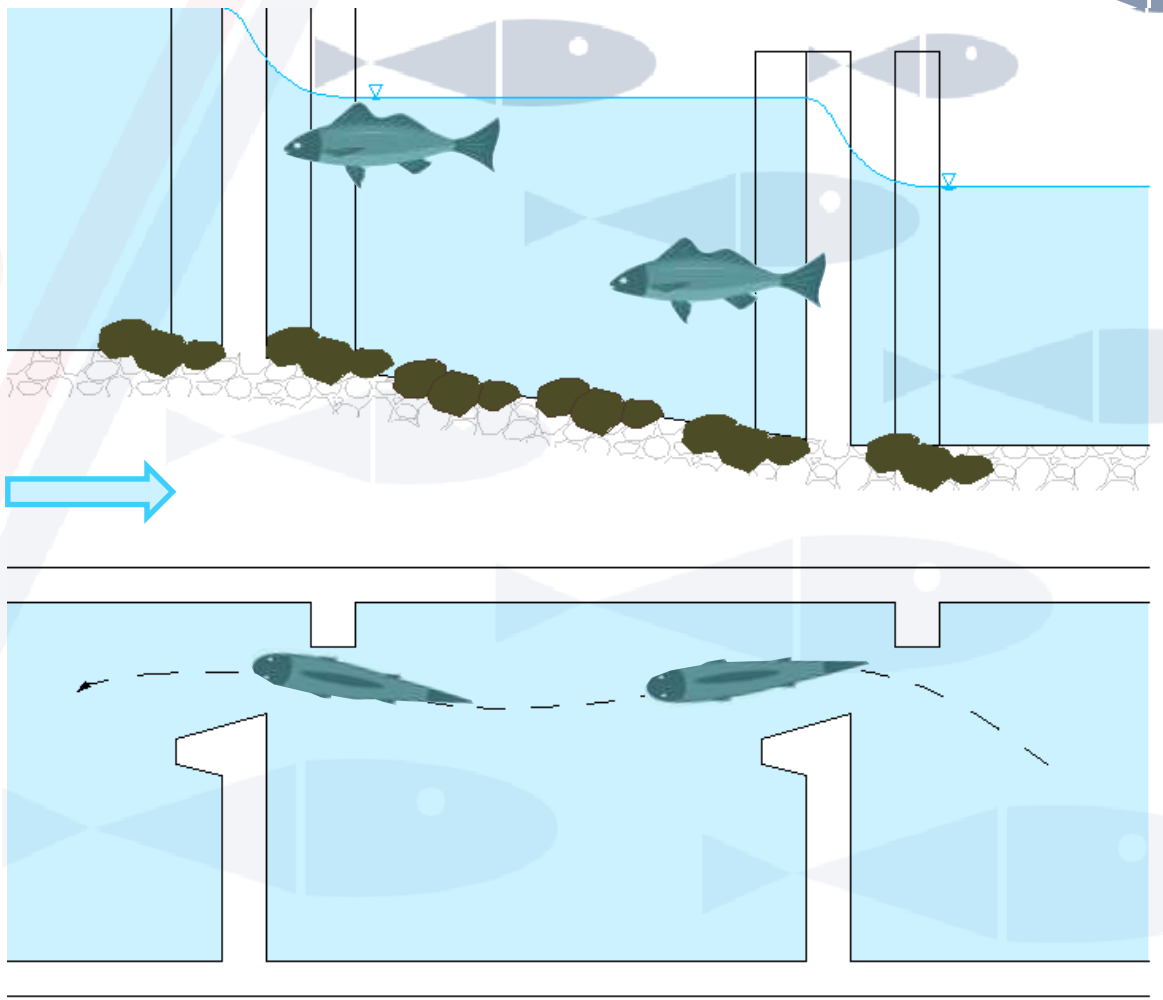
CFD methodologies have already been applied for evaluating VSFs

Powerful open-source tools are available, OpenFOAM & TELEMAC2D

Vertical Slot Fishways

Design requirements

- A VSF should provide suitable migration pathway and resting zone
- Baffles provide a vertical passing slot
- Jets should be clearly defined for upstream guidance
- Recirculation zones should be large enough to provide suitable resting zones
- Volumetric power dissipation should be in the range 150 – 200 W/m^3
- VSF dimensions are related to the biological requirements of the targeted species.



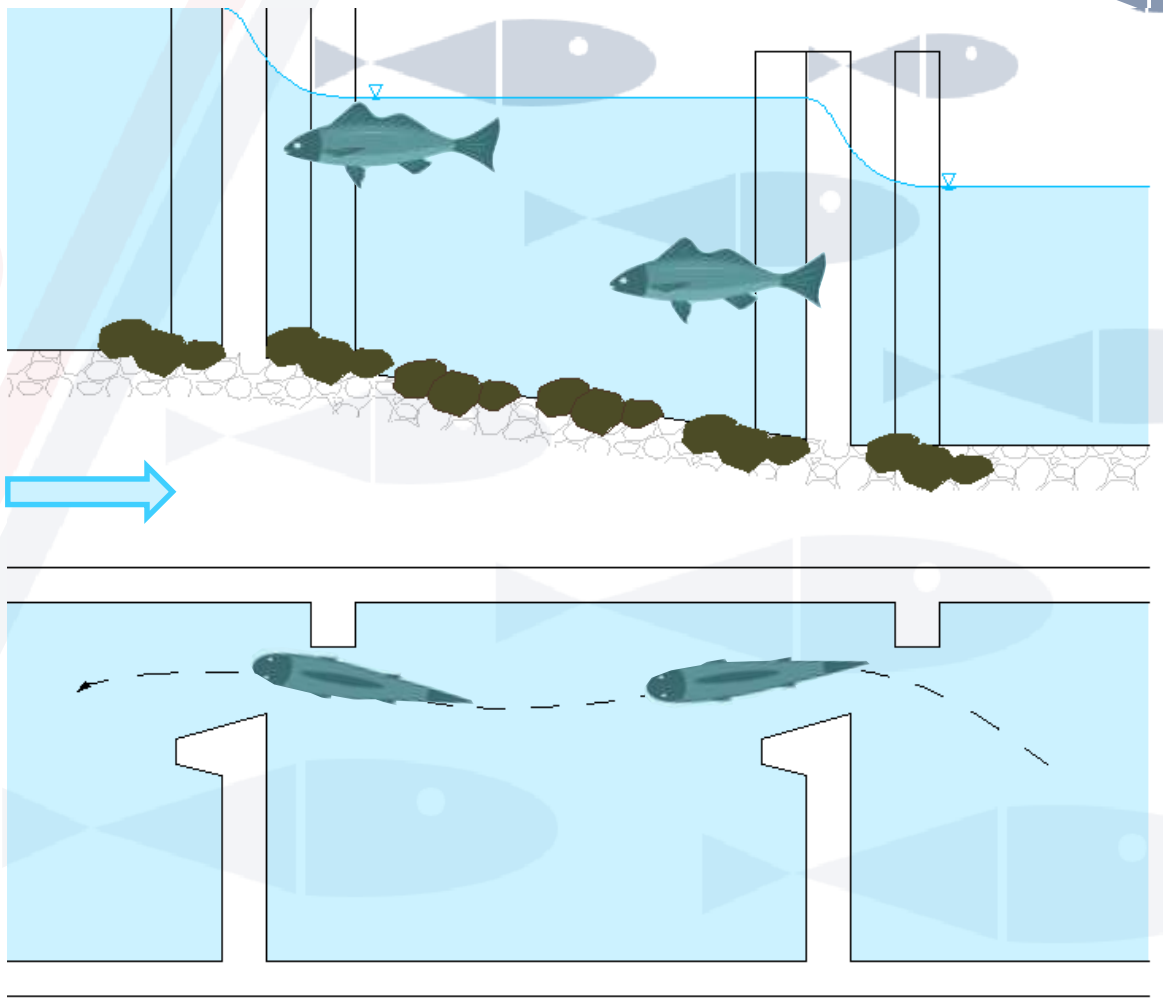
Vertical Slot Fishways

Hypothesis

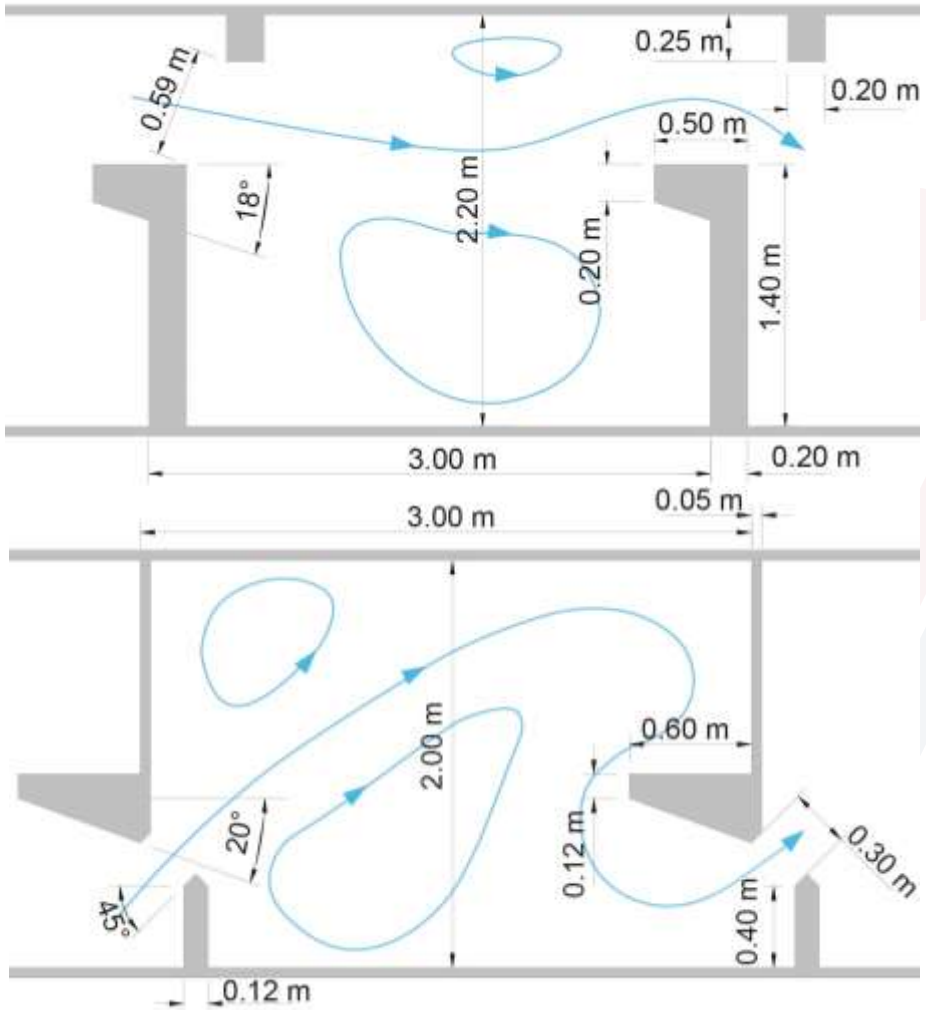
- Fully 3D hydraulic behavior is rarely found in the working discharges on VSF. Therefore, hydraulics can be represented by both 2D and 3D simulations

Objectives

- To evaluate the hydraulics of VSF through numerical simulations applying open-source modelling tools
- To explore the advantages and disadvantages of 2D and 3D modelling approaches
- To evaluate the influence of physical parameters (slope, friction)



Experimental data



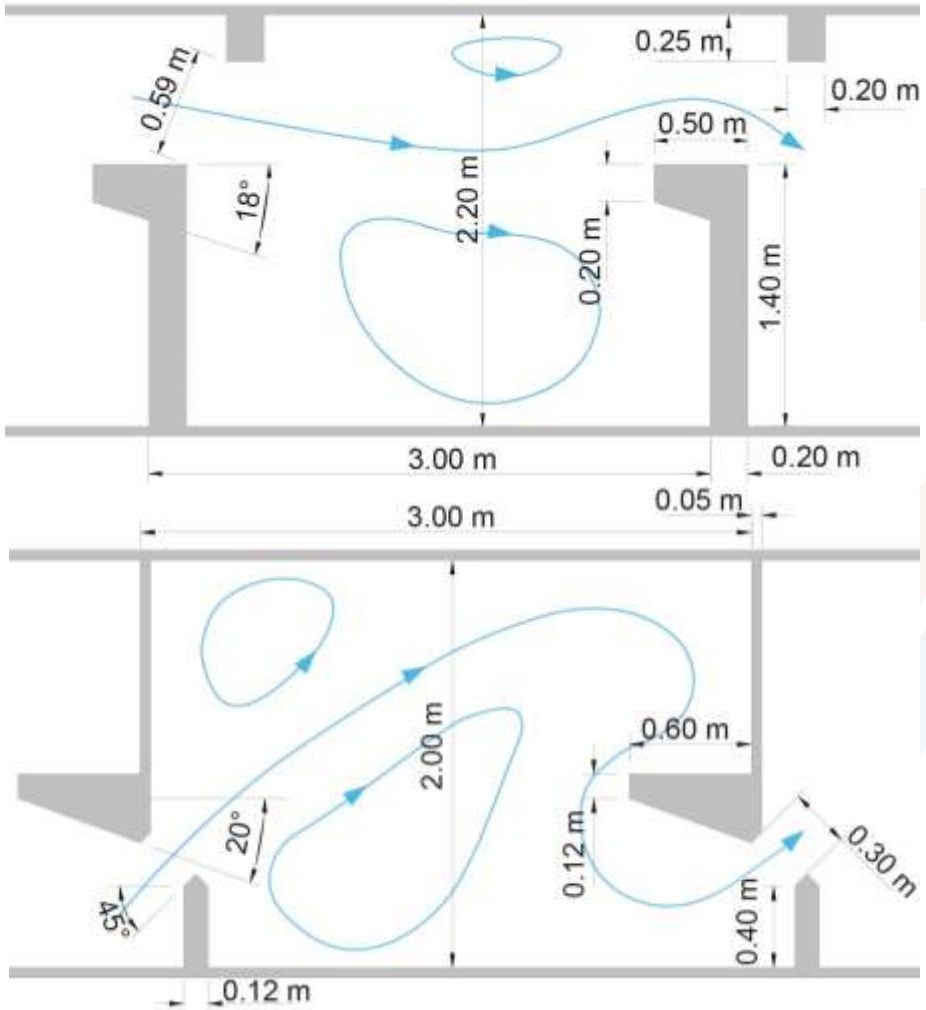
Mild – slope

- Bombač et. al (2015).
- Built at Arto-Blanca hydropower plant in Slovenia
- Scale model 1:1
- 2D & 3D simulations
- ADV measurements from 4 cross sections

Geometry

- L_p: 3.0 m
- B : 2.2 m
- N : 5 pools
- Slope : 0.0167 m/m

Experimental data



Steep – slope

- Chorda et. al (2010).
- Laboratoire d'Etudes Aérodynamicques, France
- Scale model 1:4
- 2D simulations
- ADV and PIV measurements from 2 cross sections

Geometry

- L_p: 3.0 m
- B : 2.0 m
- N : 5 pools
- Slope : 0.1 m/m

Theoretical Background:

Three – dimensional simulations

Inc. Navier – Stokes Equations	OpenFOAM v2112, FVM (*interFoam*)
Turbulence Modelling	3D k-ε model

$$\frac{\partial u_i}{\partial x_i} = 0; \qquad i, j = 1, 2, 3$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left((\nu + \nu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}k \right) + \mathrm{f}_i$$

Theoretical Background:

Two – dimensional simulations

Saint – Venant Equations	TELEMAC v8p3r0, FEM
Turbulence Modelling	2D k-ε model

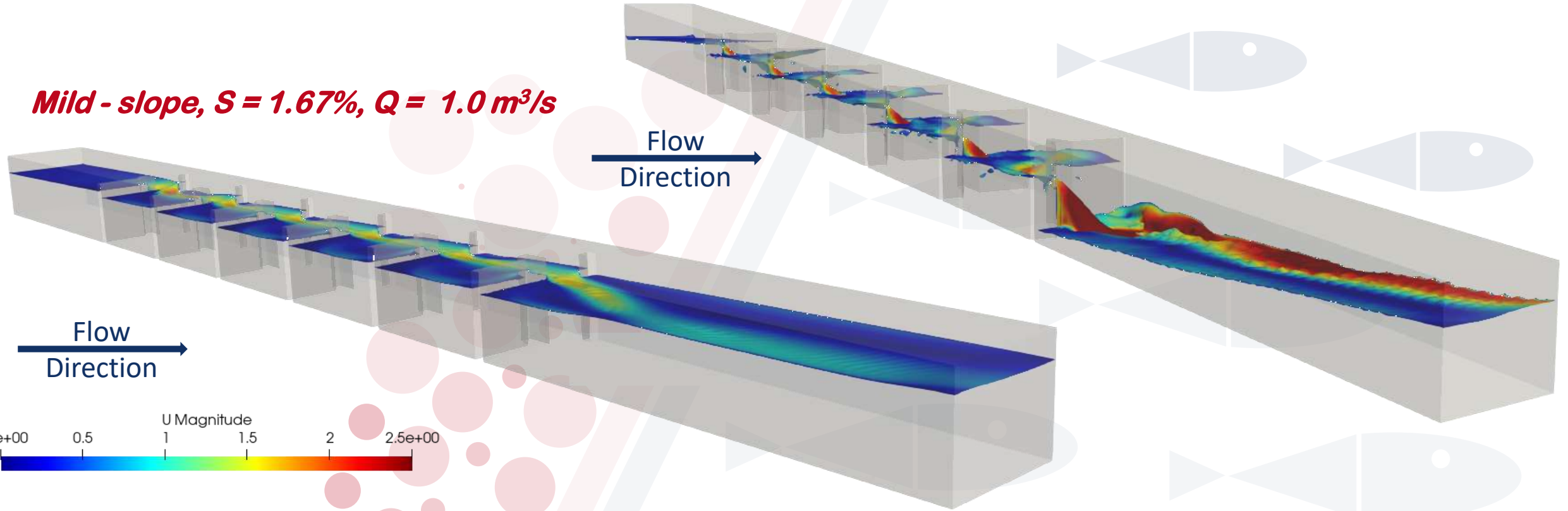
$$\frac{\partial h}{\partial t} + \frac{\partial (h\, u_i)}{\partial x_i} = 0; \qquad i, j = 1, 2$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial\, u_i}{\partial x_j} = -\frac{\partial Z}{\partial x_i} + S_f + \frac{1}{h}\frac{\partial}{\partial x_j}\left(h\, \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$$

Steady state: 3D simulations

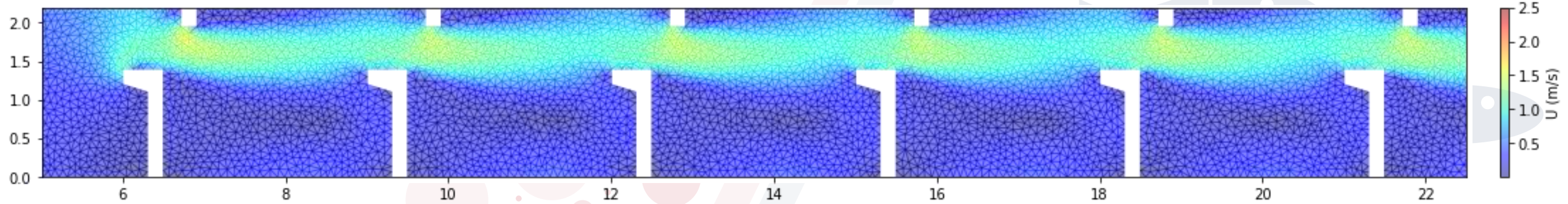
Steep - slope, S = 10.0%, Q = 0.735 m³/s

Mild - slope, S = 1.67%, Q = 1.0 m³/s

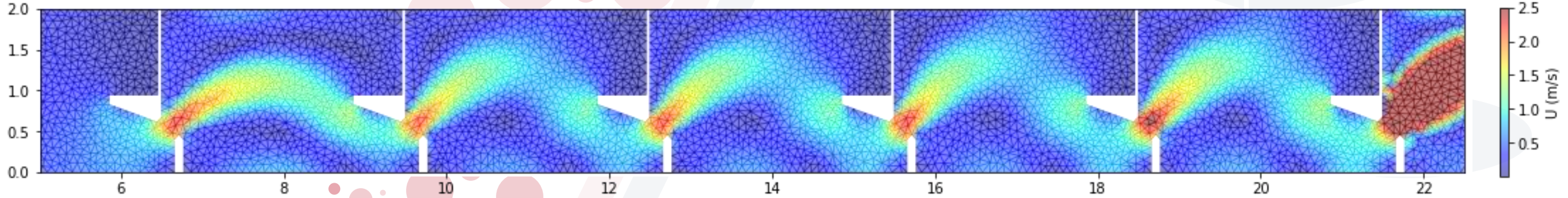


Steady state: 2D Simulations

Mild - slope, S = 1.67%, Q = 1.0 m^3/s

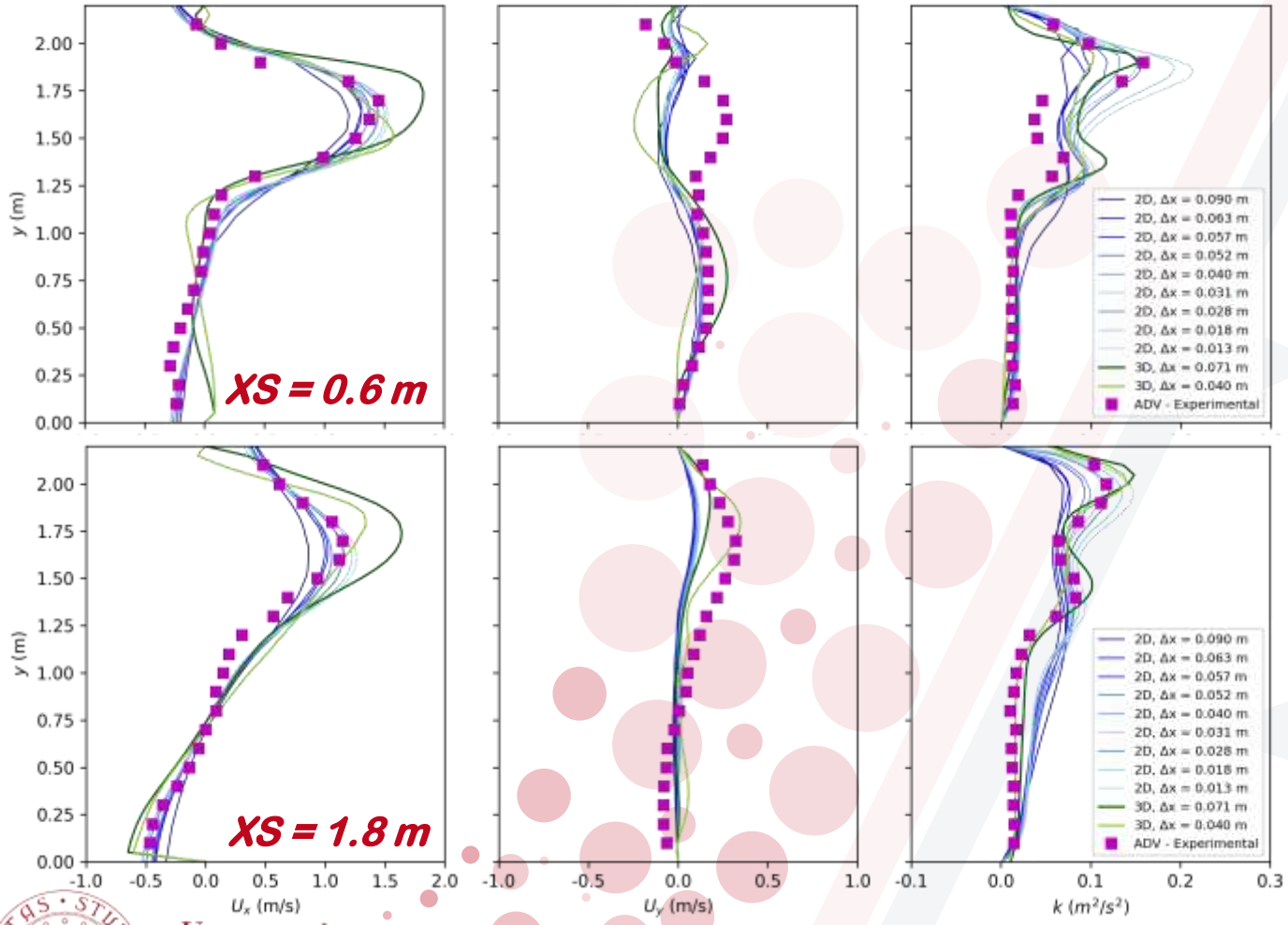


Steep - slope, S = 10.0%, Q = 0.735 m^3/s



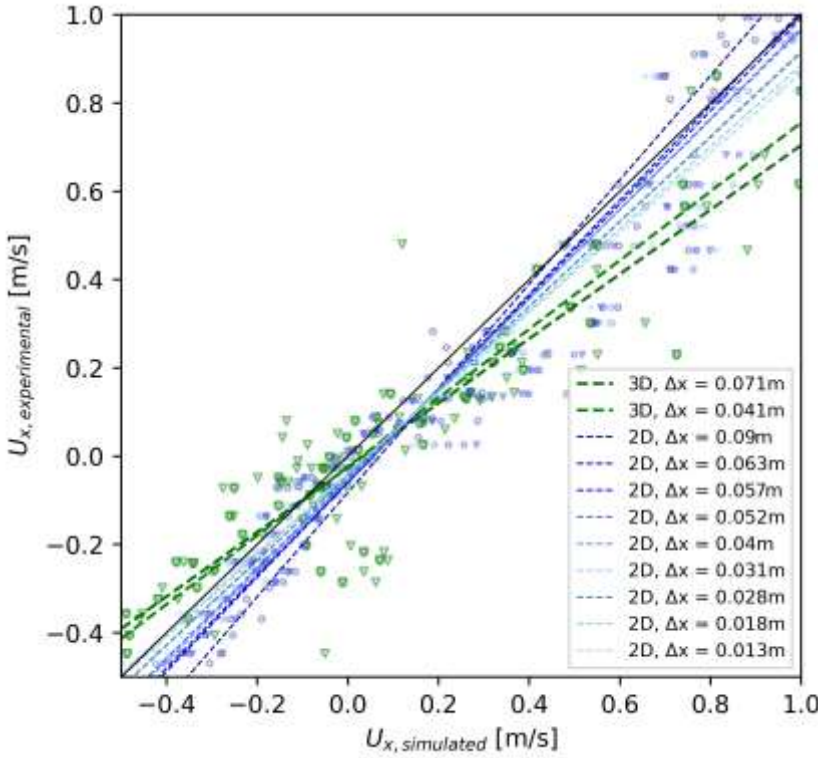
Marie Sklodowska-Curie Actions, Grant Agreement No. 860800

Results: Mild slope

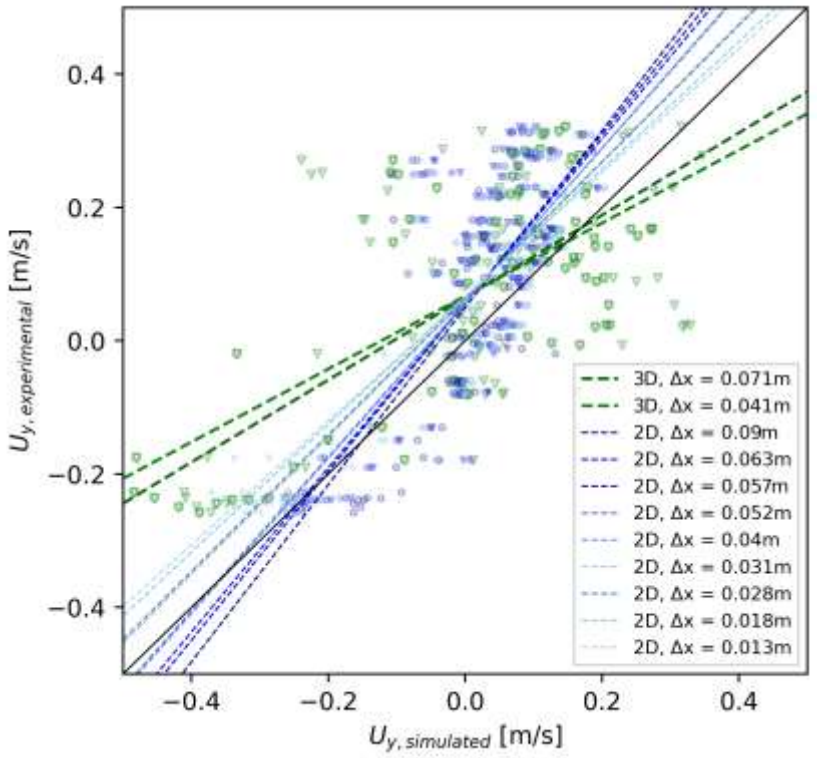


- Velocities and turbulent kinetic energy are well represented in every cross sections (XS).
- Turbulent kinetic energy is better reproduced in 3D simulations
- Coarser 3D simulations tend to overestimate the velocities
- *y*-velocities are close to zero. Therefore, relative error is sensitive to small changes

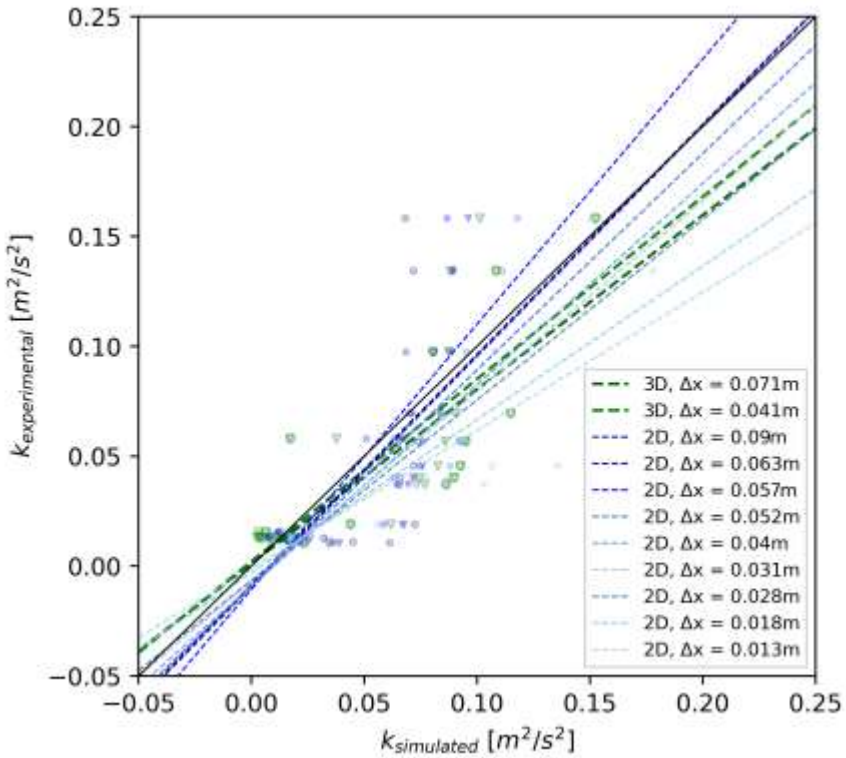
Validation: Mild slope



x-velocity

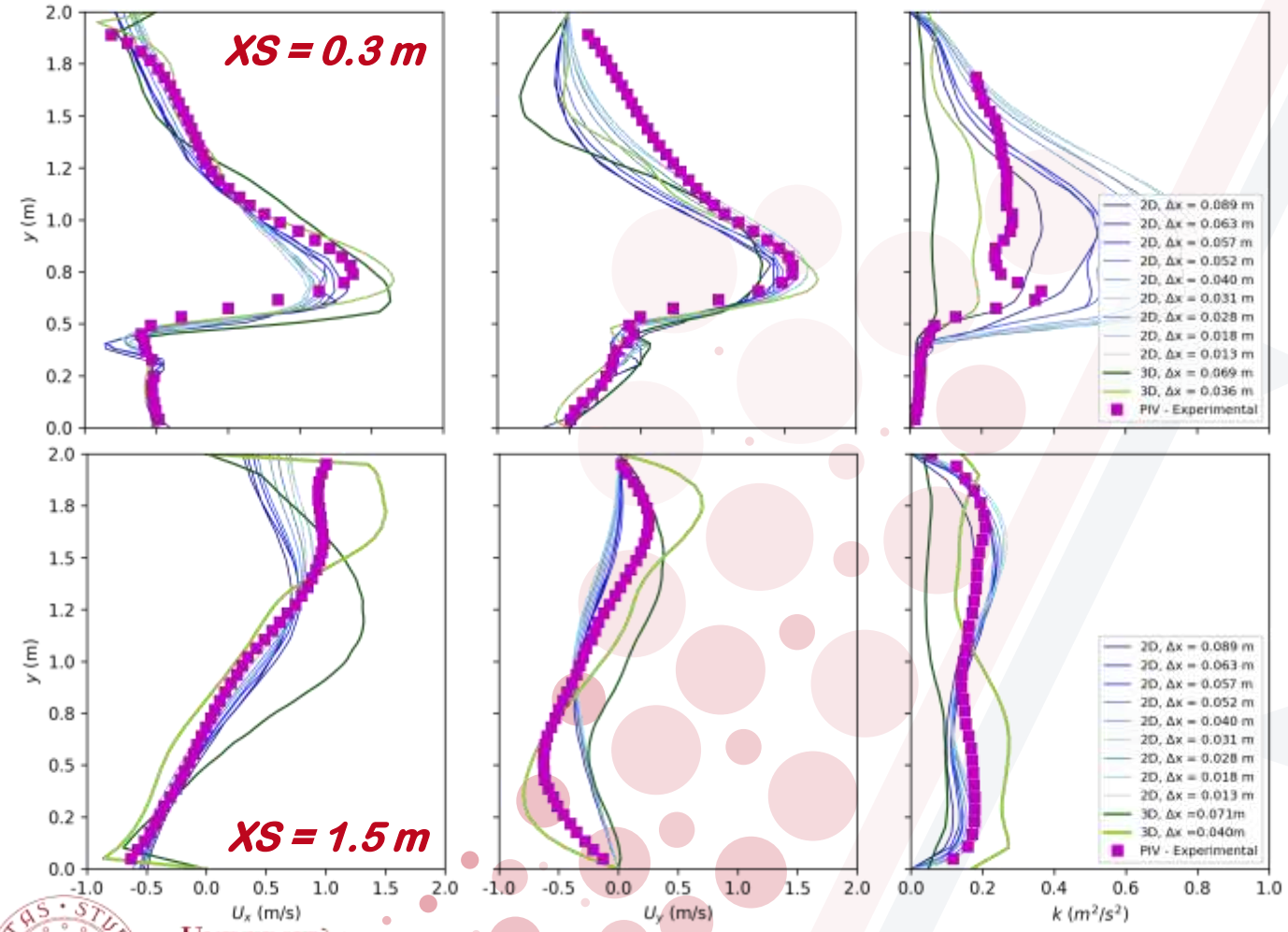


y-velocity



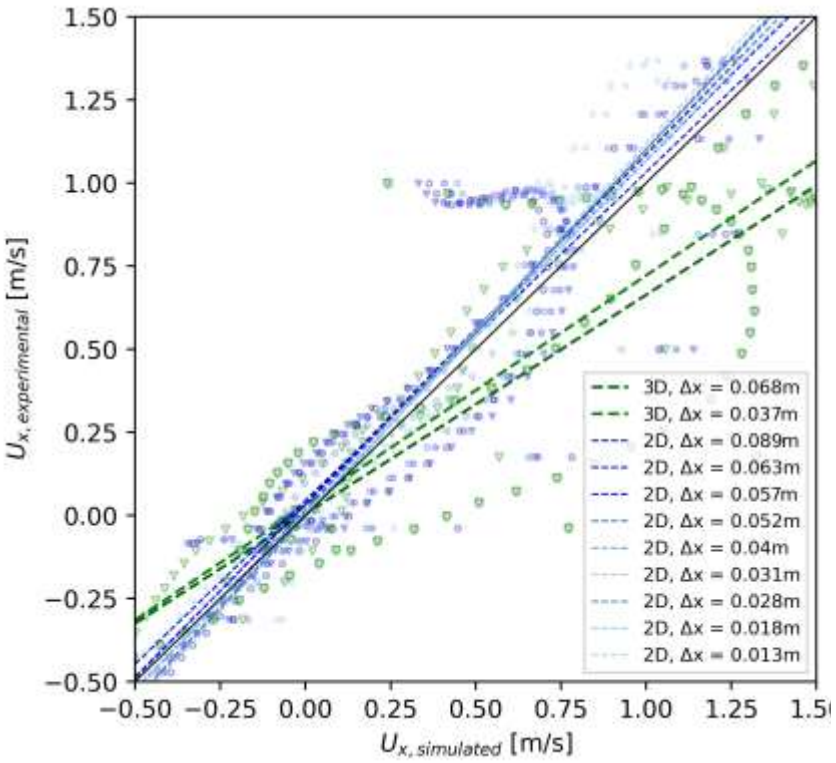
Turbulent kinetic energy

Results: Steep slope

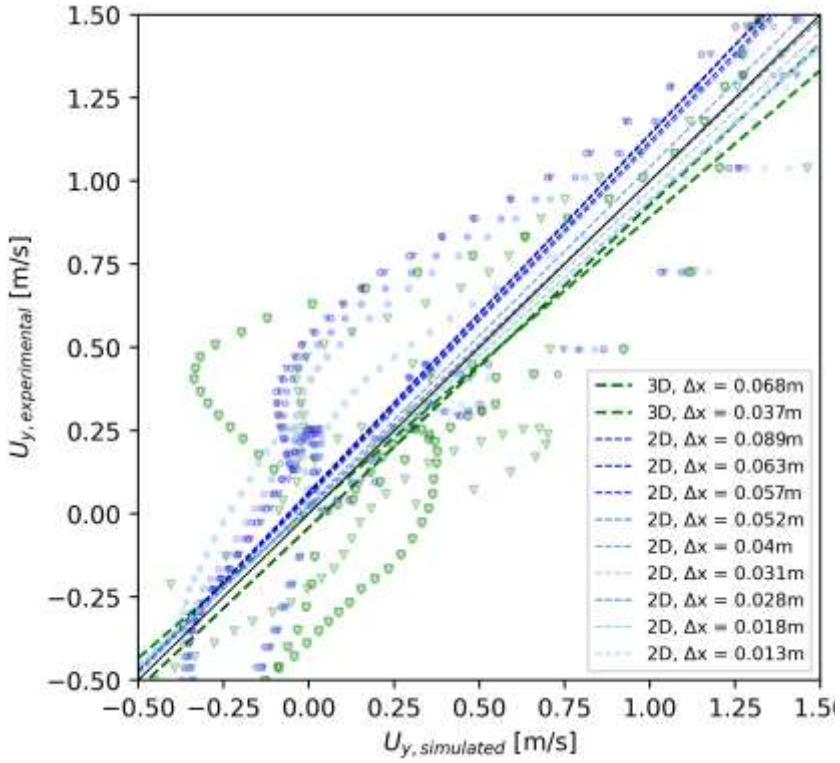


- In the cross section, closer to the slot, 2D simulations tend to overestimate turbulent kinetic energy.
- 3D simulations tend to overestimate the velocities.
- Mesh size does not improve the representation velocity representation closer to the slots
- Turbulent kinetic energy is better represented in the middle of the pool

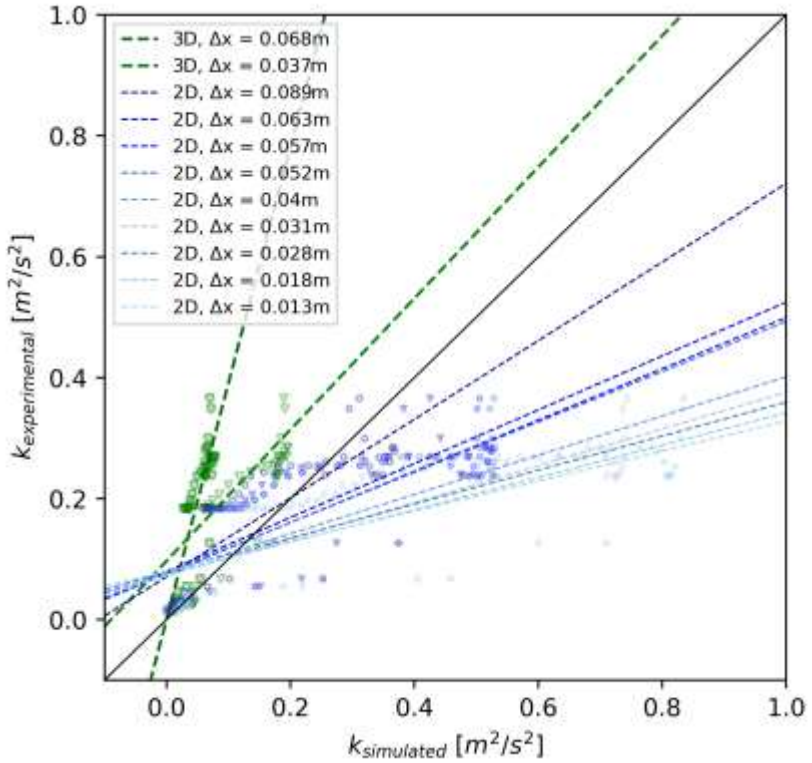
Validation: Steep slope



x-velocity

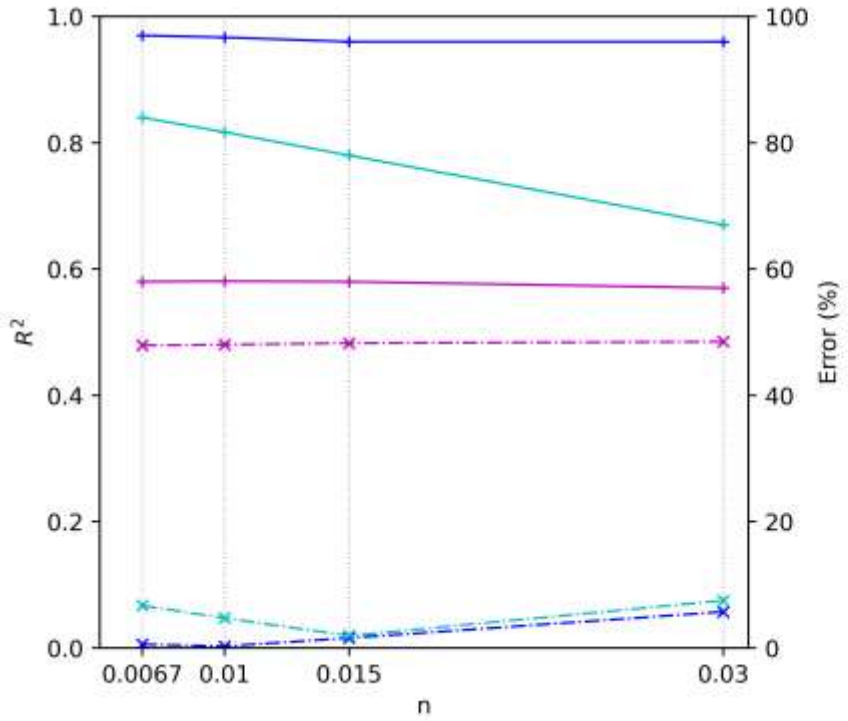


y-velocity

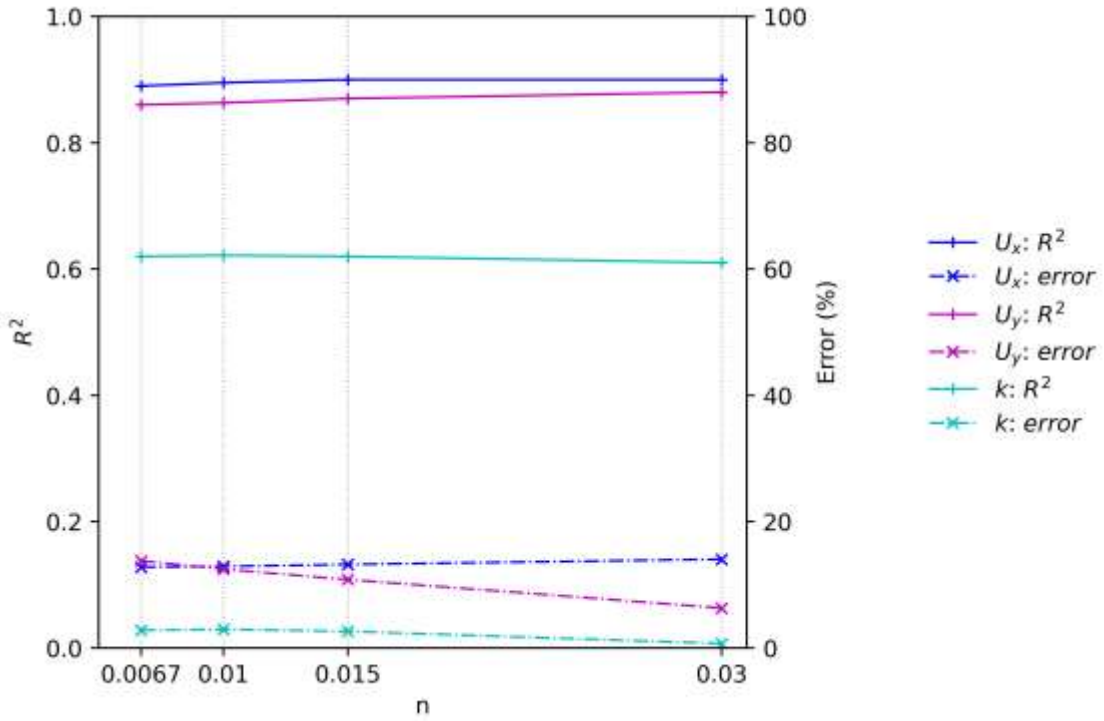


Turbulent kinetic energy

Results: Impact of friction coefficient



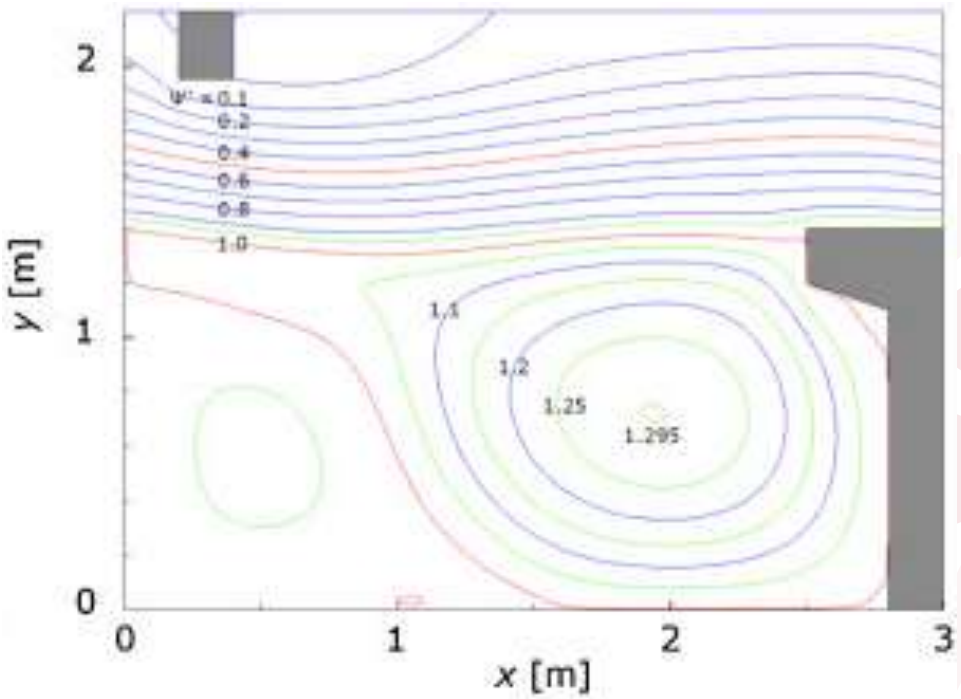
Mild - slope



Steep - slope

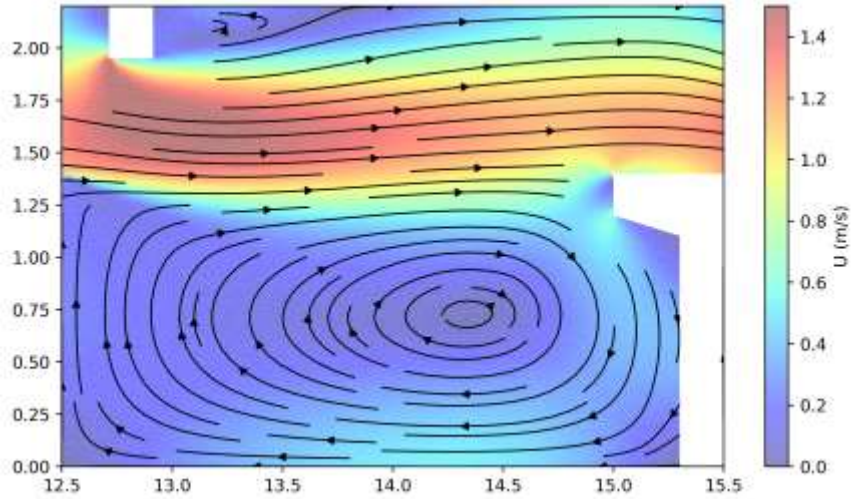
Marie Sklodowska-Curie Actions, Grant Agreement No. 860800

Flow Topology: Mild slope

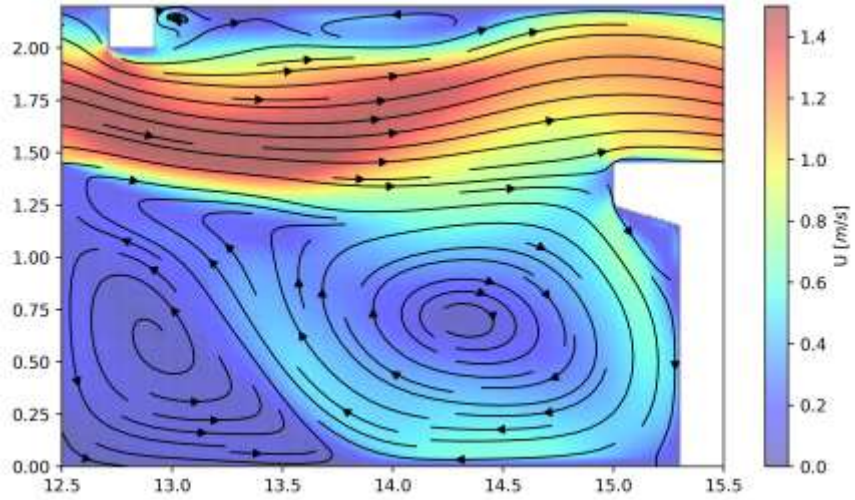


Bombač, M., Novak, G., Mlačnik, J. & Četina, M. (2015). Extensive field measurements of flow in vertical slot fishway as data for validation of numerical simulations. EcologicalEngineering, 84, 476–484. https://doi.org/10.1016/j.ecoleng.2015.09.030

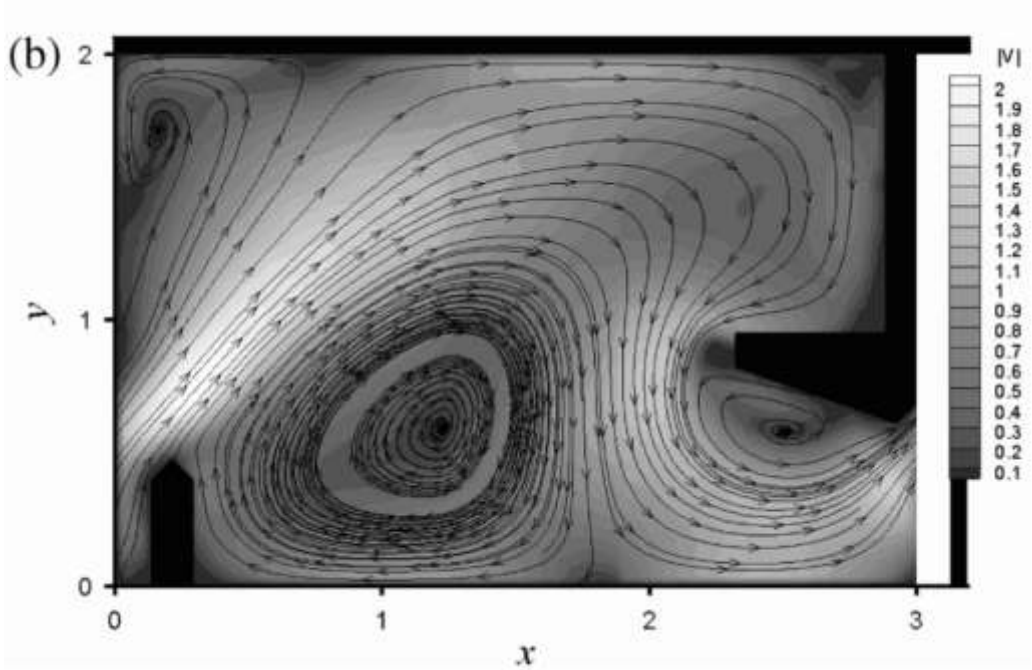
2D Simulation



3D Simulation

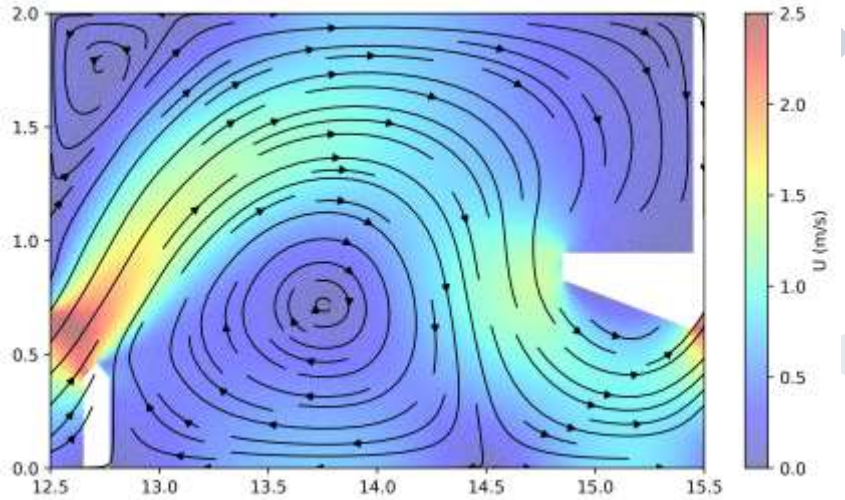


Flow Topology: Steep slope

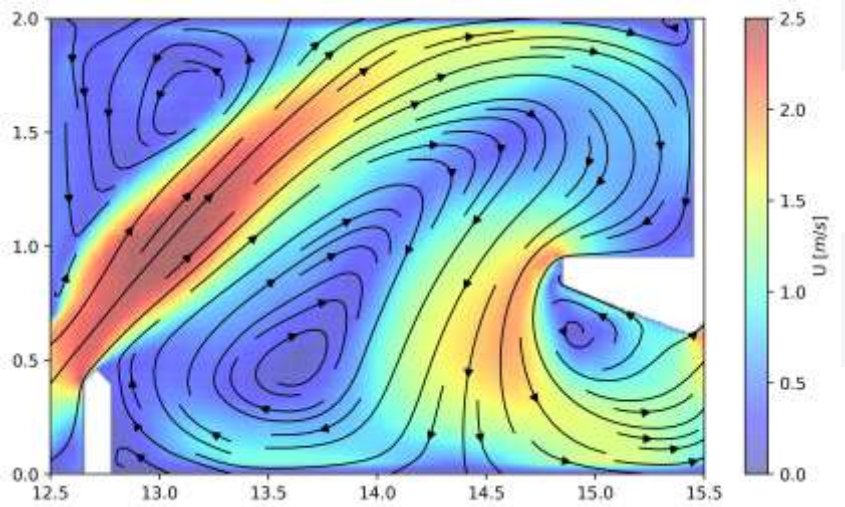


Chorda, J., Maubourguet, M. M., Roux, H., Larinier, M., Tarrade, L., & David, L. (2010). Two-dimensional free surface flow numerical model for vertical slot fishways. Journal of Hydraulic Research, 48(2), 141–151. https://doi.org/10.1080/00221681003703956

2D Simulation



3D Simulation



Model Comparison

3D Simulations (OpenFOAM)

- Simulations met the validation criteria for velocities and turbulent kinetic energy
- Mild & Steep slope hydraulics was successfully reproduced
- Flow patterns outcome reproduced flow topology observed experimentally
- **It is computationally demanding**

2D Simulations (TELEMAC-2D)

- Simulations met the validation criteria for velocities.
- **Turbulent kinetic energy was not reproduced in the steep – slope VSF**
- **Flow patterns missed some recirculation zones measured experimentally**
- Model setup and computing is much faster than 3D simulations

Conclusions and recommendations

- For all cases considered in this study, the simulation results met the validation criteria. However, accuracy was different from one case to another.
- Two - dimensional simulations displayed a considerable overestimation of turbulent kinetic energy, especially in the steepest case close to the slots.
- Variation in the friction coefficient did not significantly affect the accuracy of the 2D simulations.
- When the computational resources are available, 3D simulations should be preferred over 2D simulations.

References

Bombač, M., Novak, G., Mlačnik, J., Četina, M., 2015. Extensive field measurements of flow in vertical slot fishway as data for validation of numerical simulations. Ecol. Eng. 84, 476–484. https://doi.org/10.1016/j.ecoleng.2015.09.030

Chorda, J., Maubourguet, M. M., Roux, H., Larinier, M., Tarrade, L., & David, L. (2010).Two-dimensional free surface flow numerical model for vertical slot fishways. Journal of Hydraulic Research, 48(2), 141–151. https://doi.org/10.1080/00221681003703956

Marriner, B.A., Baki, A.B.M., Zhu, D.Z., Cooke, S.J., Katopodis, C., 2016. The hydraulics of a vertical slot fishway: A case study on the multi-species Vianney-Legendre fishway in Quebec, Canada. Ecol. Eng. 90, 190–202. https://doi.org/10.1016/j.ecoleng.2016.01.032

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., . . . Zarfl, C. (2019). Mapping the world's free-flowing rivers. Nature, 569(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9

Fuentes-Pérez, J. F., García-Vega, A., Sanz-Ronda, F. J., & Paredes, A. M. d. A. (2017). Villemonte's approach: A general method for modeling uniform and non-uniform performance in stepped fishways. Knowledge & Management of Aquatic Ecosystems, (418), 23. https://doi.org/10.1051/kmae/2017013

Thank you!

Questions…