INFRARISK, 4TH SUMMER SCHOOL WORKSHOP, 18TH JULY 2018

The hydraulic modeling of extreme flood events

Sébastien Proust, IRSTEA Lyon-Villeurbanne, France

Moselle River, France

IRSTEA

National Research Institute of Science and Technology For Environment and Agriculture

- 9 regional centers (1550 people)
- Lyon-Villeurbanne center (240 people)
- Research topics in Lyon
  - **Hazards and risks linked to the water cycle**
  - Quality of aquatic systems and ecological restoration
  - Biological and ecological responses to contamination of the aquatic environment

Outline of the presentation

1. **Context: the FlowRes project (2015-2018)**

2. **Experimental modelling of extreme flows**
   - Flows through emergent tree models
   - Flows through emergent & weakly submerged house models
   - Mixing layers for overbank flows

3. **Numerical modelling of extreme flows**
   - 1D & 3D modellings of flows through tree models
   - 1D+ & 3D modellings of overbank flows

4. **Perspectives (2019-2022)**

1. CONTEXT: FLOWRES PROJECT (2015-2018)

AGENCE NATIONALE DE LA RECHERCHE ANR

https://flowres.irstea.fr/en/

'Predicting the flow in the floodplains with evolving land occupations during extreme flood events'

Partners: Irstea Lyon, LMFA, IMFT, EDF (France); UCL, Lab. Châtelet (Belgium); IST, LNEC (Portugal); UiA (Norway); K.I.T (Germany); Aberdeen Univ. (UK); ENPA (Algeria), CNR (France), AKKA Technologies (France), NIT Rourkela (India)
Coordinator: S. Proust

1. CONTEXT: FLOWRES PROJECT (2015-2018)

‘Predicting the flow in the floodplains with evolving land occupations during extreme flood events’

- European Flood Directive:

  1. Extreme events: return period T $\geq$ 1000-year

  2. Flood hazard maps in areas with significant flood risk (with **flow depths** and **velocities)**

- No field data for such events to validate the models

- Physical processes partly driven by land occupation

FLOW RESistance affected by

1. **Lateral** and **longitudinal** changes in land occupation, i.e. in hydraulic roughness

2. **Variable submergence** of the roughness elements (function of flow depth, and of the type of element)

3. **Inhomogeneity** of the roughness elements
   (increases with T)

Objective

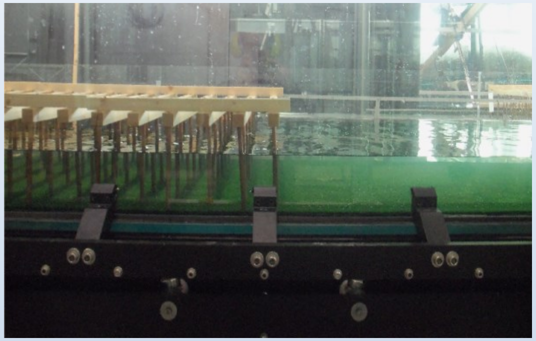
Improving the assessment of **flow depth** and **velocity** on the floodplains by

1) analysing the physical processes for **various land occupations** and **discharge magnitudes**, focusing on the flow resistance associated with **meadows**, **trees** and **houses**

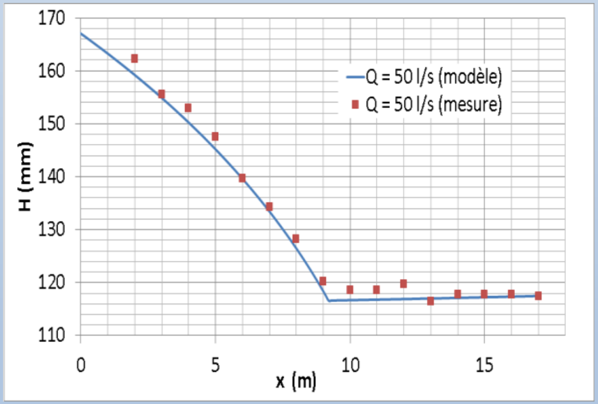
2) assessing if the existing modelling practices used for T ~ 100-year are still valid to predict flows with $T \geq 1000$-year

Methodology

1) Laboratory experiments



2) Comparison experimental data / numerical modelling (1D to 3D).

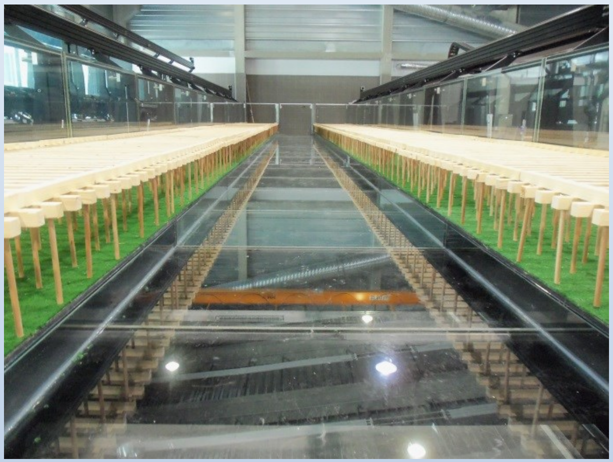


3) Field case: floods of the Doubs river at Besançon

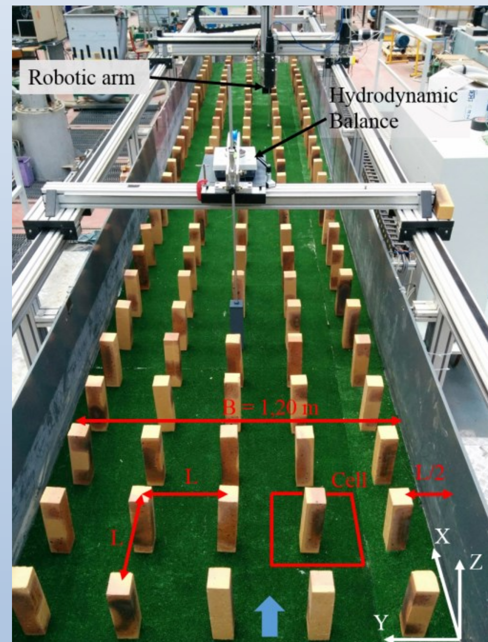
2. Experimental modelling of extreme flows

Experiments conducted at:

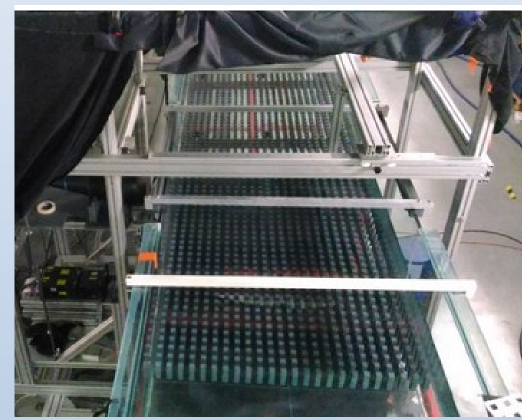
Irstea flume (18 m x 3 m)



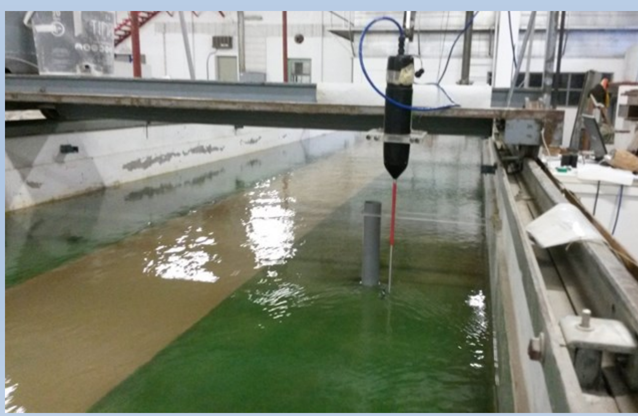
LMFA flume
(8 m x 1.2 m)



IMFT flume (24 m x 1.1 m)



LNEC flume (10 m x 2 m)



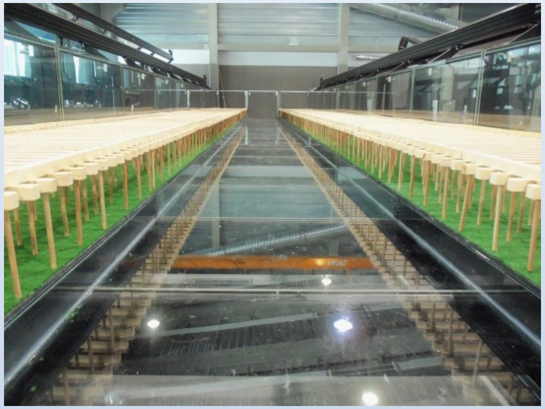
Irstea flume (18 m x 1 m)

2.1. Flows through emergent tree models

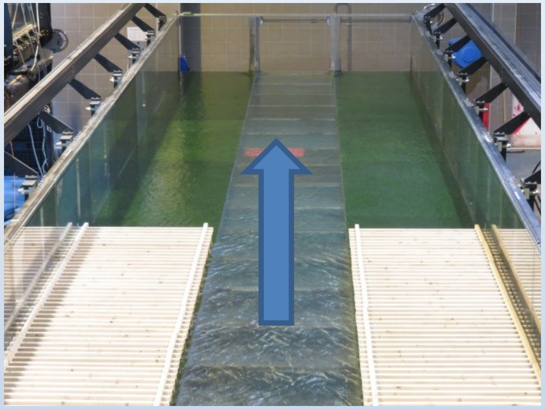
- Compound channel

> video

Meadow over the floodplains

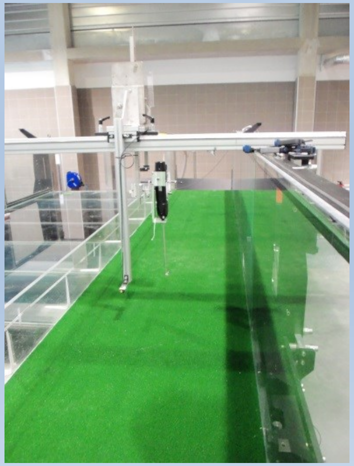


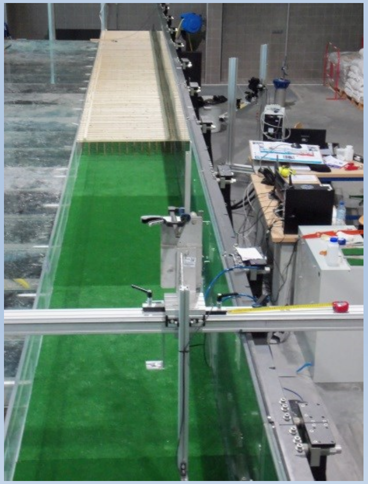
Tree models + meadow



Trees + meadow → meadow (& vice versa)

- Single channel





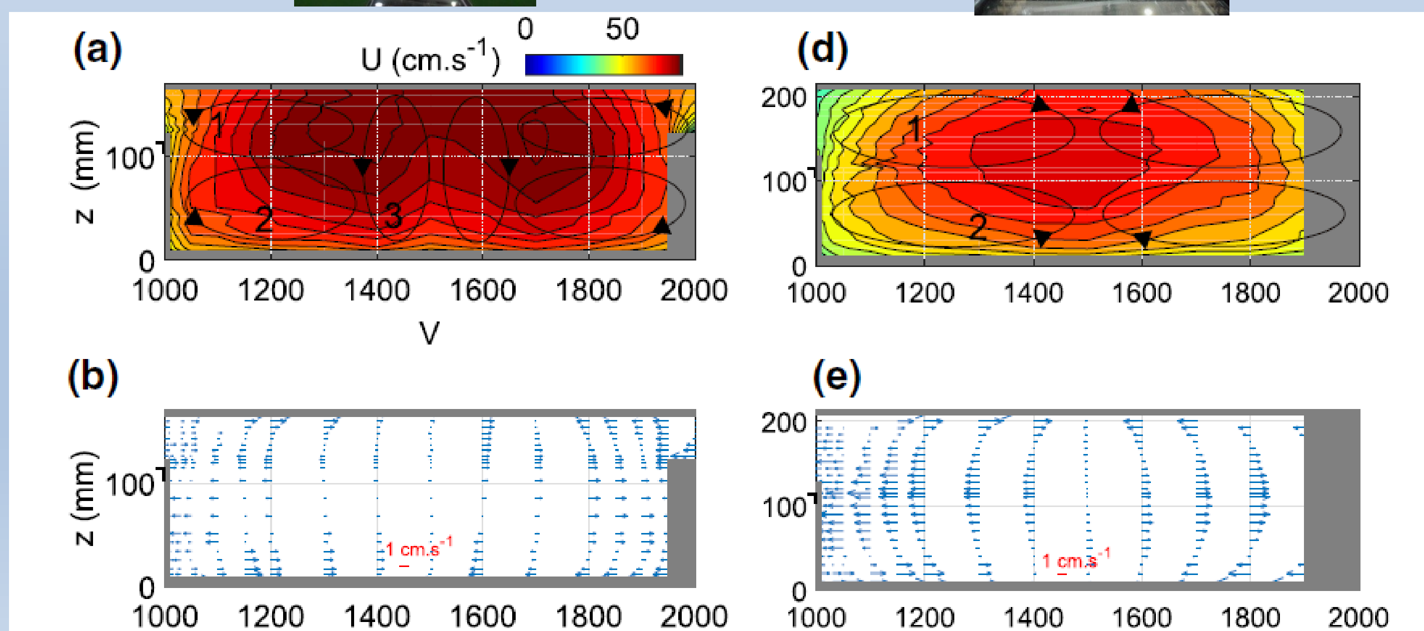
2.1. Flows through emergent tree models

<u>Key issues</u>: effects on flow structure of

- the floodplain (FP) land use (and its variation)
- the discharge magnitude
- the interaction 'flow in the main channel (MC) / flow in the FPs'

<u>1st example of result:</u> effect of the FP land use on the MC flow

Nb: discharge Q = constant



Dupuis et al. (2017), *Exp. In Fluids*

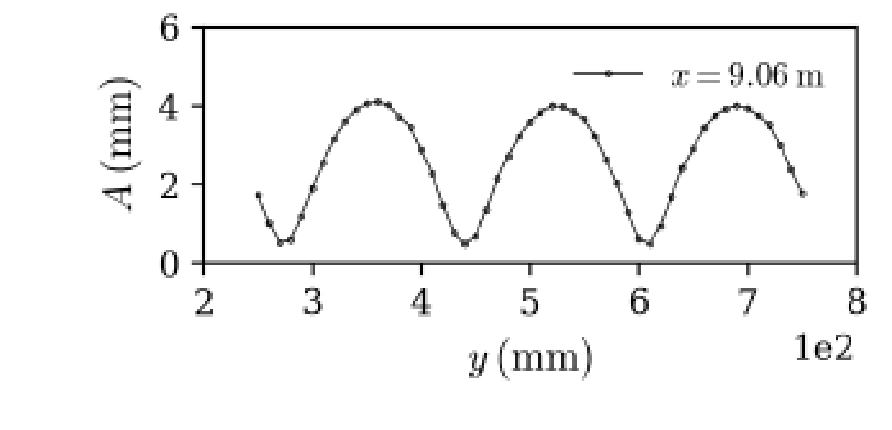
Dupuis et al. (2016, 2017), *Env. Fluid Mech.*

2.1. Flows through emergent tree models

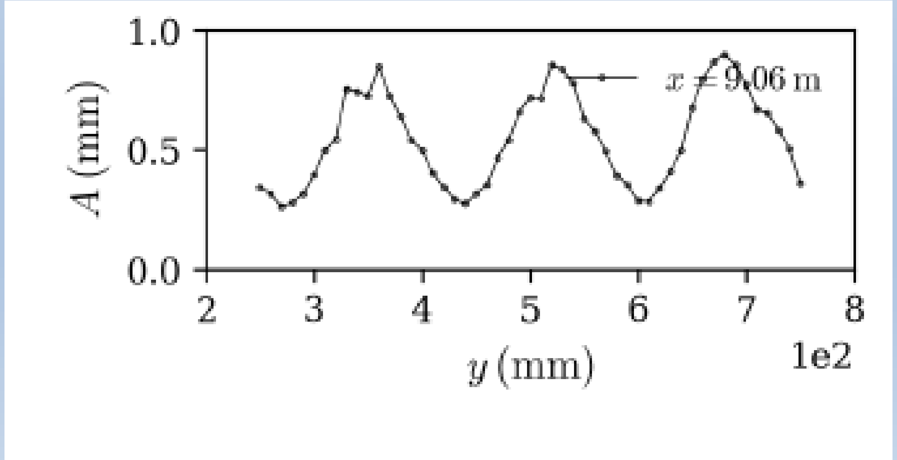
<u>2nd example</u>: effect of discharge magnitude on water surface oscillations (induced by vortex shedding)

> video

Q = 13 L/s, Flow depth D = 99 mm

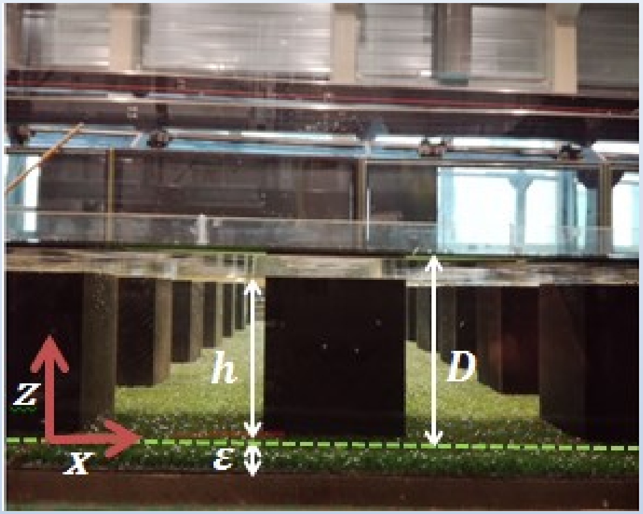


Q = 7 L/s, Flow depth D = 56 mm



2.2. FLOWS THROUGH HOUSE MODELS

From emergent to weakly submerged house models



Key issues:

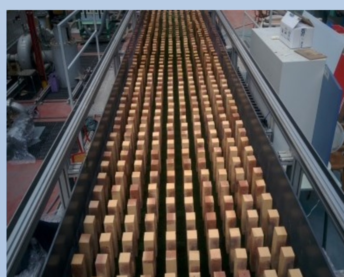
- Effect of submergence *D / h* on flow structure and water surface oscillations
- Comparison streamwise uniform / non-uniform flows

Result: lock-in process (see video)

Chetibi et al. (2018), *in review*

2.2. Flows through house models

LMFA flume

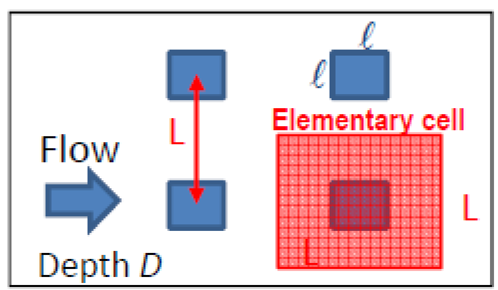


Key issues:
Effect of the frontal density of roughness elements λ_f on

- The drag force exerted on an element
- The bed friction

for various discharge magnitudes

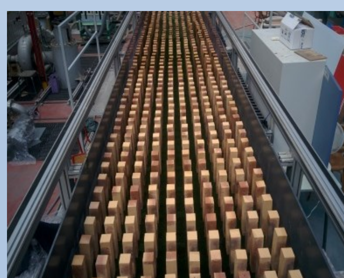
Hydrodynamic balance



$$\lambda_f = \frac{D\ell}{L^2}$$

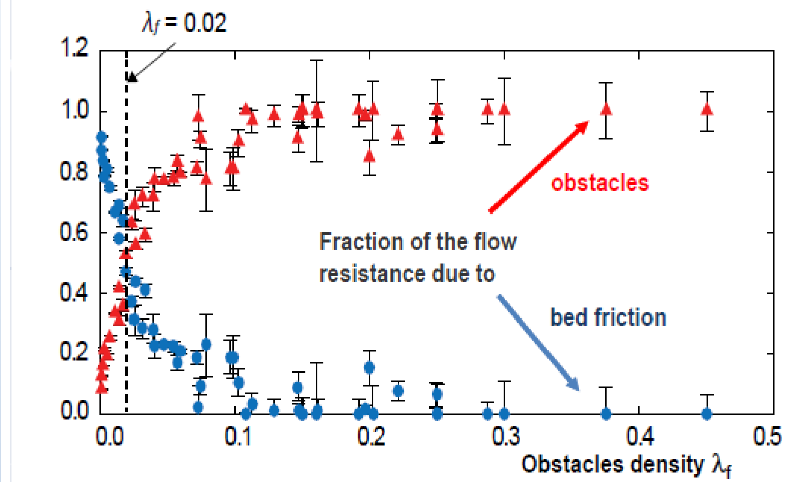
2.2. Flows through house models

LMFA flume

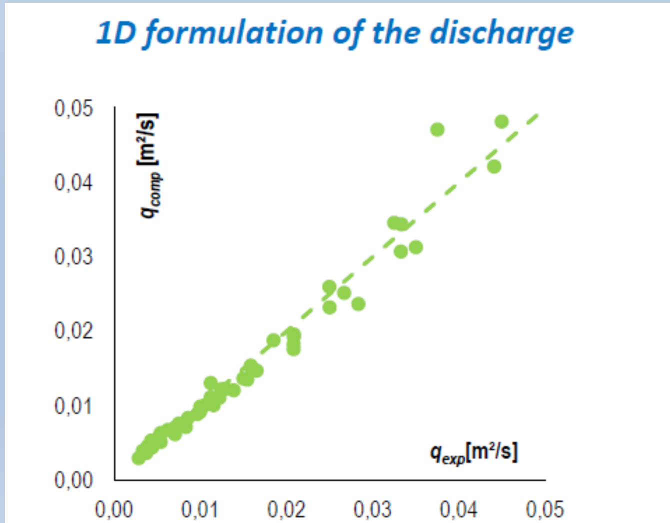


<u>Example of results:</u>

- Origin of flow resistance: friction or drag ?
- 1D formulation of the discharge



- Bed friction influent only for small densities of obstacles (λ_f<0.02)

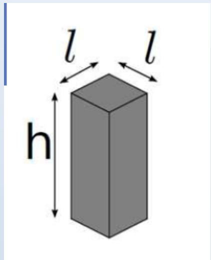


Ludena et al. (2017), *IAHR*
Ludena et al. (2018), *in prep.*

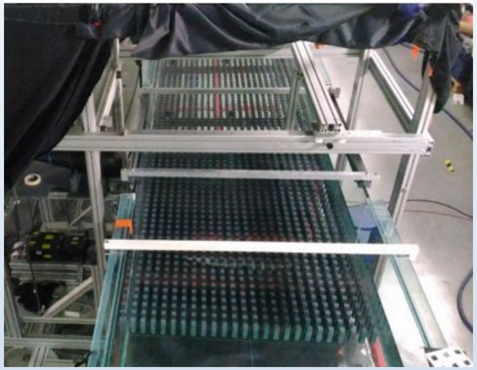
2.2. FLOWS THROUGH HOUSE MODELS

<u>Key issues</u>: effects on flow structure of
- submergence D / h
- modified submergence $\beta = (D-h) / \ell$

for $h / \ell = 1$; 3; 6

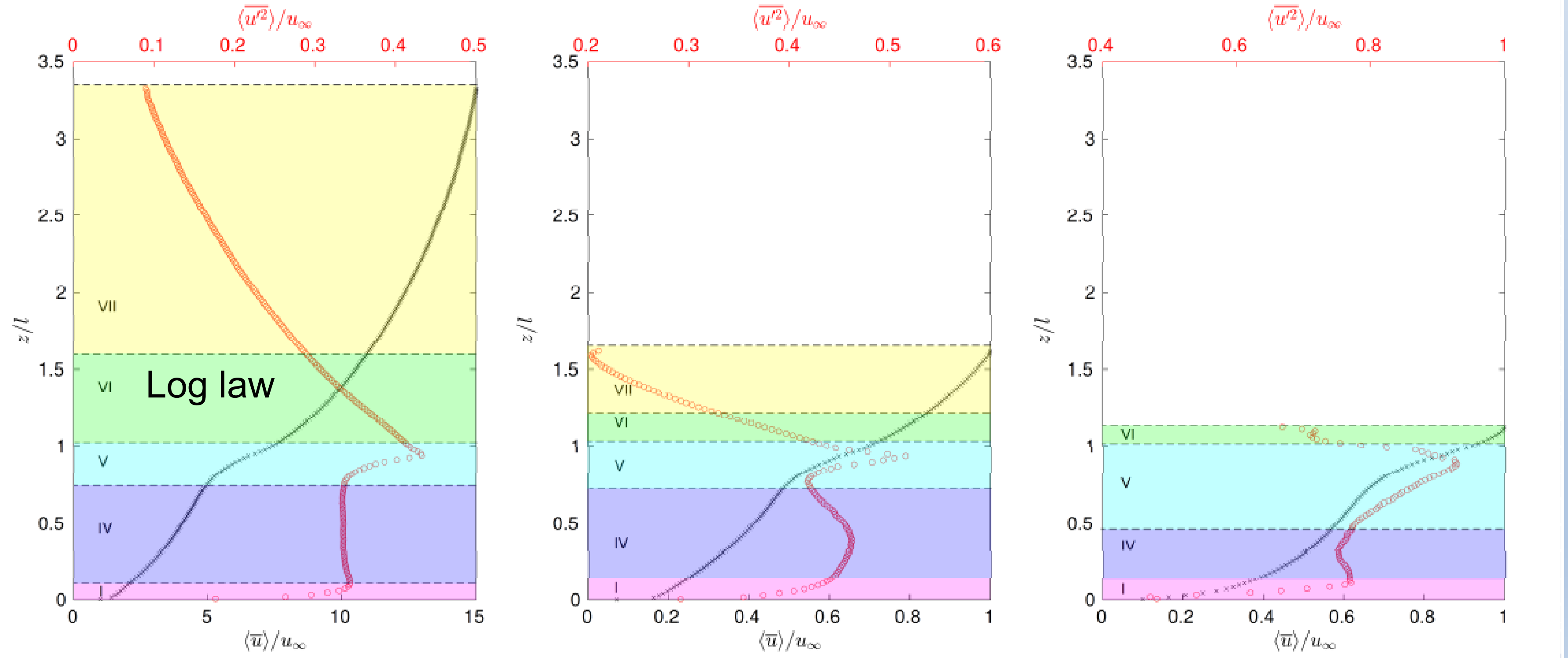


IMFT flume



<u>Result for $h / \ell = 1$</u>

Chagot *et al.*, (2018), in prep.

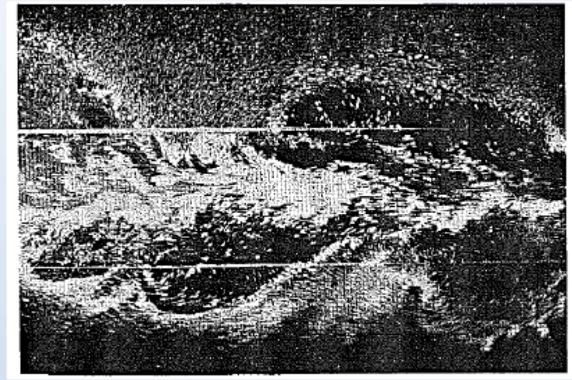


D/h=4.1, β =3.1

D/h=2, β =1

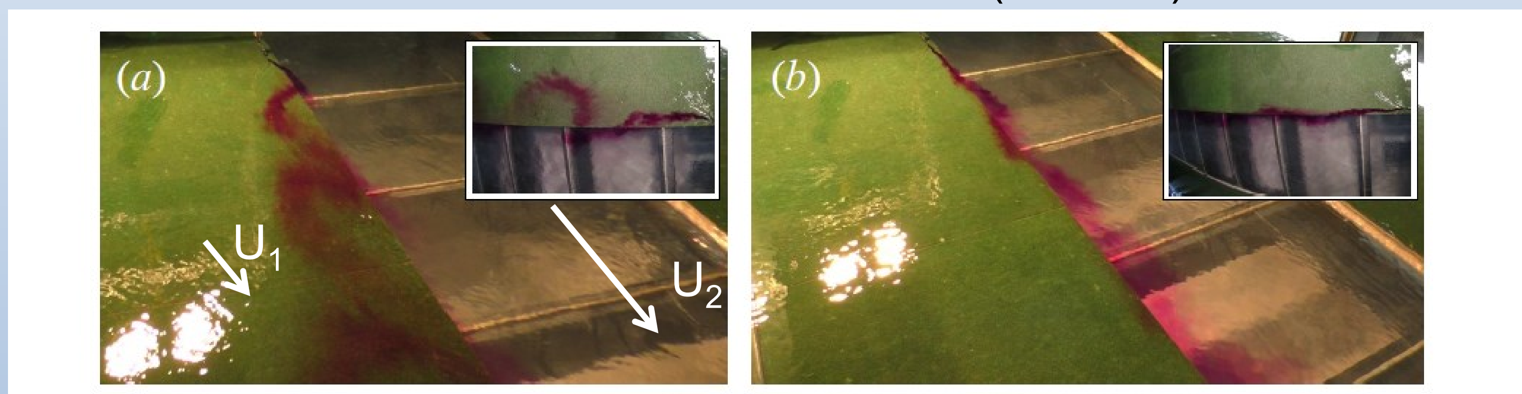
D/h=1.3 β =0.3

2.3. MIXING LAYERS FOR OVERBANK FLOWS



Lab. exp. of Sellin (1964)
→ U_{max} reduced by -26% in the main channel

<u>Key issue</u>: conditions of existence of 2D coherent structures (2D CSs) ?



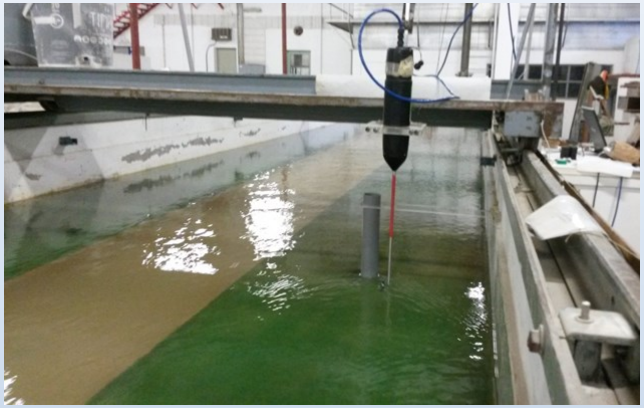
$\lambda = 0.7$ $\lambda = 0.3$

- Existence of 2D CSs if dimensionless shear $\lambda = (U_2-U_1)/(U_2+U_1) \geq 0,3$
- 2D CSs magnitude increases with λ

Proust et al. (2017), *WRR*
Proust & Nikora (2018), *in prep.*

2.3 - Mixing layers for overbank flows

LNEC



Gymnopoulos et al. (2018), *in review*

Test	d	h_{fp}	h_{mc}	h_r	Re_d
	(m)	(m)	(m)	(m)	(-)
S0	0.045	0.045	0.145	0.31	8365
S1	0.045	0.045	0.145	0.31	12032

h_{fp}: flow depth in the floodplain

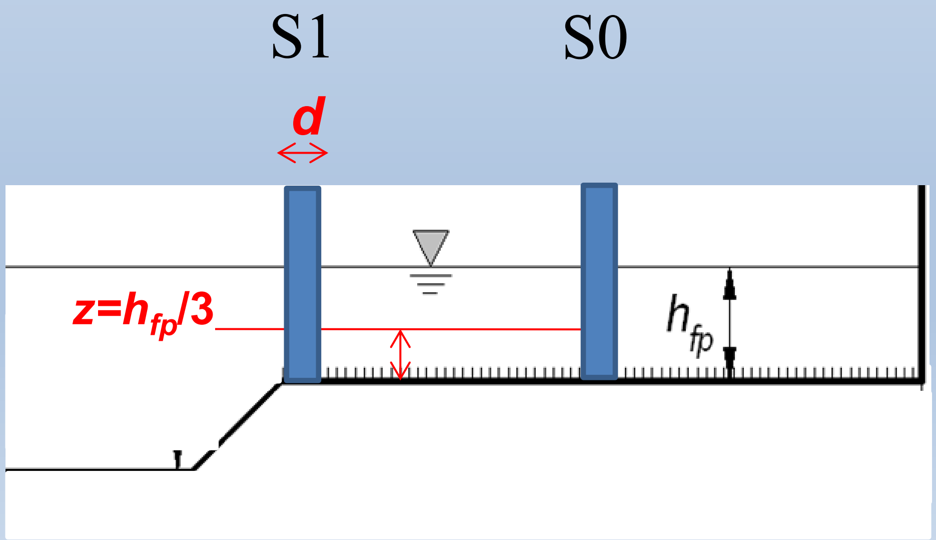
h_{mc}: flow depth in the main channel

$h_r = h_{fp}/h_{mc}$

<u>Key issue</u>: assessing the drag force on square cylinder, under the effect of a compound-channel shear layer

$$C_d = \frac{2R_x}{\rho U_0^2 d}$$

where R_x is the drag force per unit submerged length at level z and U_0 is the mean velocity upstream the cylinder



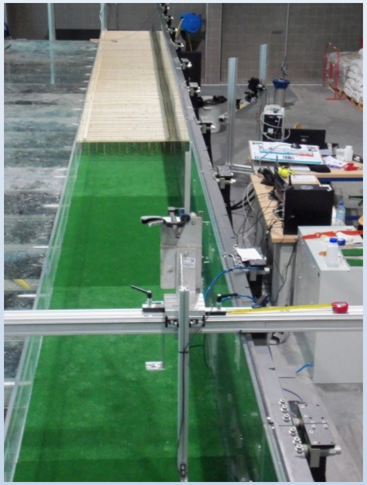
2.3 - Mixing layers for overbank flows

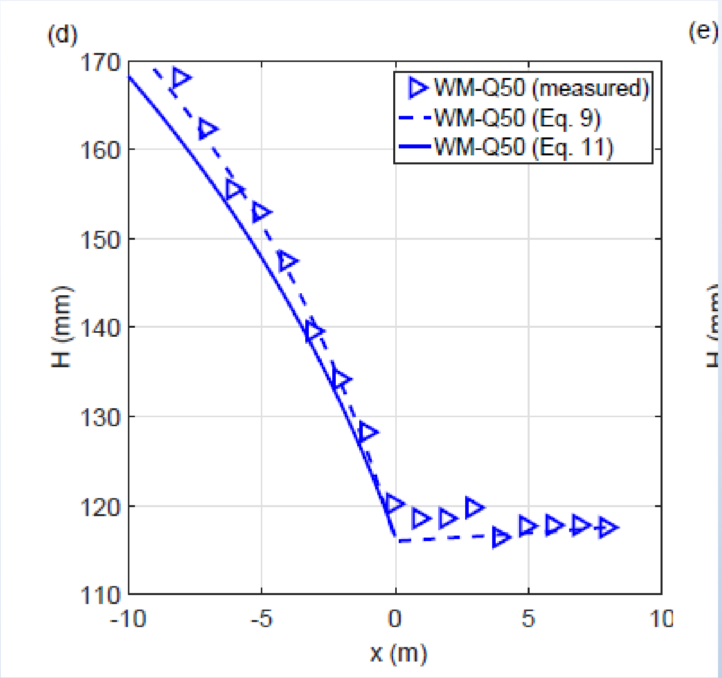
Result:

Studies	Flow type	Re_d	C_d
		(-)	(-)
S0	Compound channel	8365	2.06
S1	Compound channel	12032	2.00
Yen and Yang, 2011	Air flow	6300	1.86
Norberg, 1993	Air flow	13000	2.15
Yen and Liu, 2011	Air flow	21000	2.06
Lyn et al., 1995	Water tunnel	21400	2.10
Robertson, 2016	Open channel	10000-22000	2.11

marginally reduced C_d of the cylinder in shear flow (S1), comparatively to the case with uniformly distributed approach velocity (S0)

3.1 - 1D NUMERICAL MODELLING OF FLOWS THROUGH TREE MODELS





Bed friction **Volume drag force (a = 0.81, C_D = 1.2)**

$$\frac{\partial H}{\partial x}\left(1-\frac{Q^2}{gB^2H^3}\right)=S_0-\frac{n^2Q^2}{H^{10/3}B^2}-\frac{aC_DQ^2}{2gH^2B^2} \qquad (9)$$

Analytical solution if bed friction is negligible

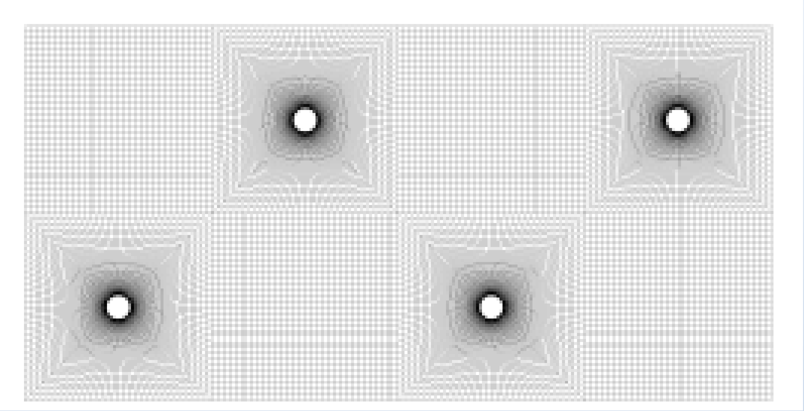
$$\frac{H-H_{dw}}{H_{up}}-\operatorname{atanh}\frac{H}{H_{up}}+\operatorname{atanh}\frac{H_{dw}}{H_{up}}=S_0\frac{x}{H_{up}}. \qquad (11)$$

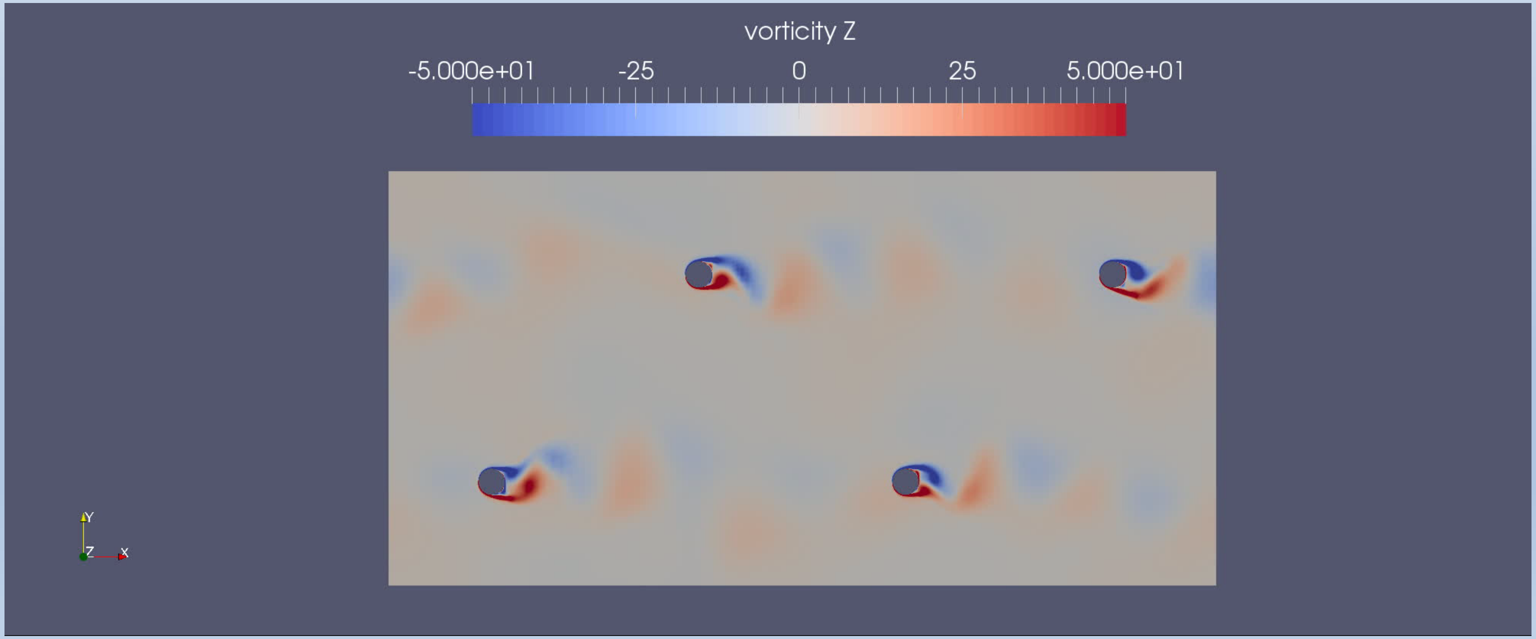
Dupuis et al. 2016, *Env. Fluid. Mech.*

3.1 - 3D NUMERICAL MODELLING OF FLOWS THROUGH TREE MODELS

- CFD code Open FOAM
- Turbulence modelling:
  - *k*-ω SST-SAS model

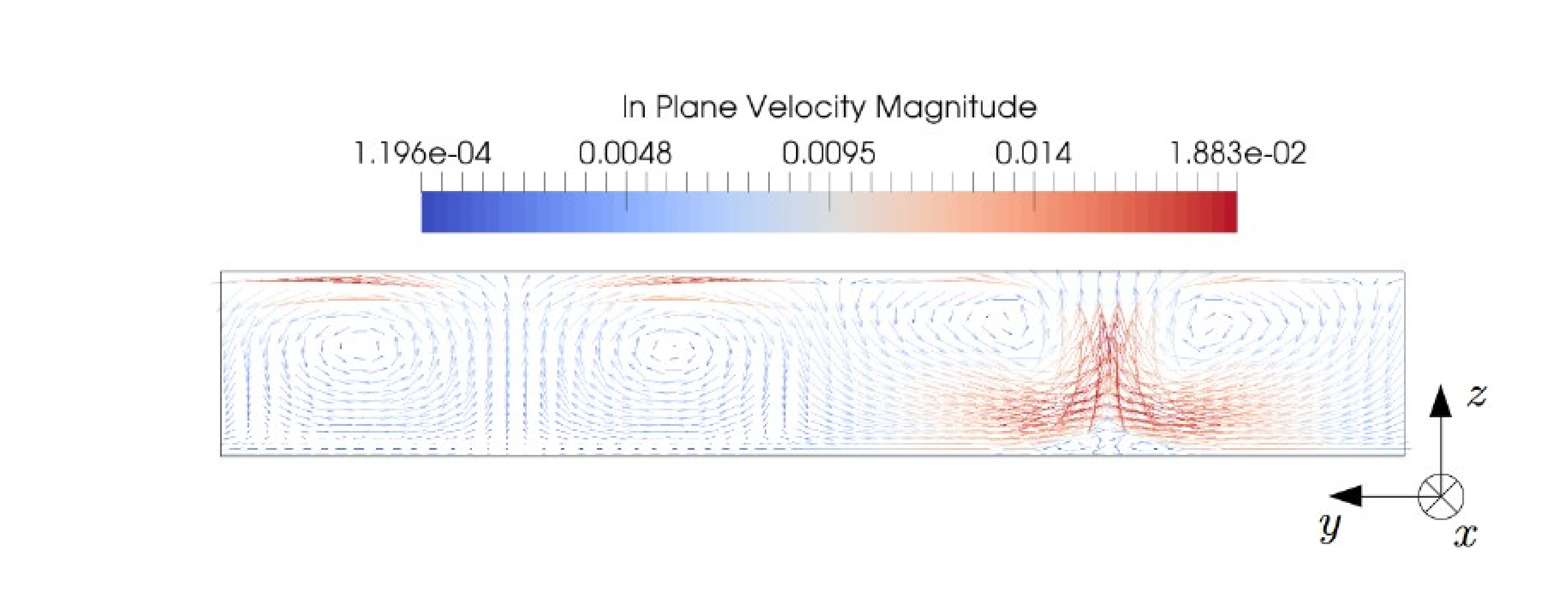
(hybrid RANS/LES model)



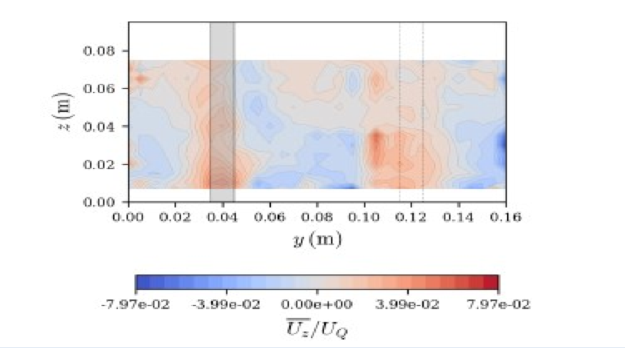


3.1 - 3D MODELLING OF FLOWS THROUGH TREE MODELS

Mean flow: base vortices in a transverse plane

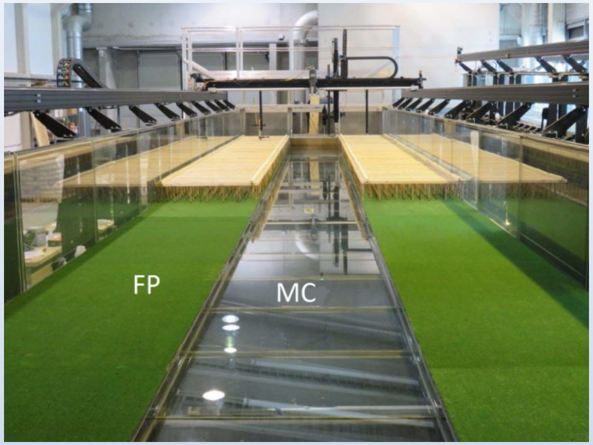


Are being compared with experimental data



Chatelain & Proust (2018), in *prep.*

3.2 - 1D+ MODELLING OF OVERBANK FLOWS



Independent Subsections Method (ISM)

Proust et al. (2009), *WRR*

Mass exchange

$$\left(1-\frac{U_r^{\,2}}{gh_r}\right)\frac{dh_r}{dx}=S_o-S_r^f-S_r^D+\frac{\tau_{rm}.h_r}{\rho g A_r}+\frac{q_{rm}\left(2U_r-U_{\mathrm{int}.rm}\right)}{gA_r} \qquad (1)$$

Bed friction

Turbulent mixing

Volume drag force

$$\left(1-\frac{U_l^{\,2}}{gh_l}\right)\frac{dh_l}{dx}=S_o-S_l^f-S_l^D+\frac{\tau_{lm}.h_l}{\rho g A_l}+\frac{q_{lm}\left(2U_l-U_{\mathrm{int}.lm}\right)}{gA_l} \qquad (2)$$

$$\left(1-\frac{U_m^{\,2}}{gh_m}\right)\frac{dh_m}{dx}=S_o-S_m^f-\frac{\tau_{lm}.h_l}{\rho g A_m}-\frac{\tau_{rm}.h_r}{\rho g A_m}\ldots \qquad (3)$$

$$\ldots-\frac{q_{lm}\left(2U_m-U_{\mathrm{int}.lm}\right)}{gA_m}-\frac{q_{rm}\left(2U_m-U_{\mathrm{int}.rm}\right)}{gA_m}$$

$$\frac{dQ_m}{dx}+\frac{dQ_l}{dx}+\frac{dQ_r}{dx}=0 \qquad (4)$$

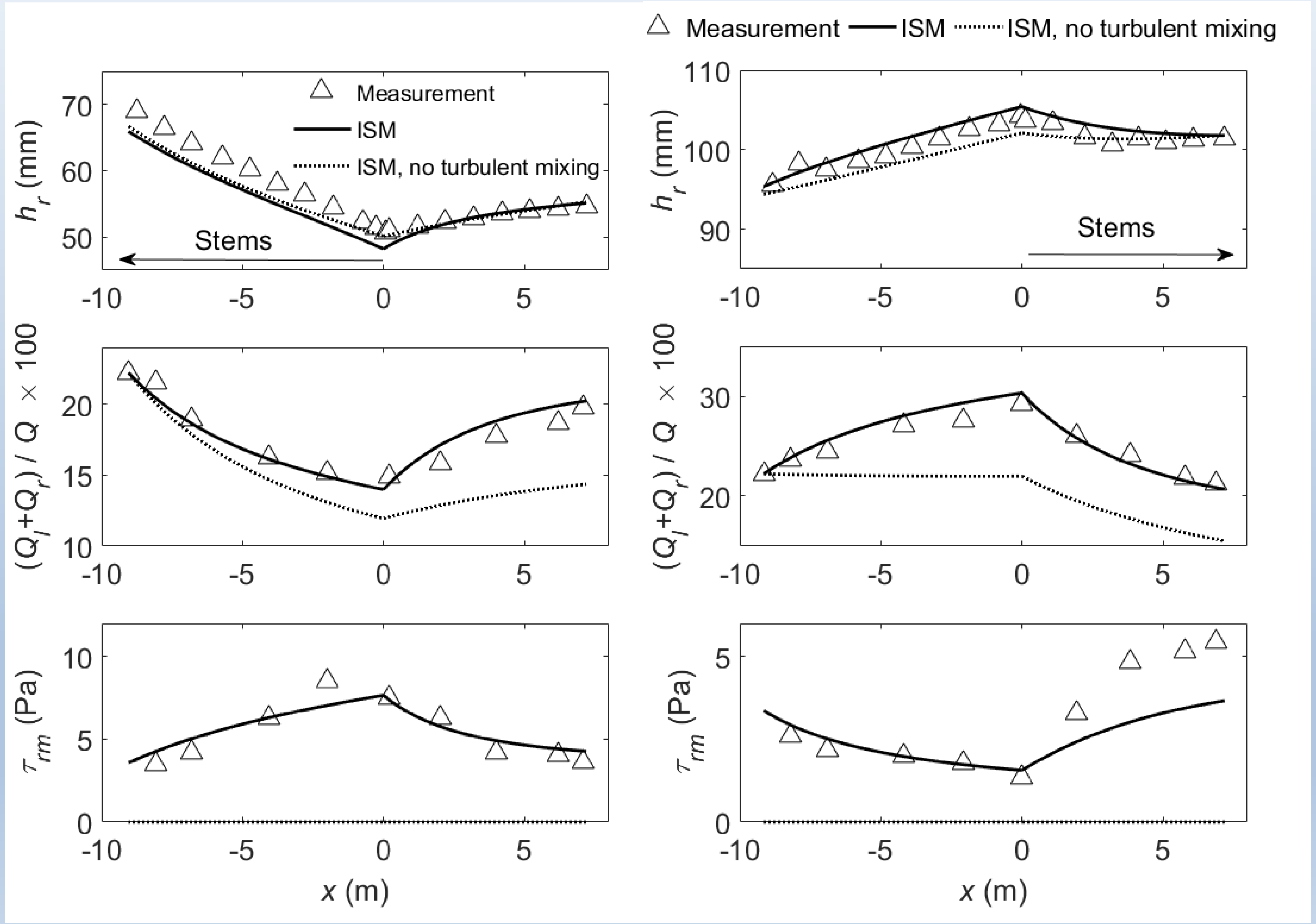
3.2 - 1D+ MODELLING OF OVERBANK FLOWS

Stems / Meadow | Meadow / Stems

Flow depth

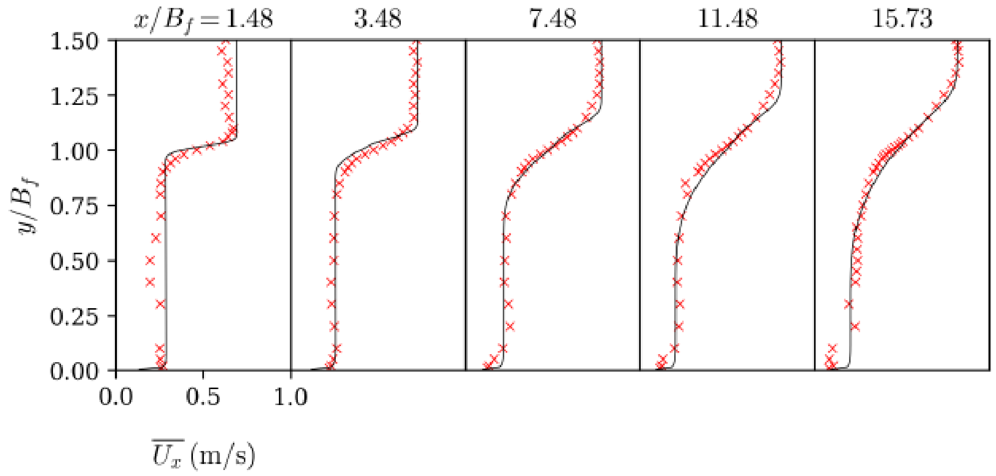
Proportion of FP discharge

Interfacial Reynolds stress



3.2 - 3D MODELLING OF OVERBANK FLOWS

Longitudinal development of the mean velocity profile



- Open FOAM
- *k*-ω SST-SAS model

Development of the 2D Kelvin-Helmholtz type coherent structures (2D CSs)

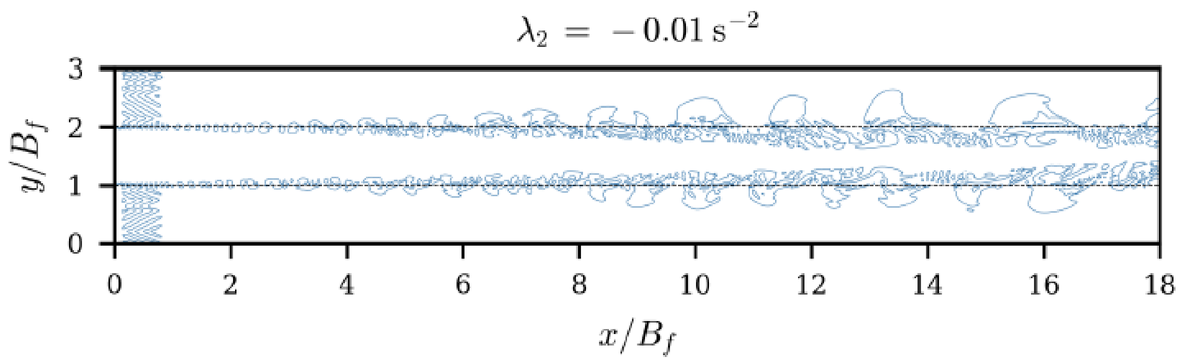
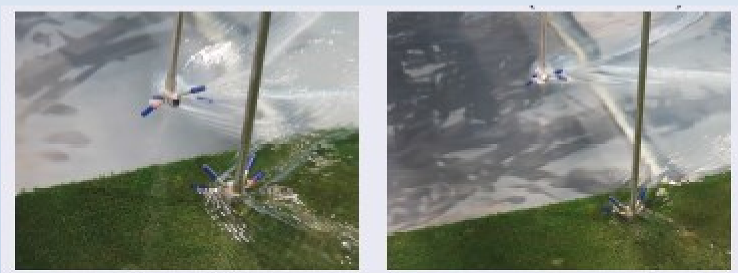


Figure 18: Qf-8 - Instantaneous iso-value of λ_2 criterion in the horizontal plane located at $z = 132.5\,\mathrm{mm}$.

3.2 - 3D MODELLING OF OVERBANK FLOWS

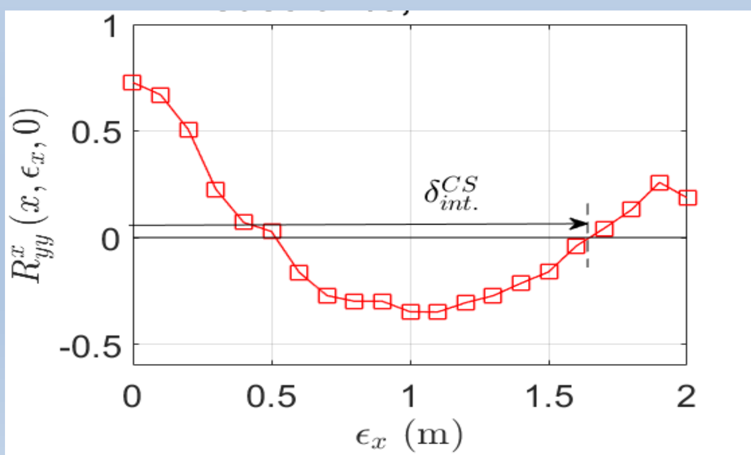
Focus on the 2D CSs length scales

Two-point velocity measurement → Space time correlation function

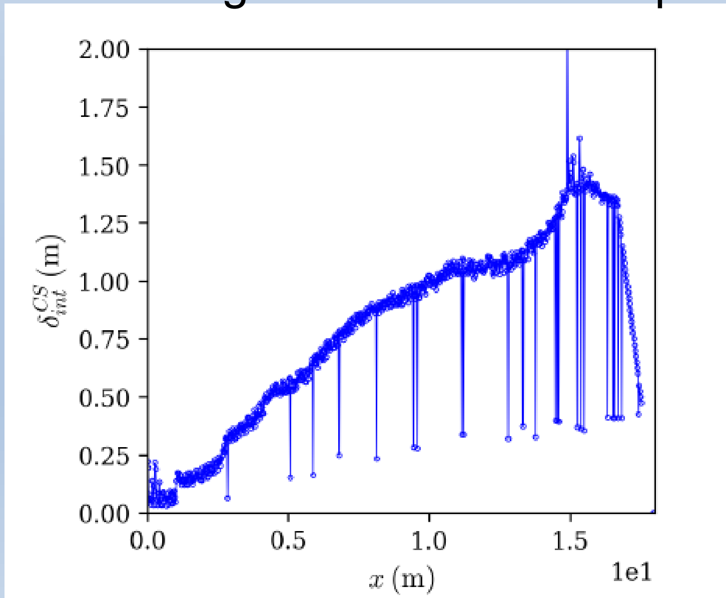


$$R^k_{ij}\left(k,\epsilon_k,\tau\right)=\frac{\overline{u'_i\left(k,t\right)u'_j\left(k+\epsilon_k,t+\tau\right)}}{\sqrt{\overline{u'^2_i\left(k\right)}\;\overline{u'^2_j\left(k+\epsilon_k\right)}}}$$

Experimental longitudinal scale at given x-position



Simulated longitudinal scale vs. x-position

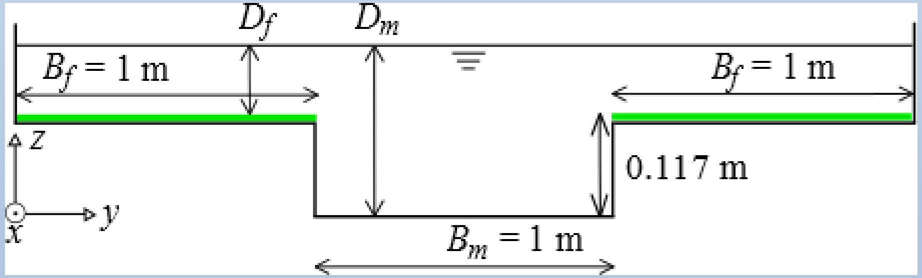


4.1 - PERSPECTIVES (2019-2022): MIXING LAYERS IN NON-COMPOUND CHANNELS

What drives the existence of Kelvin-Helmholtz instabilities in free-surface shear flows ?

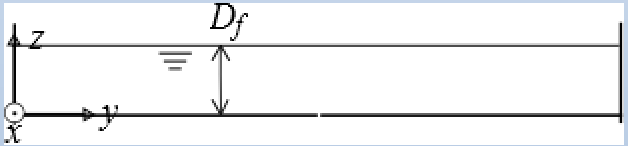
FOCUSING ON FLOWS IN ….

- **Compound** channel (2013-2018)



S. Proust, V. Dupuis, C. Berni, V. Nikora, J. Fernandes, J. Leal, N. Rivière, Y. Peltier, A. Paquier

- **Single** channel (2018-2019)



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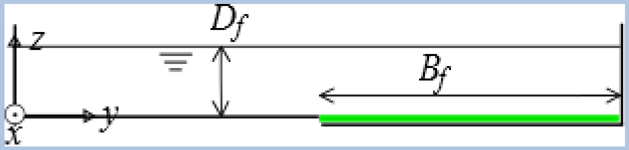
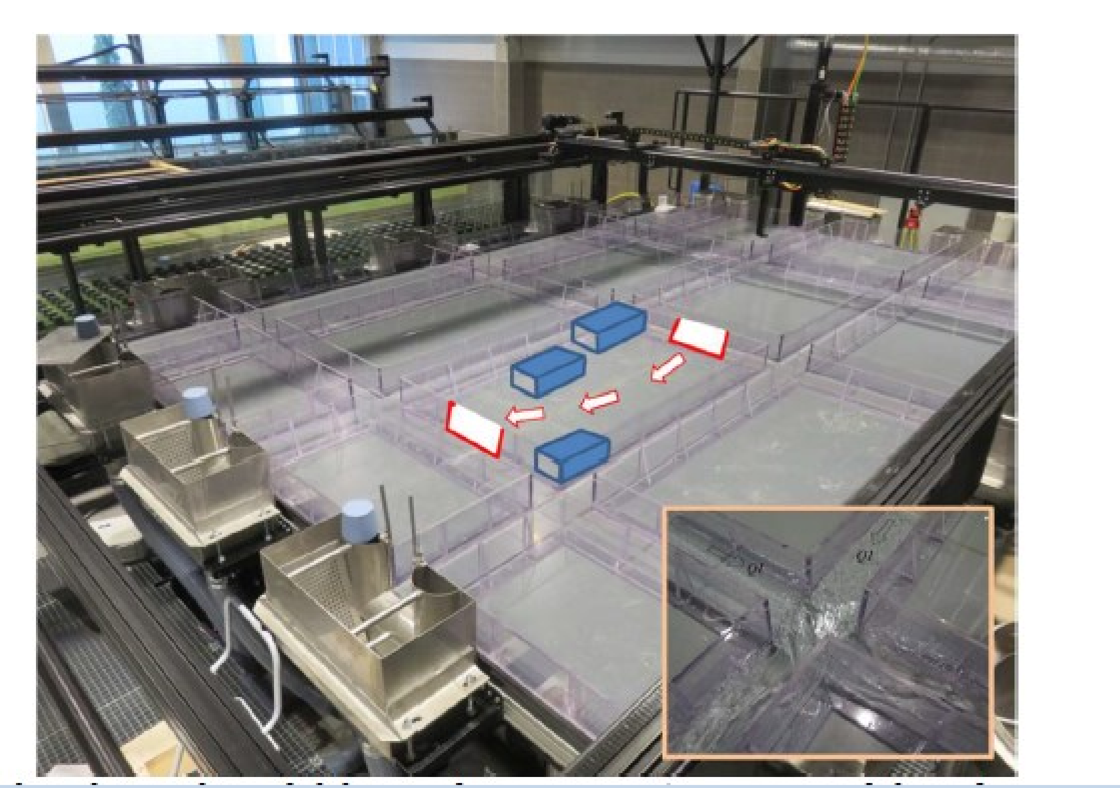
- **Composite** channel (2018-2019)



S. Proust, V. Nikora, C. Berni

4.2 - Perspectives (2019-2022): urban flood processes

- Project DEUFI (Detailing Urban Flood Impact) funded by the ANR (2019-2022)
  - Influence of lateral interfaces in urban flood processes (PhD of M. Meija from nov. 2018- nov. 2021)

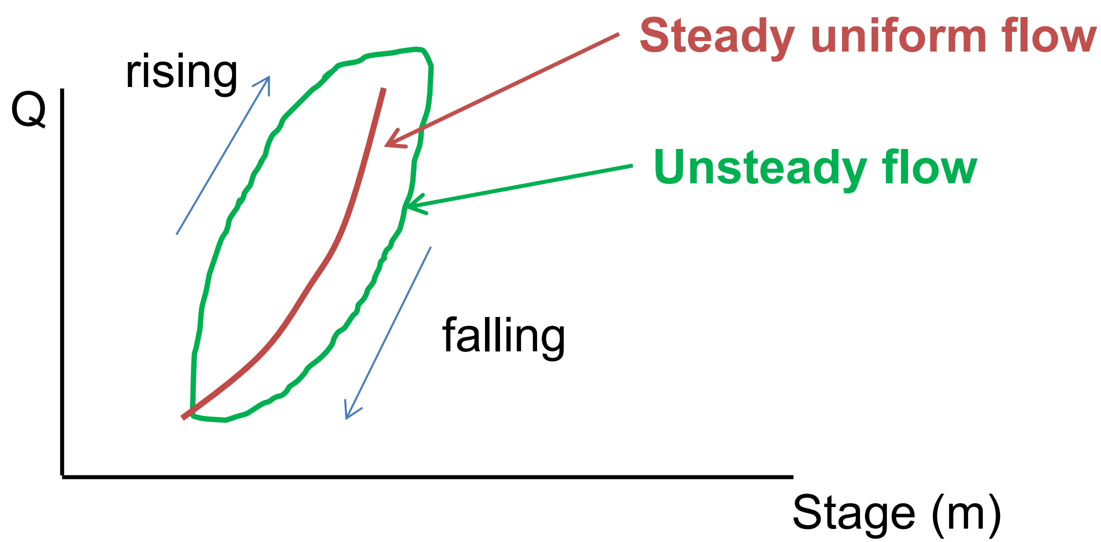


Block scale
WP1 Laboratory experiments
WP1b *Impact of opening porosity on flow depth and velocity in the block and neighboring streets.* *Effect of the urbanistic organization inside the block (courtyards vs. small buildings) on flow pattern and time of submersion T* RiverLy, MURI model (5.4 m×3.8m). **Mapping of flow depth and velocity for steady flows and time scale for unsteady flows**

4.3 - Perspectives (2019-2022): unsteady flow effects on overbank flows

PhD of Y. Kaddi (2018-2021): '1D+ Modelling (ISM) of a complex hydraulic network. Application to the operational forecasting of high flow events and floods related to the sizing of civil engineering structures.'

- July-Nov 2018: validation of ISM under unsteady flow conditions



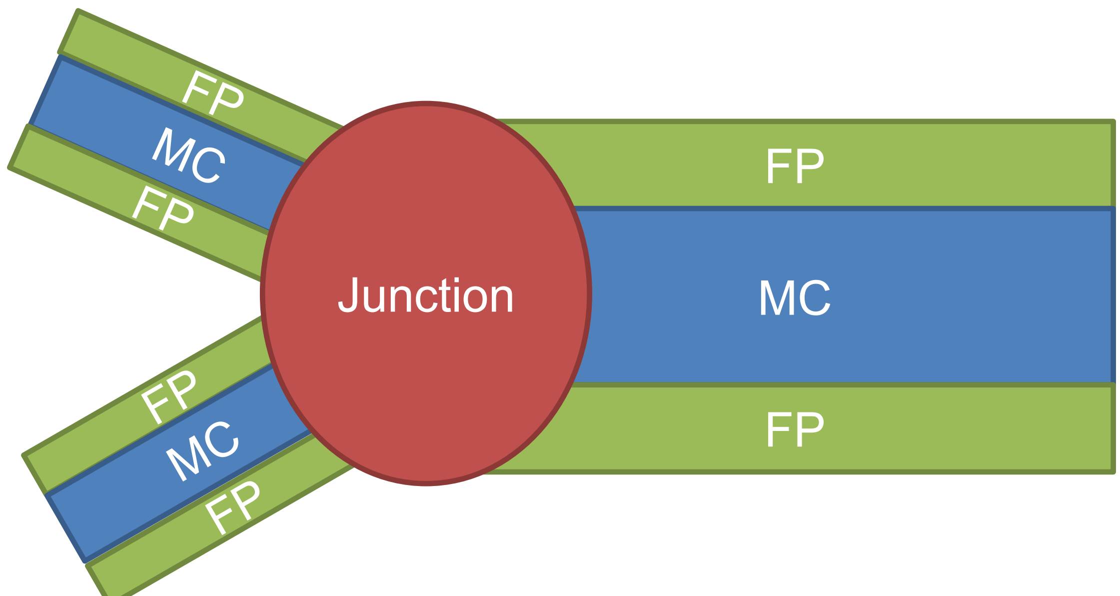
4.4 - Perspectives (2019-2022): 1D+ ISM for complex networks

- Then, application to the Rhône river (PhD half-funded by the Compagnie Nationale du Rhône)

Confluence Rhône / Ardêche, 2003

100-year return period discharge

- Make ISM operational for networks with junctions



Thank you for your attention !

…. any questions ?