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Hybrid numerical-physical hydraulic modelling prevents a fish pass from clogging - Arve River Geneva-CH

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Abstract

Due to its alpine nival regime, the Arve River (F-CH) possesses a heavy sediment transport causing frequent clogging of the Vessy right-bank fish ladder constructed in 2007 on a 156-year-old spillway. The *Service industriel de Genève* (SIG) inquired a detailed analysis from the Laboratory for Applied Hydraulics (LHA) of HEPIA to find a sustainable solution replacing the inoperative fish ladder by a bypass river. This measure, based on Larinier, Courret and Gomes (2006), was proposed by an alternative analysis of Gobat (2016). Numerical 2D simulations of Wohlwend (2015) explained the key phenomenon of clogging of the existing fish ladder. On these achievements, a hybrid modelling was carried out, combining movable-bed physical modelling by the LHA and 3D numerical simulation by Jaeger (2020). Physical modelling provided a solution preserving the bypass river from Arve's bed-load (Vecsernyés et al. 2019), by implementing a combined groin structure in front of the water intake. Color $KMnO_4$ dye tracer pointed out the persistence of a clear fish waterway between the bypass-river and the main Arve River, even during low-flow conditions following floods. Dye tracer also highlighted varying conditions of turbulence behind the water intake and within the bypass river. Consecutive flood/low-flow conditions were tested by hybrid numerical-physical simulation. The 3D numerical simulations helped to define the hydraulic works reducing fine-sediment deposit potential at the water intake and within the bypass river. The hybrid modelling provided a robust solution for the construction of a bypass river and its hydraulic works.

Keywords: Hybrid modelling; Movable-bed physical model; Flow-3D numerical simulation; Suspended and bed load simulation; Fish pass

1. INTRODUCTION

Fish migration in the Vessy meander of the Arve River is hindered by a 220 m long and 3.5 m high spillway (Figure 1) erected in 1866 by the *Société des eaux de l'Arve*, fragmentising and isolating the habitats of fish populations. Over more than a century, this hydraulic structure conveyed a part of the river discharge to a pumping station in order to supply local municipalities of Geneva with drinking water. In 1988 the *Service Industriel de Genève* (SIG) overtook these activities and constructed a low-head hydroelectric power plant. In order to guarantee free upstream fish migration, two concrete fish ladder were constructed. Yet, soon after the operations started, an annual return period flood clogged the right-bank fish pass and revealed that it would be frequently inoperative due to the strong sediments load and floated debris of the Arve River.

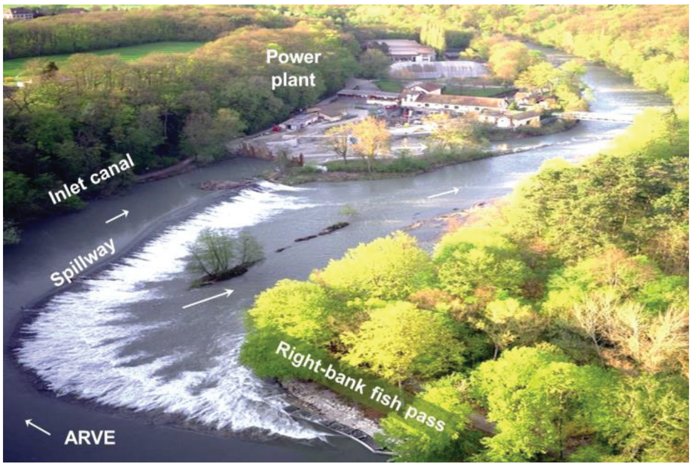
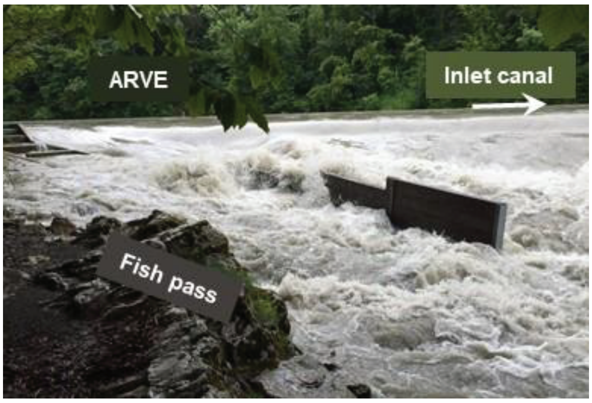


Figure 1. Overall view of Arve's Vessy meander, the spillway and the right-bank fish pass frequently clogged

The heavy suspended sediment and bed load of the Arve River engender natural alternate bars, point bars and local bed erosion along the river. Downstream from de Vessy spillway, these patterns evolve due to successive flood and low-water conditions. Floods larger than annual submerge the Vessy fish passes and are responsible for their failing due to suspended sediment and woody debris, as demonstrated in Figure 2.



a)

b)

Figure 2. a) The submerged right-bank fish pass. **b)** The clogged right-bank fish pass.

Given the high complexity of the hydraulic and sediment dynamic conditions of the Vessy meander the SIG mandated the Laboratory for Applied Hydraulics of HEPIA to determine, by means of a movable-bed physical model and by 3D numerical simulation the appropriate arrangement of the water intake and the hydraulic works of the future bypass river.

2. OBJECTIVES

The present study pursued the following objectives:

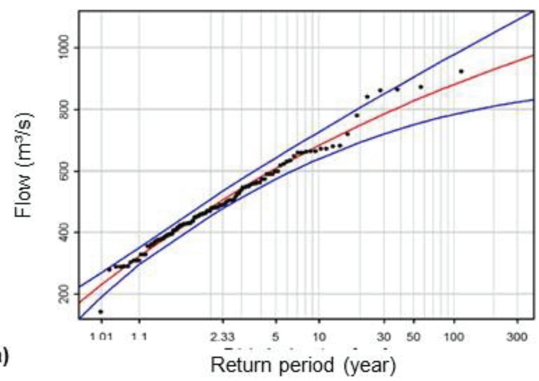
i. Find a solution on the physical model avoiding the transfer of Arve's bed load to the bypass river.
ii. Determine by 3D numerical simulation the most efficient arrangement of the water intake's hydraulic works preventing the bypass river from clogging due to fine sediments.

3. PRELIMINARY DATA

3.1 Hydrological data

The Arve River starts in the Mont-Blanc mountain range and possesses an alpine nival hydrological regime. Its main stream extends in France over 95 km upstream from Geneva with a 1976 km² catchment. Arve River's peak discharge statistics as well as low-water statistics were used from Swiss Federal Office for the Environment (FOEN 2019) at the *Bout-du-Monde* hydrometric gauge station (Figure 3).

a)



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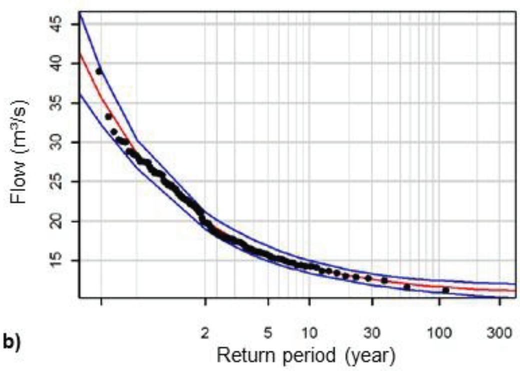


Figure 3. a) High-water statistics; **b**) Low-water statistics of Arve River, at the *Bout-du-monde* hydrometric gauge station Geneva (FOEN). Black scatter: observed events; red line: best estimate; blue lines: 95% confidence interval of returns.

The alternative analysis was carried out on the physical model with the stationary peak discharge flow of three return periods, T = 1 year; 2 years and 10 years. Floods were systematically followed by a low-flow condition. At the water intake, the upstream boundary condition of the main stream is defined by the 3.5 m high spillway, culminating at 388.20 m a.s.l. Within the bypass river a quasi-uniform flow was assumed.

3.2 Biological data

For restoring free fish migration at the Vessy meander, five fish target species were identified out of twenty inventoried (GREN 2009), as follows: Brown trout (*Salmo trutta fario, L.*), Lake trout (*Salmo trutta lacustris, L.*), Grayling (*Thymallus thymallus, L.*), Chub (*Leusiscus cephalus, L.*), Barbel (*Barbus barbus, L.*). Migration period of each of them related to Arve's hydrological regime is shown in Figure 4. During winter, the migration period of brown and lake trout corresponds to low-flow conditions. Snow melting generates high suspended sediment concentration, during the migration of the three other target species. The Vessy fish pass structure must enable upstream migration of the target species, no matter their developmental stage nor their swimming and jumping ability, according to Aigoui and Dufour (2008). While cruising, water depth must be at least 0.3-0.4 m with a flow velocity not exceeding 0.8 m/s. Waterfalls should not exceed 0.20 m and surge velocity 2.0 m/s.

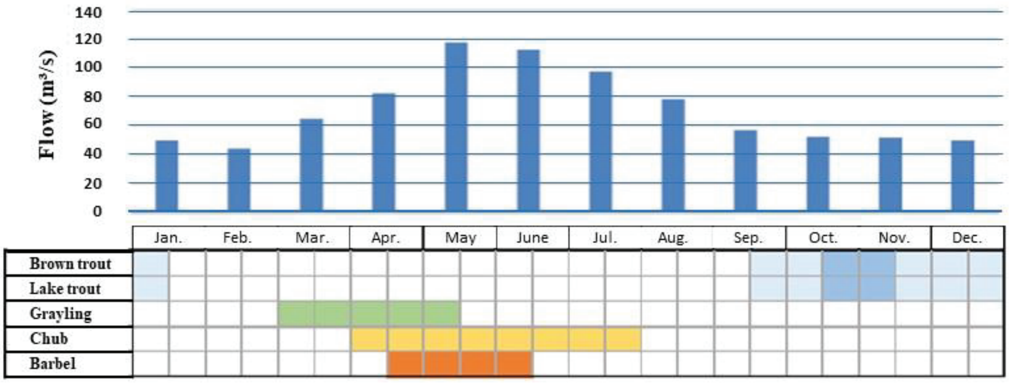


Figure 4. Hydrological regime of Arve River, and migration periods of the five target species.

3.3 Sediment data

Suspended sediment transport data has been recorded by the SIG at the *Bout-du-monde* site of the Swiss federal hydrological station (FOEN data). There are few bed load data available on the Geneva reach. The watershed, composed of steep mountain streams, constitutes the sediment production area. Due to snowmelt, the daily high-water is accompanied with heavy suspended load with a concentration higher than 1000 mg/l. The alluvial Arve River conveys an annual suspended sediment volume of 700'000 m³/y and an annual bed load of about 15'000 m³/y.

Although the annual bed-load discharge is estimated by the SIG, it could not be exploited for modelling purposes on a time scale of flooding events. The Laboratory for Applied Hydraulics therefore carried out bed grain distribution sampling on 11 sites of the Vessy meander, which yielded 14 sediment samples. The five most relevant bed-grain distribution curves obtained from field sampling by the Laboratory for Applied Hydraulics of HEPIA are presented in Figure 5.

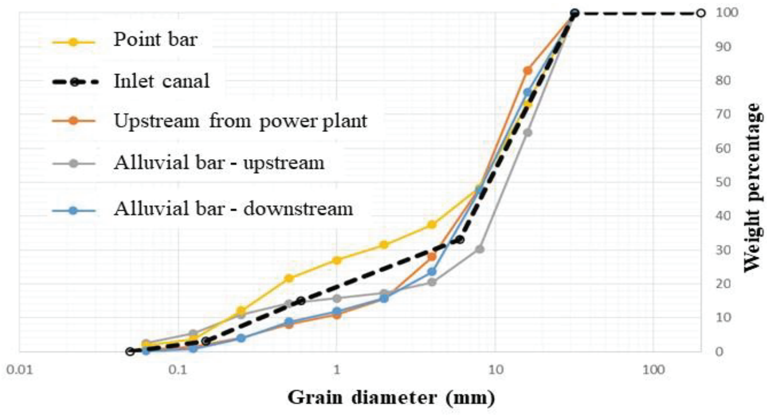


Figure 5. The five most relevant bed-grain distribution curves of the Vessy meander (by LHA-HEPIA).

4. EXPERIMENTAL SETUP

4.1 Physical model scaling laws

The movable-bed physical hydraulic model of the Vessy meander was constructed and exploited at the Laboratory for Applied Hydraulics – HEPIA (Figure 7) with a 1:40 geometrical scale.

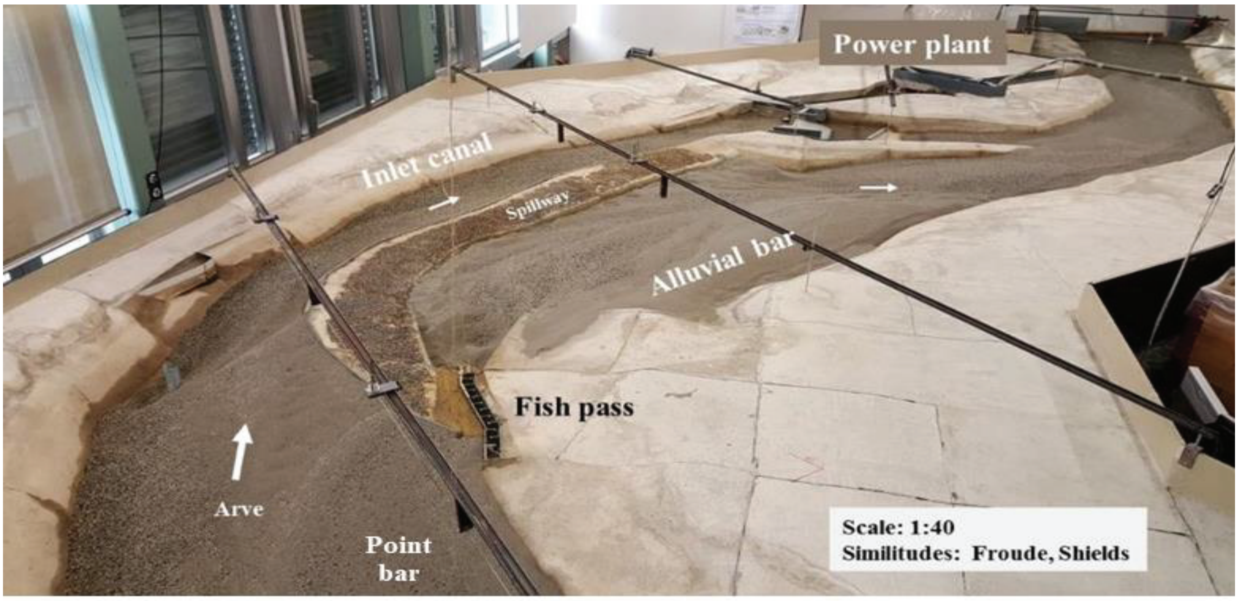


Figure 6. The Vessy movable-bed physical model at the Laboratory for Applied Hydraulics – HEPIA Geneva, corresponding to the initial state of modelling.

The physical hydraulic model obeys the Froude similarity law assuming the conservation of ratio between inertial and gravity forces (see Vecsernyés et al. 2014). The scaling factors of the primary physical parameters are presented in Table 1.

Table 1. Model scaling laws for different hydraulic variables, obeying Froude similarity, with λ = 40 geometry scale. Index p for prototype; index m for model.

Physical parameters	Scaling ratio	Scaling factor
Length, L (m) Pressure, P (m water column)	$\frac{L_p}{L_m} = \frac{P_p}{P_m} = \lambda$	40
Velocity, V (ms^{-1}) Time, t [s]	$\frac{V_p}{V_m} = \frac{t_p}{t_m} = \lambda^{1/2}$	6.32
Discharge, Q (m^3s^{-1})	$\frac{Q_p}{Q_m} = \lambda^{5/2}$	10’119
Roughness, K ($m^{1/3}s^{-1}$)	$\frac{K_m}{K_p} = \lambda^{1/6}$	1.849

4.2 Physical model-bed load similarity

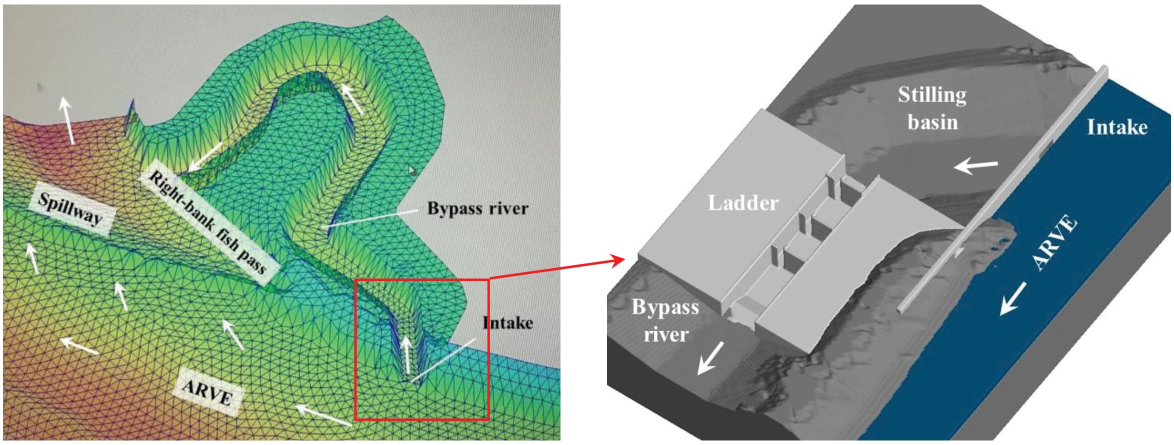
For the sediment transport analyses, the physical model is exploited due to bed load similarity and the flowing hypotheses:

- Sediments are composed of non-cohesive grain material and characterised by their specific mass and mean grain diameter, d_m.
- The mean grain diameter and grain size distribution of the natural river sediments were obtained by sampling carried out on site by the Laboratory (cf. Figure 5).

- The model grain-size distribution was defined due to two similarity laws: the initiation of bed grain motion due to Shields criteria and the bed instability criteria due to roughness Reynolds number, Re*.
- Wall roughness of the model has been fitted on the bases of Swiss Federal hydrological data (FOEN 2019) and HEC-RAS backwater profile simulation.

4.3 Numerical model hydrodynamics and sediment transport analysis

The aim of the 3D numerical simulation of the Vessy bypass river was to optimise the structural layout of its water intake and reduce fine-sediment deposit potential. The numerical model was created on Flow-3D (Flow science 2019). The programme is intended for free-surface flow computation, based on flow and turbulence equations (conservation of mass, momentum and energy). Flow-3D generates its own finite volume mesh, based on *.stl files (Standard Tesselation Language) or raster files: a grid of pixels baring altitude and roughness data. The grid was generated both for the Arve River and the bypass river (Figure 6-a). The numerical model of the upstream part of the bypass river was implemented, with the water intake, a stilling basin and a three-lock ladder (Figure 6-b). The cell size choice depended on the compromise between mesh refining and numerical stability goals. The numerical solutions were reached by resolving second-order differential equations. Pressure and velocity results were provided by a discretised-volume mesh.



a) b)

Figure 6. a) Finite volume Flow-3D mesh of the Arve River, the spillway and the bypass river. **b**) Numerical model of the upstream part of the bypass river with its water intake, stilling basin and three-lock ladder.

The Method of Finite Differences (MFD) is used in Flow-3D, approximating solutions for the Navier-Stockes general flow equations (conservation of mass, momentum and energy), which cannot be solved analytically.

Computation starts with given initial conditions and stabilises as boundary conditions are reached, based on FOEN 2019 field data sets, measurements and samples collected by the LHA as well as the physical modelling results. The latter allowed a recursive adjustment between the numerical and physical models.

The numerical sediment model was added to the hydrodynamic one once a stationary flow condition has been reached. Sediments were considered as non-cohesive and classified in grainsize groups (0.0625 mm – 1.0 mm). Flow-3D uses an empirical model to predict the Shields parameter and the bed load transport mode (Wilcock 2001).

5. HYBRID MODELLING RESULTS

5.1 Physical modelling results

Physical model tests were first carried on the initial state. Model fitting for hydraulic and morphological field conditions confirmed, among others, the clogging of the right-bank fish (Figure 7). Sediment and woody debris form a mixture due to highly turbulent flow while submerging the fish pass. Tests on floated wood confirmed the observations, especially how they reach the hydraulic works of the power plant and where they beach.

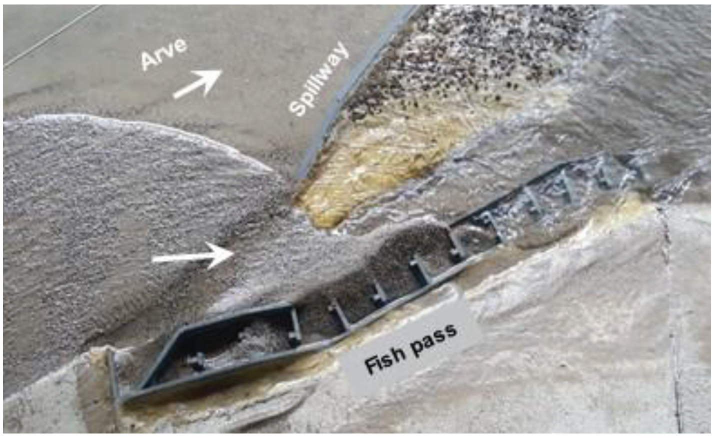


Figure 7. Clogging of the Vessy fish pass demonstrated on the movable-bed physical model (cf. Figure 2).

The alternative analysis completed on the bypass river and its water intake yielded the configuration shown in Figure 8 (Vecsernyés et al. 2019). A combined groin pattern installed in front of the water intake avoids bed-load transfer to the bypass river and preserves a clear waterway to Arve even during its low flow, enabling free upstream fish migration (Figure 9). At the water intake, a sluice gate and three-lock ladder guarantee fish friendly head loss conditions and appropriate flow rate for the bypass river. The latter is modelled with its successive weirs.

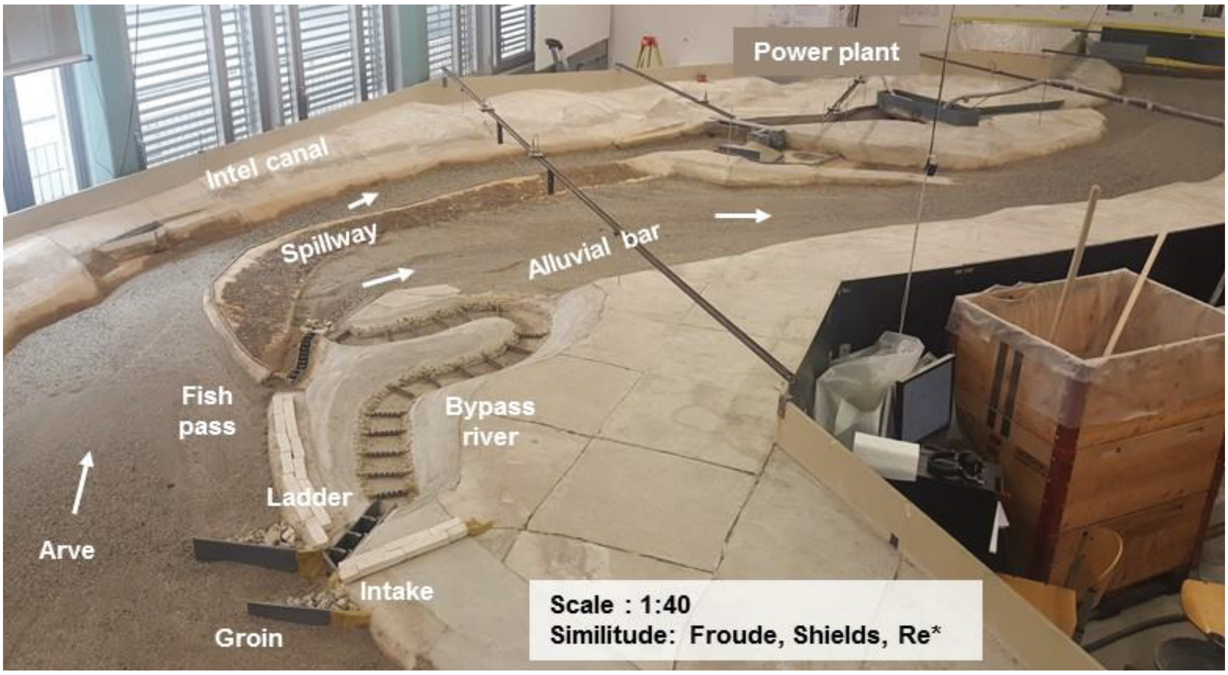
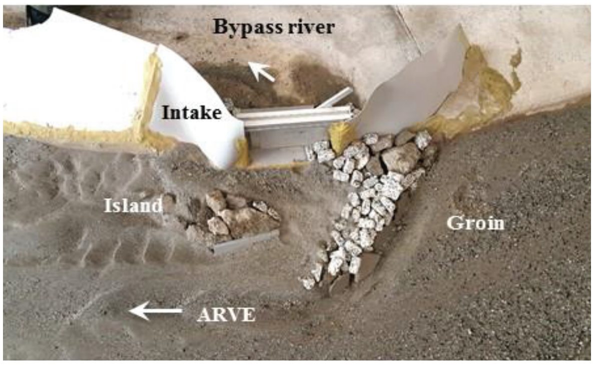


Figure 8. The bypass river and its water intake implemented on the physical model. A combined groin pattern placed avoids Arve's bed-load transfer to the bypass river. A sluice gate and a three-lock ladder yield an appropriate flow rate management of the bypass.

Tests conducted on the physical model helped to find a structural solution guaranteeing free fish migration of the target species of Arve River.



a)


b)

Figure 9. a) The bypass river is protected from Arve's bed load transfer. **b)** Dye-tracer $KMnO_4$ reveals the persistence of a clear waterway during low flow of the Arve River, enabling free upstream fish migration.

5.2 Numerical modelling results

The numerical analyses of the bypass river were carried out on a Flow-3D model (c.f. Figure 6). In order to model the behaviour of suspended sediment, an accurate hydrodynamic model was first completed, fitted to hydraulic calculations (Figure 10). Flow velocity patterns obtained from Flow-3D are presented in Figure 11.

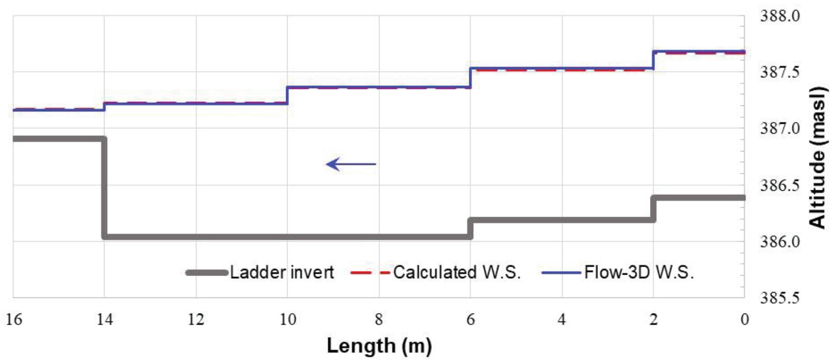
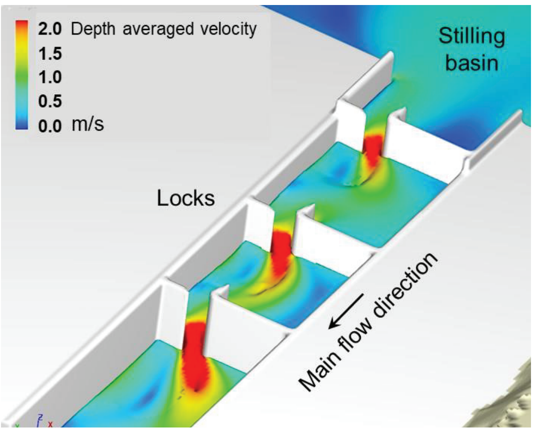


Figure 10. Flow-3D was fitted to hydraulic water surface (W.S.) calculations.



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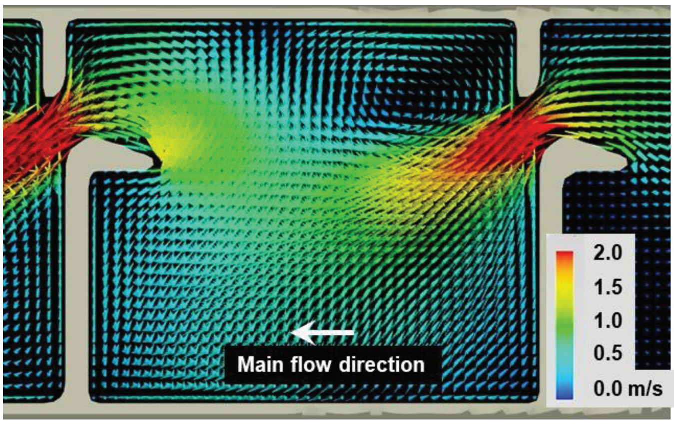

b)

Figure 11. Flow-3D flow velocity simulation results within the three-lock ladder of the bypass river.

Arve's bed material is deviated by a combined groin pattern in front of the water intake as shown in section 5.1. Since suspended sediment gets through the latter, its concentration has to be reduced upstream in order to protect the future fish pass from clogging. Numerical simulations bear witness of fine sediment deposit within the stilling basin as shown in Figure 12. The fish ladder and the consecutive bypass river are preserved from fine sediments, hence protected from clogging.

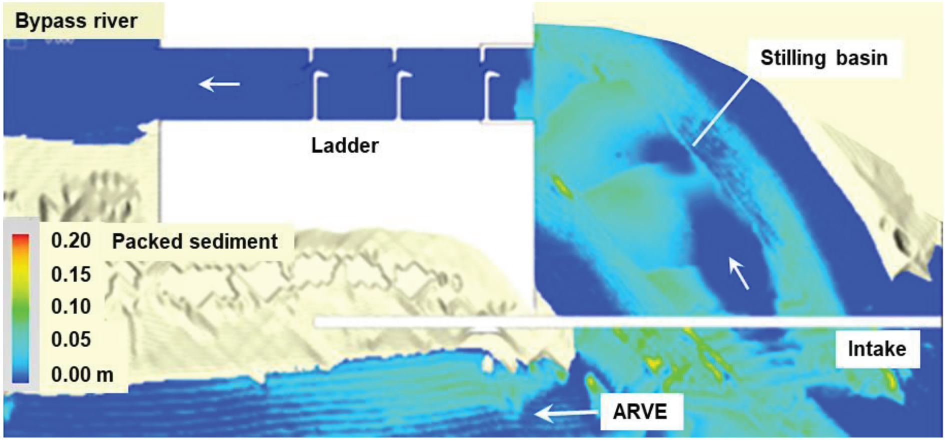

Figure 12. Packed fine-sediment simulation result by Flow-3D. Fine sediment forms deposit within the stilling basin due to flow velocity drop, protecting the consecutive three-lock ladder and the bypass river from clogging.

The hybrid modelling of flow and sediment transport carried out for various conditions between the Arve River and the future bypass river of the Vessy meander yielded relevant results. The proposed hydraulic structures provide an effective protection of the future Vessy fish pass from clogging.

6. CONCLUSIONS

The hybrid hydraulic modelling carried out at the Laboratory for Applied Hydraulics of HEPIA on a movable-bed physical hydraulic model and by 3D numerical simulation yielded a solution for replacing the existing right-bank Vessy fish pass suffering from clogging. The main achievements of the investigations are:

i. The physical model, completed prior to numerical analyses, provided a robust structural solution preventing the water intake of the future bypass river from Arve River's bed load.
ii. The numerical modelling revealed that a stilling basin placed between the water intake and a three-lock fish ladder would lower the fine sediment concentration and reduce clogging potential within the locks and the consecutive bypass river.

The new fish pass will offer optimal flow and ecological conditions for all fish target species and can therefore be constructed at the Vessy meander of the Arve River in Geneva.

7. REFERENCES

Aigoui F., Dufour M. (2008). Guide passes à poissons – Voies navigables de France.
Flow Science (2019). Inc., Santa Fe, NM, USA. FLOW-3D® Version 12.0.
FOEN (2019), Swiss Federal Office for the Environment.
Gobat, K. (2016). Adaptation des conditions d'écoulement de l'Arve au droit de la passe à poissons rive droite de Vessy – Genève. HES-SO HEPIA, Bachelor thesis.
GREN (2009). Inventaire piscicole des cours d'eau du canton de Genève. SECOE, République et canton de Genève.
Jaeger, A. (2020), Sediment transport 3D numerical simulation of a water intake, HES-SO MIT, Master thesis.
Larinier M., Courret D., Gomes P. (2006). Guide technique pour la conception des passes « naturelles ». Rapport GHAAPPE RA.06.05-V1
Vecsernyés, Z., Andreini, N., Consuegra, D. Boillat, J-L. (2014). Physical modeling of the third stage of the Aire revitalisation project. River Fow 2014.
Vecsernyés, Z., Gobat K., Wohlwend, F. (2019). Rapport intermediaire Vessy I. Service Industriel de Genève.
Vecsernyés, Z., Wohlwend, F., Gobat, K., Andreini, A. (2019) A movable-bed physical model yields an innovative solution for replacing a fish pass suffering from clogging, 38th IAHR World Congress, Panama City, Panama.
Wilcock P. (2001). Toward a practical method for estimating sediment-transport rate in gravel-bed rivers. Earth Surface Processes and Landforms 26, 1395-1408.
Wohlwend, F. (2015). Etude des conditions d'augmentation du débit turbiné de Vessy-II, par simulation hydraulique numérique. HES-SO MIT, Mater thesis.