Floods, inundations, submersion: Part 1: Hydro-sedimentary modelling

Benoît CAMENEN

UR Riverly, INRAE, River Hydraulics team

Villeurbanne

IMPT, Morphological impact of climate change,

23-26 novembre 2021, Lyon

Introduction of the 3rd course on "Flood, inondation, and submersion"

- 25/11/2021, 14:00 – 16:00 : Benoît Camenen

  Some issues in hydro-sedimentary modelling in rivers
- 25/11/2021, 16:30 - 18:30 : Julien Chauchat

  Mutli-scale approach for sediment transport in the nearshore
- 26/11/2021, 09:00 - 11:00 : Gaël Richard

  Numerical issues in 2D/3D modelling

- My specific presentation made in collaboration with André Paquier & Jean-Baptiste Faure (INRAE, RiverLy)

Use of numerical modelling in river engineering

- Hydraulics
  - Flood forecasting (active channels, urban flooding)
  - Low water modelling
  - River habitat, refuge area
- Sediment transport and morphodynamics
  - Pollution dynamics, fine sediment fluxes modelling
  - Prediction of erosion and deposition (at the reach scale or close to structures)

Hydraulic modelling

- Based on the Barré-de-Saint-Venant (BSV) equations (shallow water equations) : at each time step, calculation of water level and velocity for :
  - each cross-section (1D model)
  - each element (2D model)
- 1D equations :
  - Mass conservation : $$\frac{\partial S_w}{\partial t} + \frac{\partial (S_w V)}{\partial x} = 0$$

    S_w : wet section area
    V : mean velocity
  - Energy conservation $$\frac{\partial V}{\partial t} + \frac{\partial [V dV + gz]}{\partial x} + g J_f = 0$$

    with $$J_f = \frac{V^2}{K^2 R_h^{4/3}}$$

    K : Strickler friction coefficient
    R_h : hydraulic radius

Why are we still using 1D modelling?

- Interest of 1D modelling
  - Possibility to test a large number of scenarios (Monte-Carlo); Real time simulation; Long-term simulation (10^3 years)
  - Large domains (river network)
  - Possibility to couple the model with hydrological models
- Drawbacks of 1D modelling
  - Need of expertise (simplifications)
  - Need to build a quasi-2D solution from 1D variables
  - Difficulty to stock data results for long/multiple computations

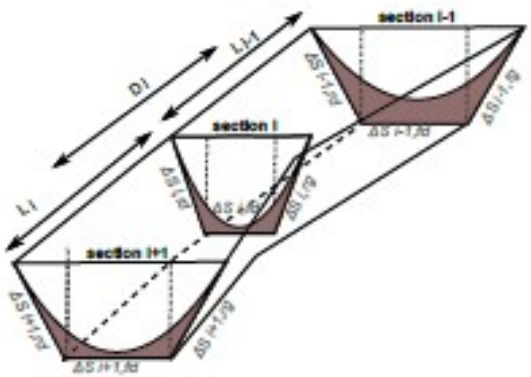
Hydraulic modelling, data needed

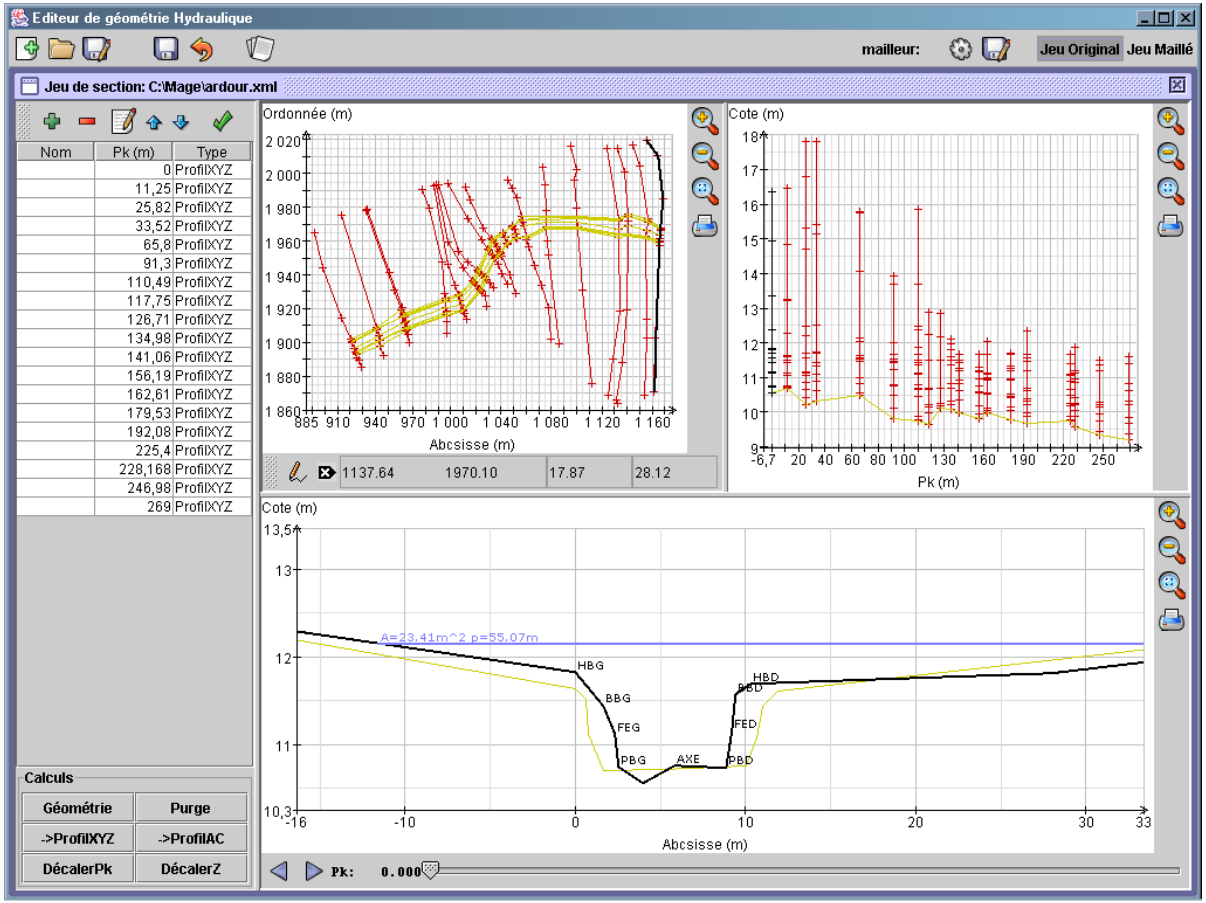
- Data to build a 1D model :
  - Network topology
  - Series of cross-sections describing the river bed (until dikes) and describe the longitudinal profile ($\Delta x \approx W$ for low flow modelling)
  - Characterisation of structures (weir, dam, …)
  - Possibly, a description of the bed roughness at different stages

Hydraulic modelling, data needed

- Data to build a 1D model :

PamHyr platform for 1D modelling (RubarBE, Mage, INRAE Lyon)





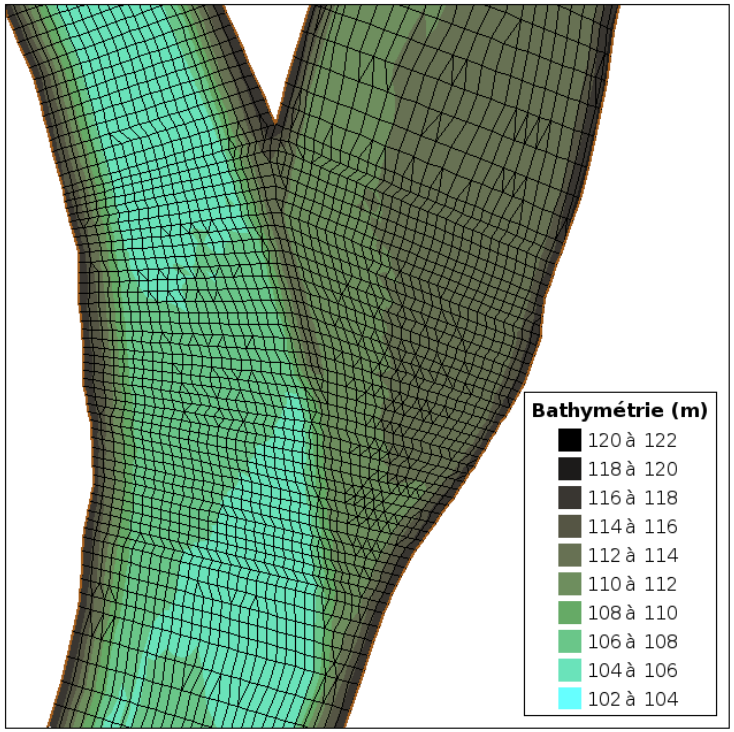
Hydraulic modelling, data needed

- Data to build a 2D model :
  - Set of bathymetric data points to describe the whole river bed including main bed forms (and structures); calculation time increase linearly with the number of nodes *n*! (increase with $n^{1.5}$ to keep the Courant-Friedrich-Levy CFL conditions)
  - Characterisation of complex structures (dam, …)
  - Possibly, a description of spatial distribution of the bed roughness

Hydraulic modelling, data needed

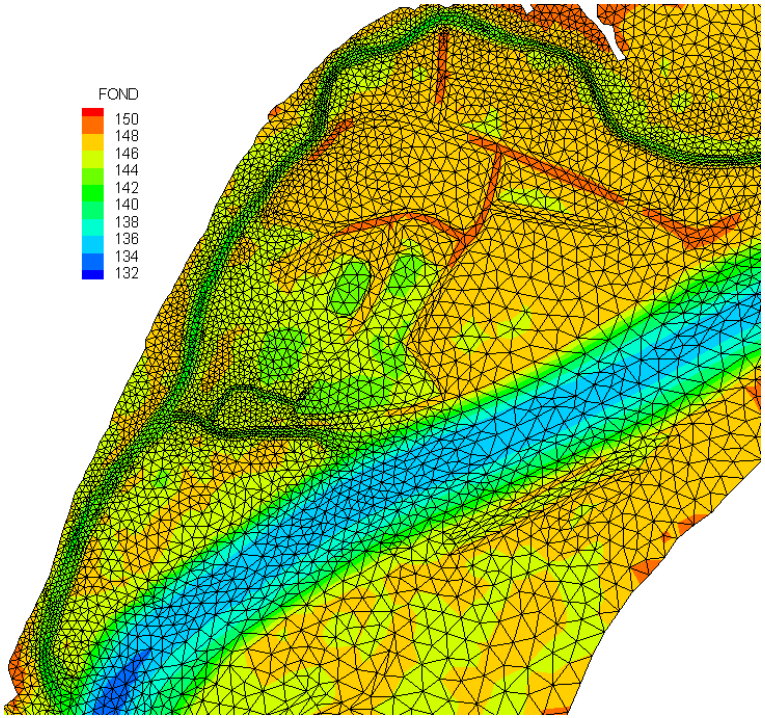
- Data to build a 2D model :

Quad mesh for finite volumes (Rubar20, INRAE Lyon)



Rhône-Isère confluence (G. Naudet)

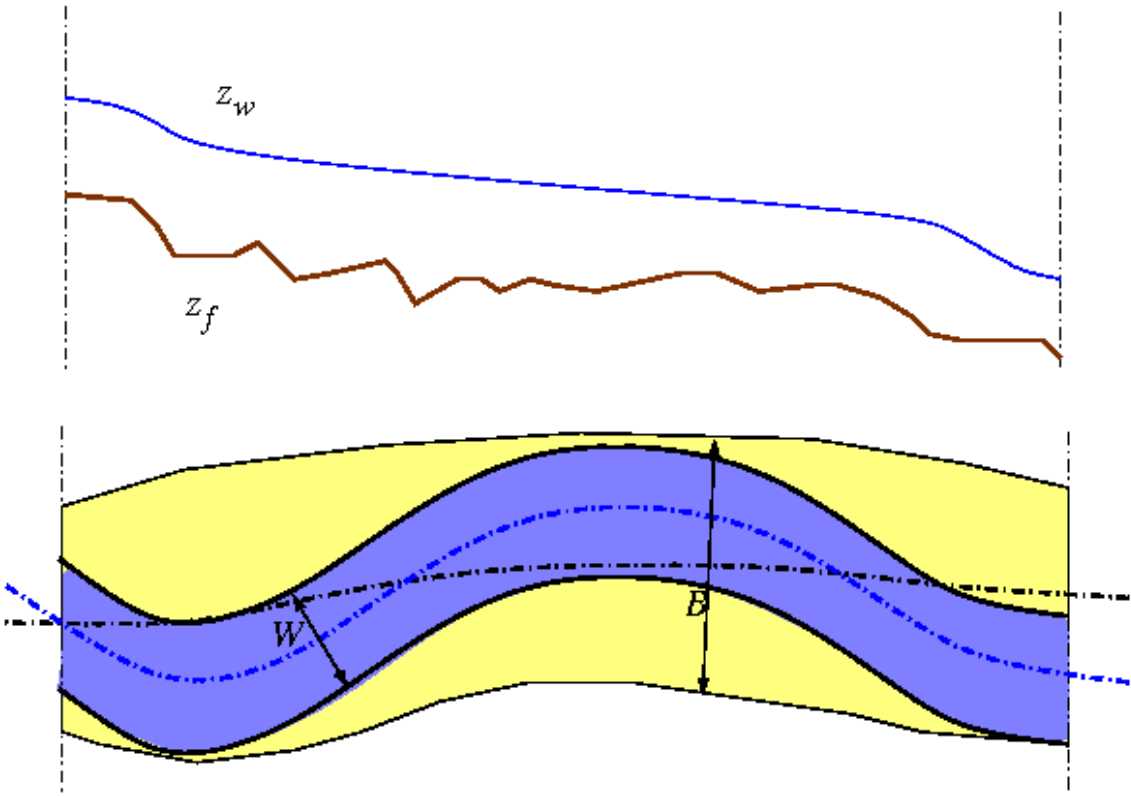
Triangular mesh for finite volumes or finite elements (Telemac, EDF-LNHE)



Lône du Beurre (Artelia)

Issues in 1D hydraulics modelling

- Need a different model for high-flow and low-flow modelling:
  - Reach length
  - Energy loss due to topography

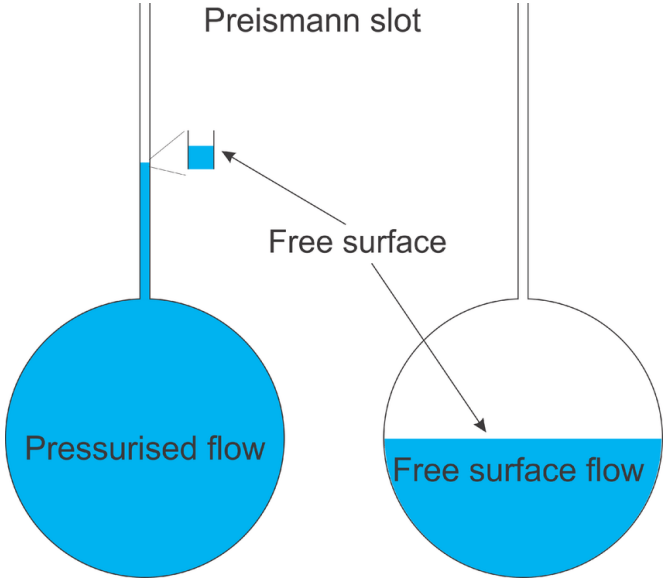


Issues in 1D hydraulics modelling

- Hydraulic structures:
  - BSV equations not valid for strong gradients (slope, river width)
  - Hydraulic laws require coefficients to be calibrated
  - Sensitivity to the water depth (submerged structure)
  - Possible numerical instabilities

    → use of the Preissmann slot

    for pressurized flows

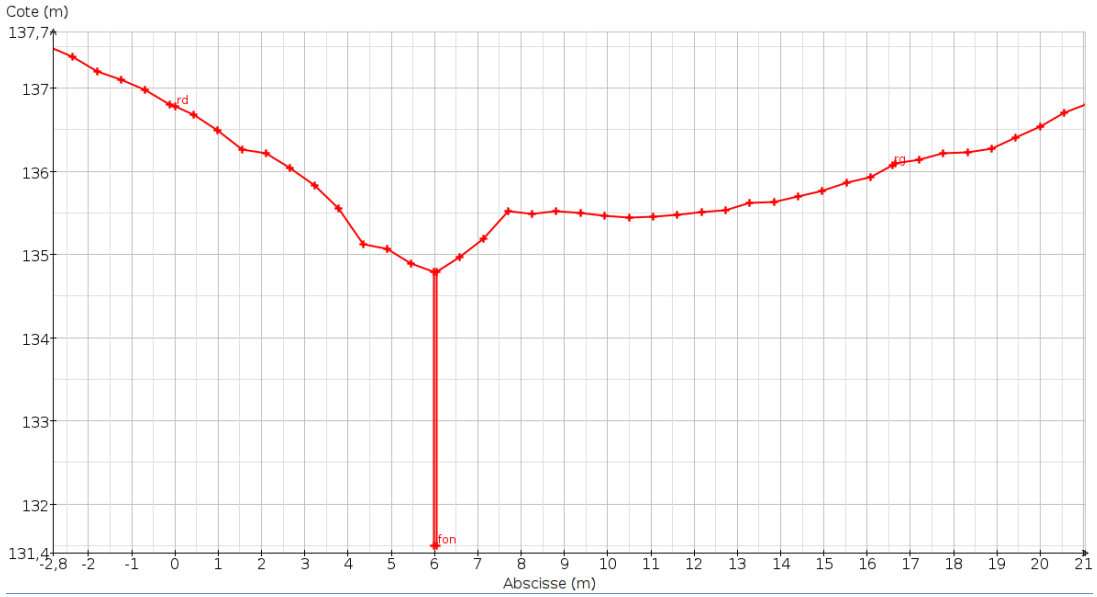


Malekpour & Karney (JHE, 2016)

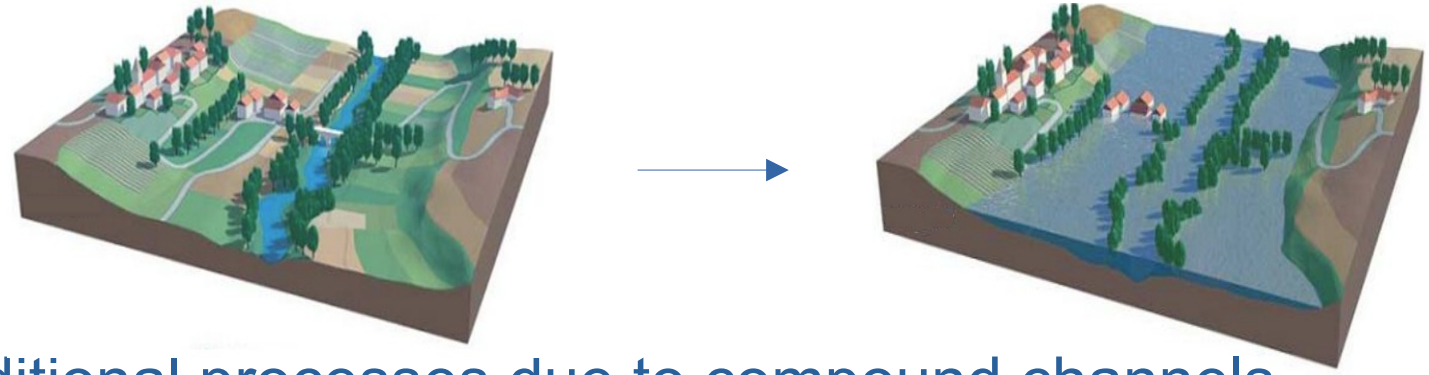
Issues in 1D hydraulics modelling

- Dry sections:

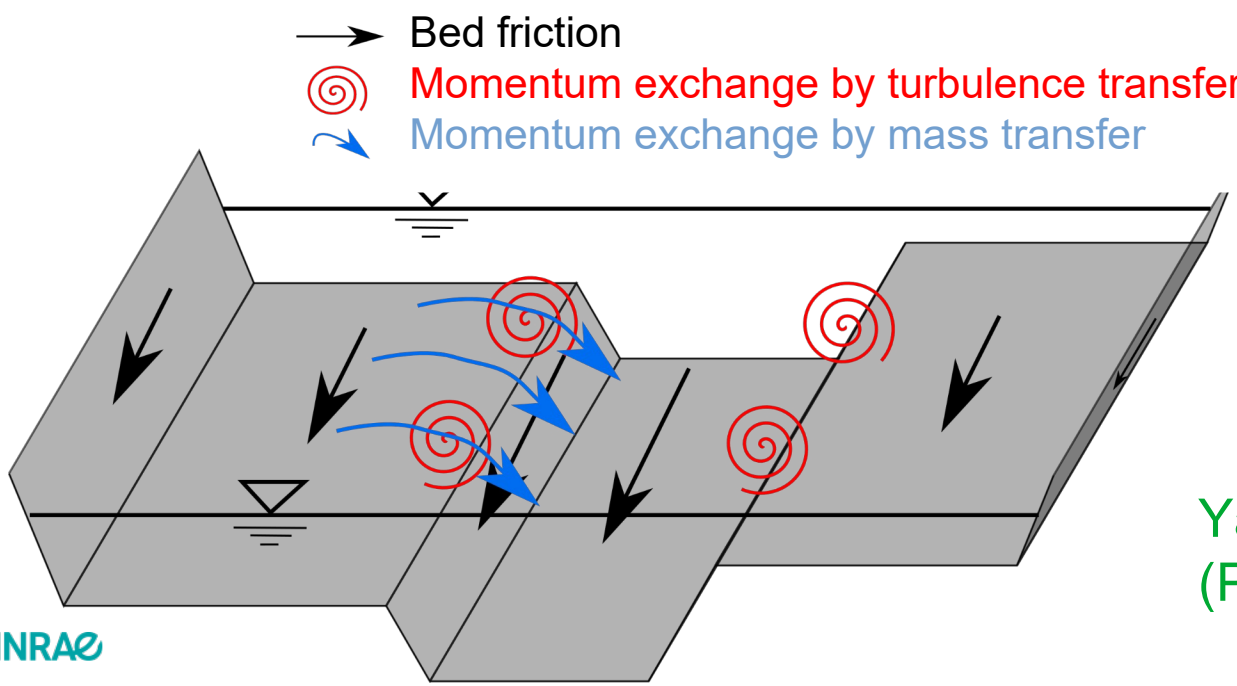
  → use of the Preissmann slot



Flow modelling in compound channels



- Additional processes due to compound channels



Yassine Kaddi
(PhD 2021)

Flow modelling in compound channels

- Divided Method Channel (Lotter, 1933)
  - Friction loss modelled for each subsection using Manning-Strickler

$$J_f = \frac{V_{mc}^2}{K_{mc}^2 R_{h,mc}^{4/3}} = \frac{V_{fp}^2}{K_{fp}^2 R_{h,fp}^{4/3}}$$

- Debord method (Nicollet & Uan, 1979)
  - Correction taking into account turbulence transfer
- Exchange Discharge Model (Bousmar and Zech, 1999)
  - Explicit modelling of turbulence and mass transfer

Flow modelling in compound channels

- Independent Subsection Method, 1D+ (Proust et al., 2010)
  - Resolution of the momentum equation for each subsection

$$\left(1-\frac{U_{mc}^2}{gh_{mc}}\right)\frac{\partial h_{mc}}{\partial t}=J_0-\boxed{J_{f,mc}}+\frac{V_{mc}^2}{gB_{mc}}\frac{\partial B_{mc}}{\partial x}-\boxed{\frac{\tau_{fm}h_{fp}}{\rho g S_{w,mc}}}+\boxed{\frac{q_{fm}(2V_{fp}-V_{fm})}{g S_{w,mc}}}$$

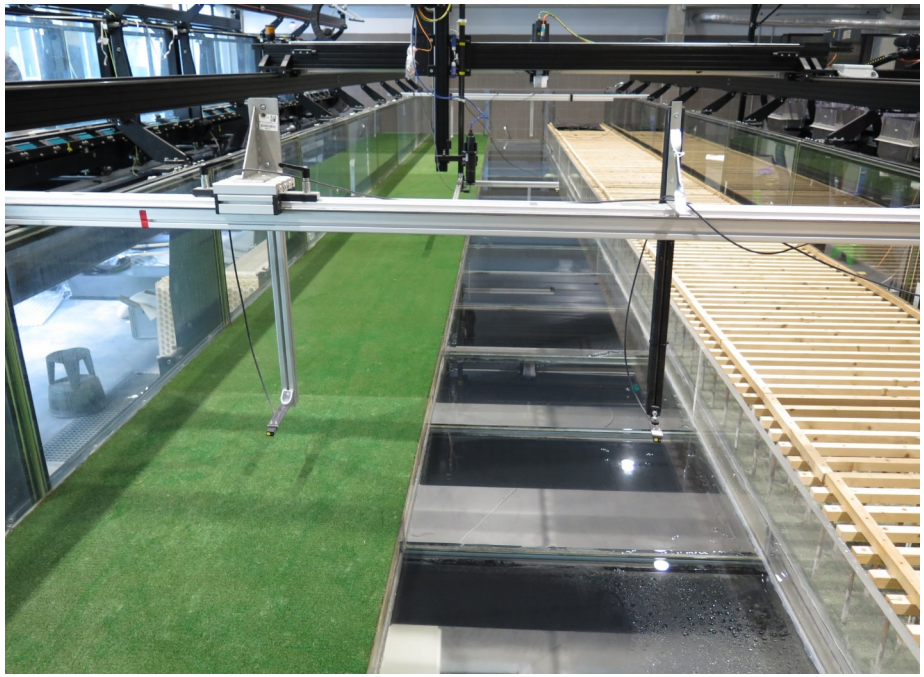
$$\left(1-\frac{U_{fp}^2}{gh_{fp}}\right)\frac{\partial h_{fp}}{\partial t}=J_0-\boxed{J_{f,fp}}+\frac{V_{fp}^2}{gB_{fp}}\frac{\partial B_{fp}}{\partial x}+\boxed{\frac{\tau_{fm}h_{fp}}{\rho g S_{w,fp}}}+\boxed{\frac{q_{fm}(2V_{fp}-V_{fm})}{g S_{w,fp}}}$$

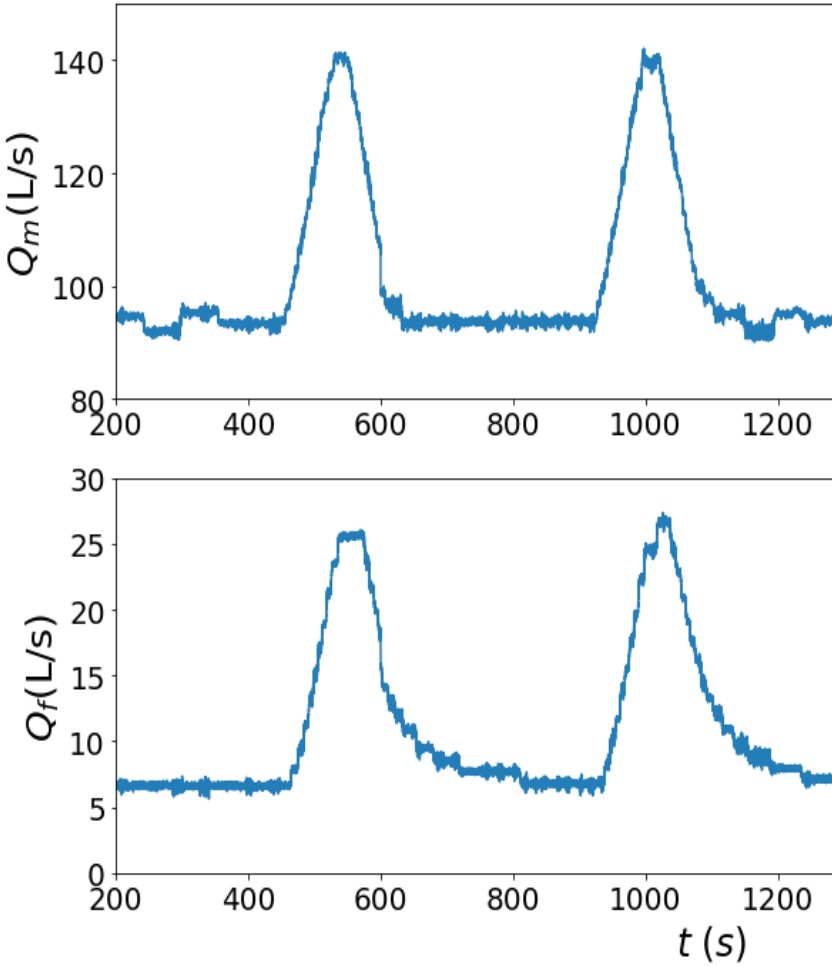
Bed friction
Momentum exchange by turbulence transfer
Momentum exchange by mass transfer

q_{fm} : mass transfer at the interface
τ_{fm} : shear stress at the interface
V_{fm} : longitudinal velocity at the interface
→ closure equations

Flow modelling in compound channels

- Test of an unsteady flow over compound channels

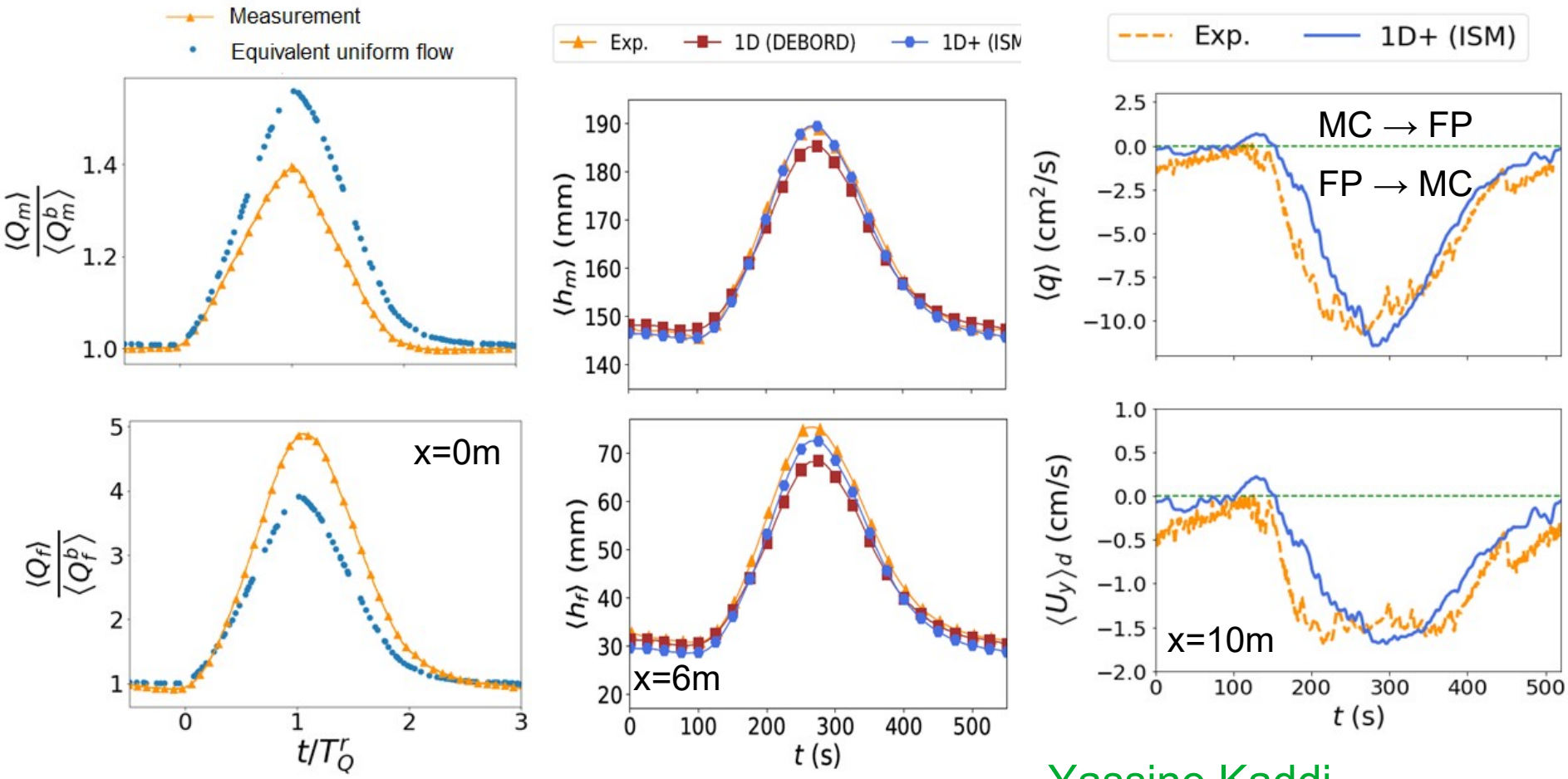




Yassine Kaddi
(PhD 2021)

Flow modelling in compound channels

- Test of an unsteady flow over compound channels

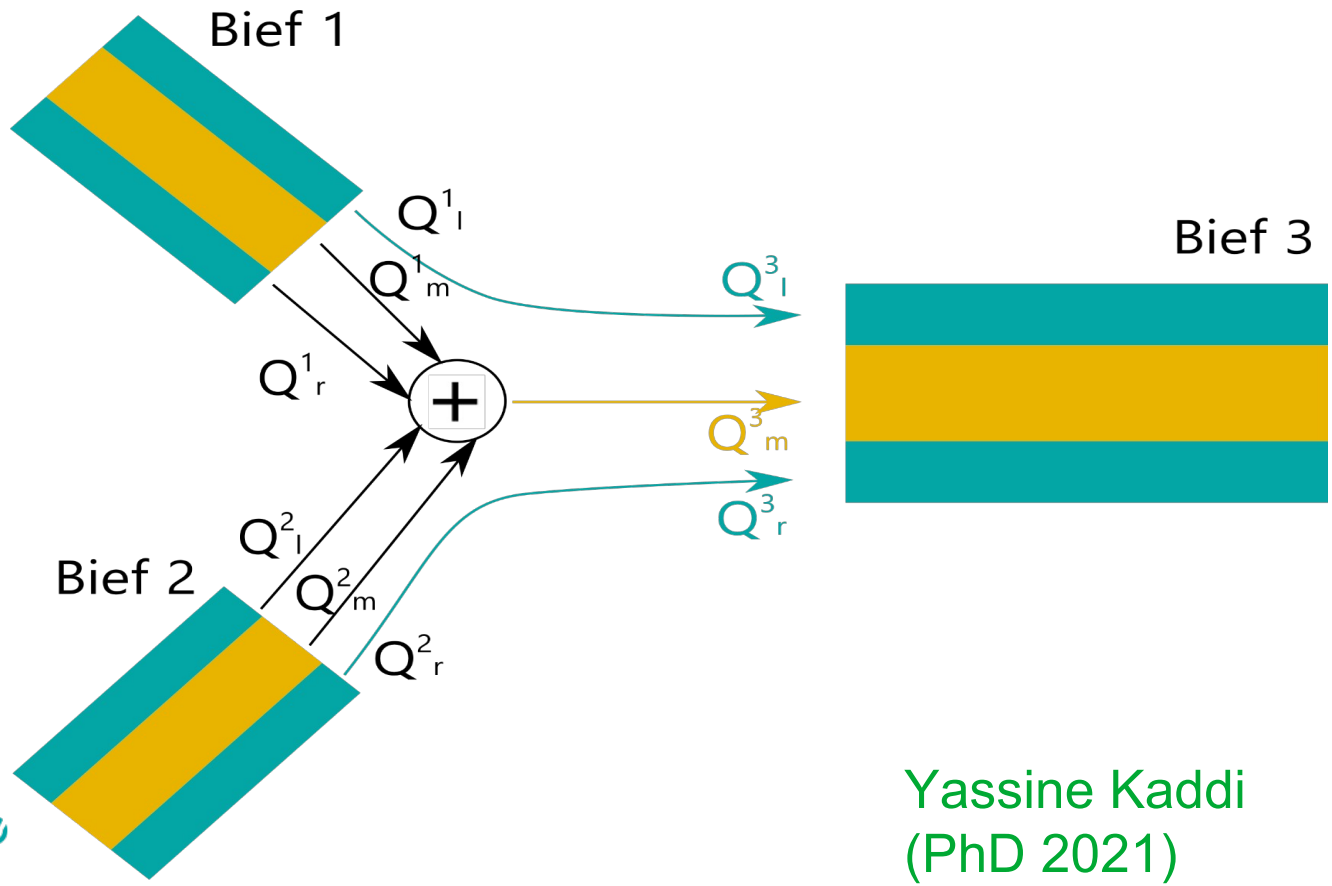


Yassine Kaddi
(PhD 2021)

Flow modelling in compound channels

- Issue of confluences

  → what flow repartition?



Yassine Kaddi
(PhD 2021)

Issues in 2D hydraulics modelling

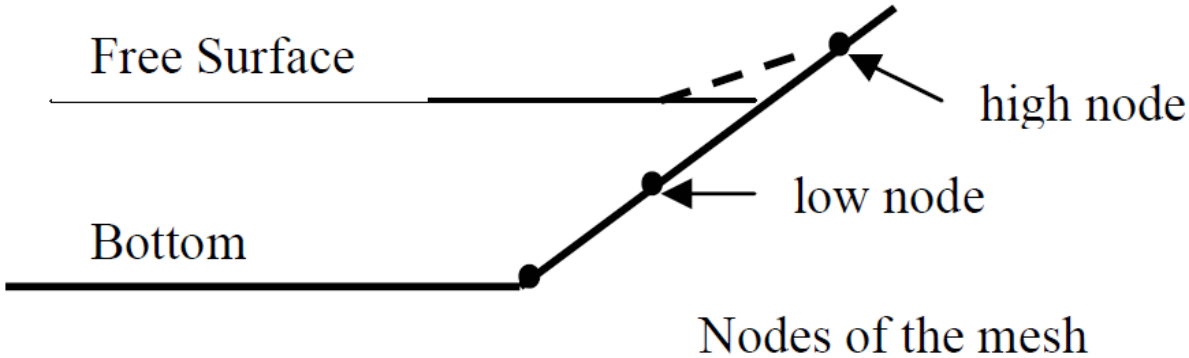
- Hydraulic structures:
  - Same issues as for 1D modelling

    → same methodologies as for 1D modelling but more complex to adapt since it needs a finer discretization

Issues in 2D hydraulics modelling

Dry cells:

- Detection and correction of the free surface gradient and smoothing of negative water depths



- Adding a porosity term to the half-dry cells
- Removing from the calculation all the elements that are not entirely wet (no clear criteria)

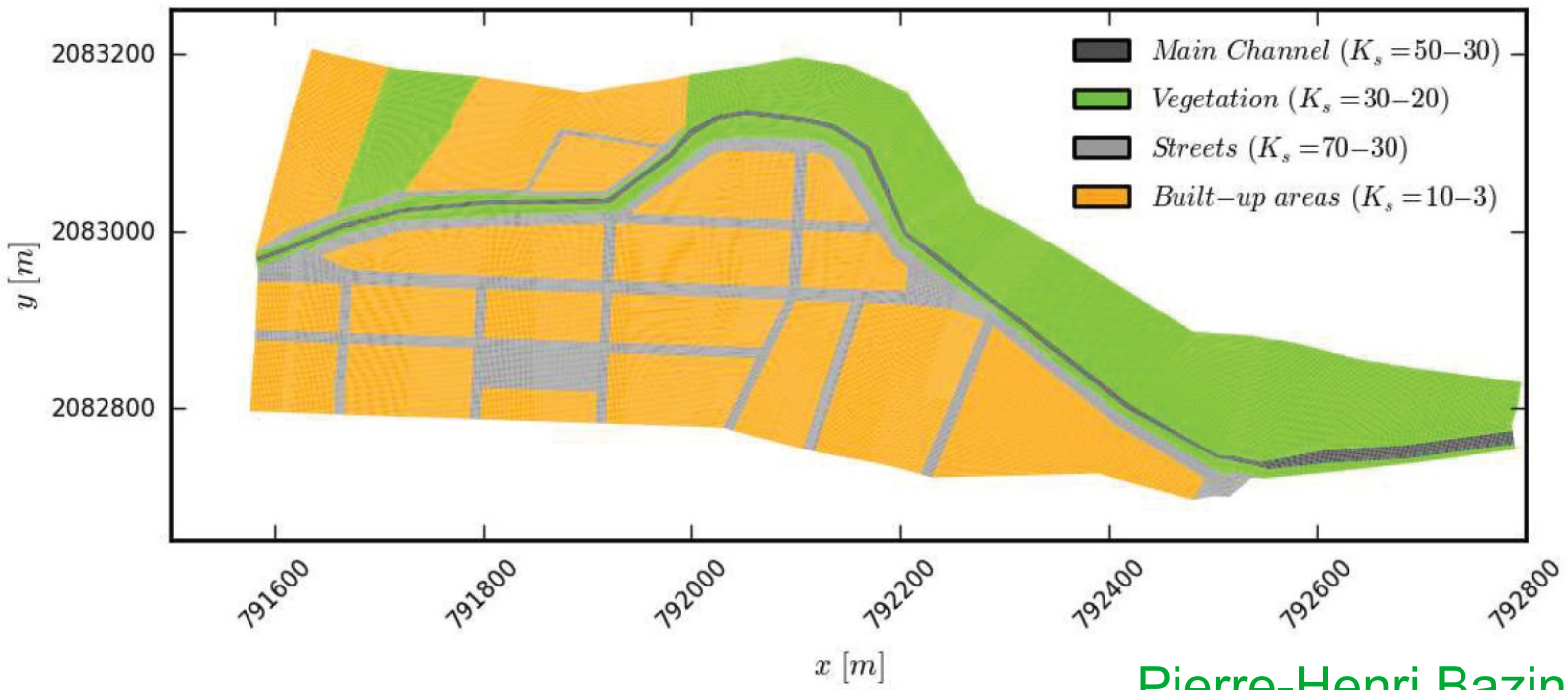
Flow modelling in urban zones

- Urban flooding: important issue in the climate change context (increasing hazard)
- How to represent different obstacles of varying size?
  - Individual houses or blocks (openings)
  - Street furniture (pavement, street light, etc.), vehicles
  - Underground spaces such as the subway
  - Drainage system

Flow modelling in urban zones

- Example of urban blocks at different scale
  - At large scale, can be roughly modelled as a roughness using a Strickler coefficient

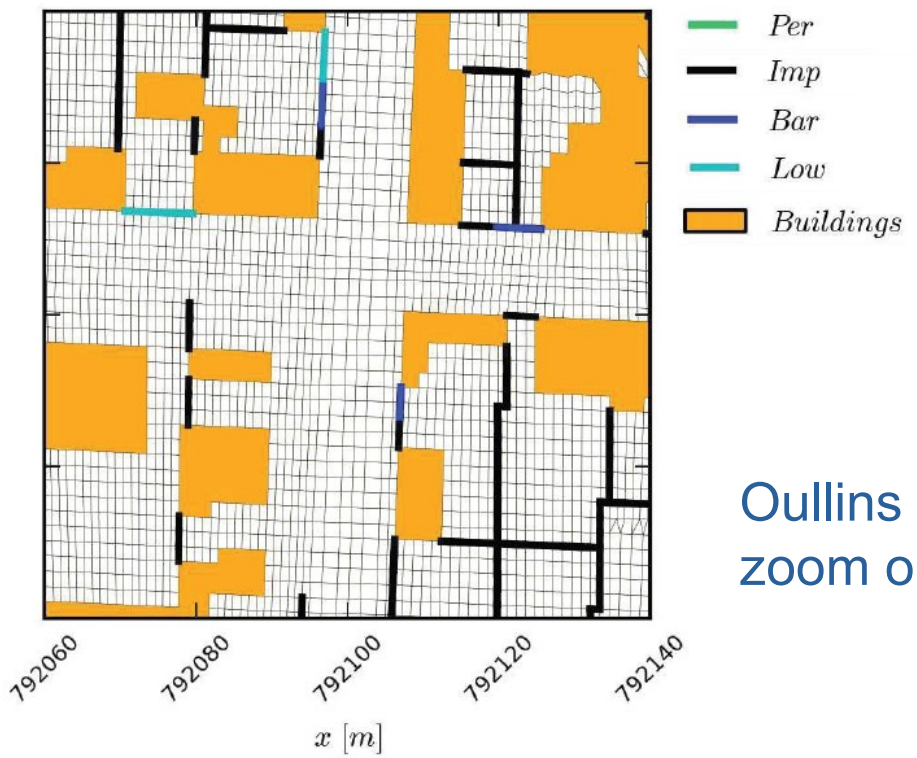
Oullins (near Lyon, France)



Pierre-Henri Bazin (PhD 2013)

Flow modelling in urban zones

- Example of urban blocks at different scale
  - At a smaller scale, need to define structure laws for sub-merged walls (low), (semi)-pervious boundaries (per, bar) or solid boundary (Imp) → increasing complexity!



Pierre-Henri Bazin
(PhD 2013)

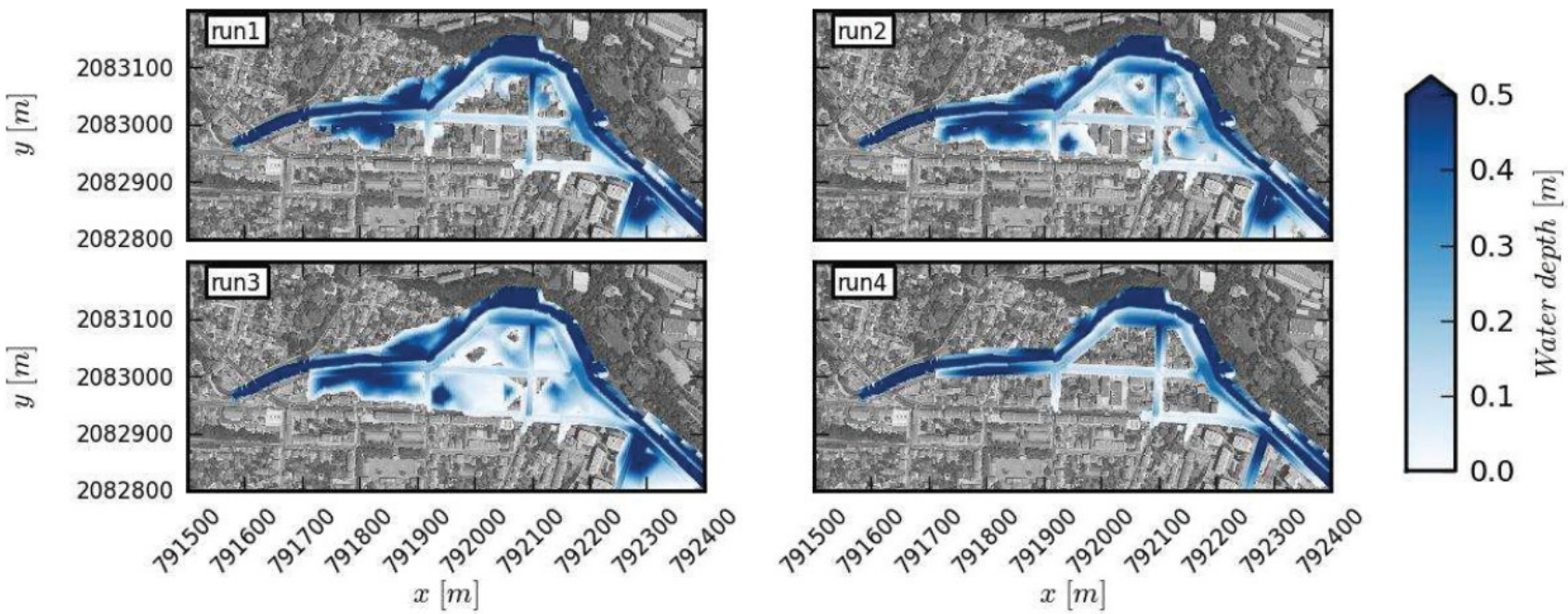
Oullins (near Lyon, France),
zoom on a cross-road

Flow modelling in urban zones

- Example of urban blocks at different scale
  - Run 1: walls, including all buildings and boundaries
  - Run 2: buildings, including buildings but with pervious boundaries only
  - Run 3: free, without building and wall
  - Run 4: streets, excluding building areas

Oullins (near Lyon, France)

Pierre-Henri Bazin (PhD 2013)



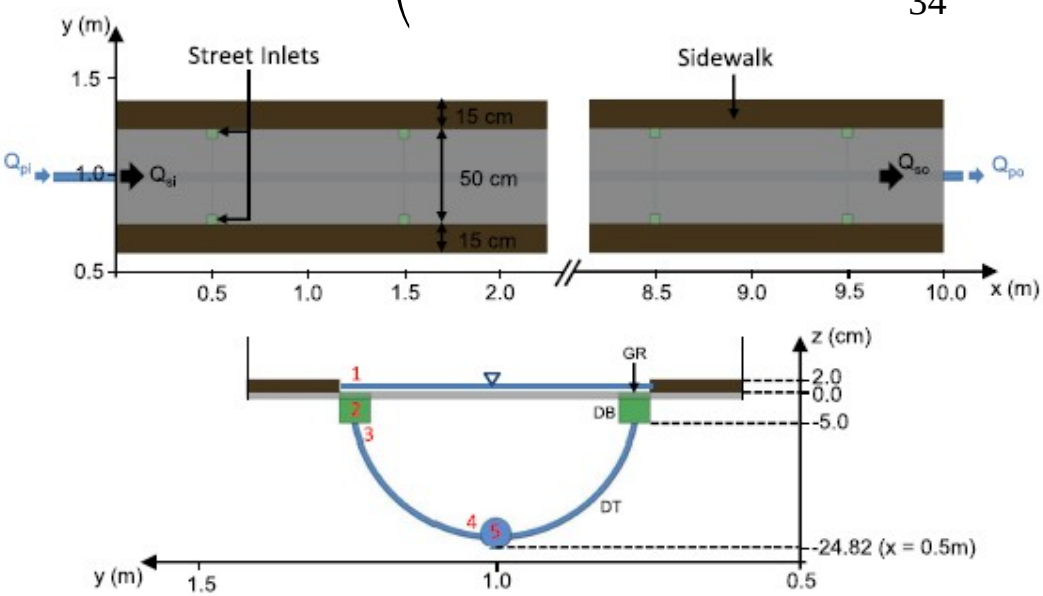
1D/2D coupling

- Often used for large simulation since 1D modelling is more efficient
- Coupling of 1D modelling (duct network, main channel) with 2D modelling (surface flow, overflow, reservoirs, etc.)
- Main issues
  - Numerical instabilities
  - Location of the interface between models?
  - Need to build a quasi-2D solution from 1D variables in a transition zone if flow from 1D model to several cells of 2D model (Mezbache et al., 2020)

1D/2D coupling

- Exchange discharge
  - 2D mass conservation: $$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hu)}{\partial y}=-q_{ex,2D}=\frac{q_{ex}}{\Delta x_{2D}}$$
  - 1D mass conservation: $$\frac{\partial S_w}{\partial t}+\frac{\partial Q}{\partial x}=q_{ex,1D}=\frac{q_{ex}}{\Delta x_{1D}}$$

$$\Delta H_{15}=\left(K_{12}\alpha_{12}^2+K_{23}+f_{34}\frac{L_{34}}{D_{34}}+K_{45}\right)\frac{q_{ex}^2}{2gA_{34}^2}$$



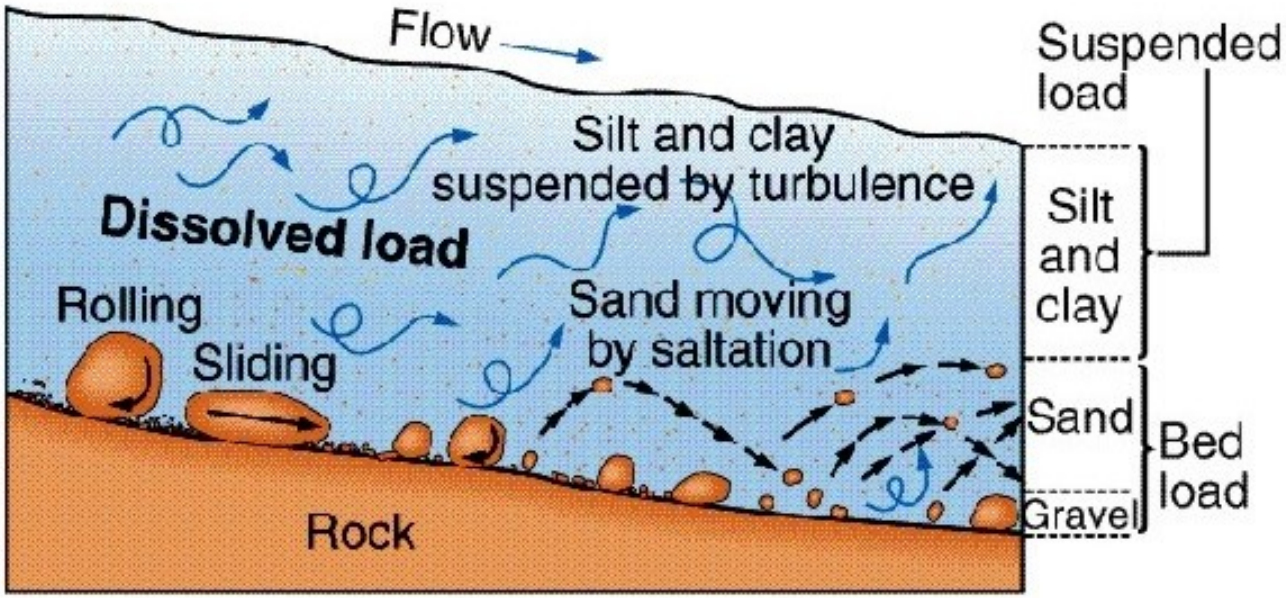
Many coefficients to evaluate
Different for drainage or over flow cases

Bazin et al. (JHE 2014)

What is sediment transport ?

- Bedload: larger sediment which is transported by saltation, rolling, and dragging on the riverbed
- Suspended load : fine sediment which is transported by the flow in the water column with a velocity close to the flow velocity and kept suspended by the fluid turbulence

Plummer, McGeary, & Carlson (2009)



Sediment transport modelling

- Sediment transport capacity C_s: quantity of sediment a uniform steady flow can transport
  - Coarse sediments (sands, gravels): there exist semi-empirical formulas to evaluate C_s
  - Fine sediments (clay, silt): $C_s \approx \infty$
- Sediment transport Q_s: quantity of sediment a flow can indeed transport including spatial (non-uniform) and temporal (unsteady) effects
  - Coarse sediments: $Q_s \approx C_s = f\left(\theta, h/d, d_*, s, \mathrm{Fr}, etc \ldots\right)$
  - Fine sediments: $Q_s = Q_{s,up} + E - D$

Sediment transport modelling

- Mass conservation equations (1D)
  - Exner equation (coarse sediments)

$$(1-p)\frac{\partial S_s}{\partial t}+\frac{\partial Q_s}{\partial x}=0$$

p : bed porosity
S_s : bed section

  - Advection-dispersion equation (fine sediments)

$$\frac{\partial(S_w C)}{\partial t}+\frac{\partial(QC)}{\partial x}-\frac{\partial}{\partial x}\left(D_f S_w \frac{\partial C}{\partial x}\right)=(E-D)W+q_{Lat}C_{Lat}$$

C : sediment concentration
D_f : dispersion coefficient
W: river width

E : erosion flux
D : deposition flux

$$(1-p)\frac{\partial S_s}{\partial t}=(E-D)W$$

Adaptation length

- Distance L_a for which sediment transport Q_s reaches its transport capacity Cs

$$\frac{\partial Q_s}{\partial x} = \frac{(C_s - Q_s)}{L_a}$$

Daubert & Lebreton (1967)

- L_a ~ average distance of a particle jump
  - Bedload: function of the grain size
  - Suspended load : function of the Rouse parameter $P_R = \frac{W_s}{\kappa u_*}$

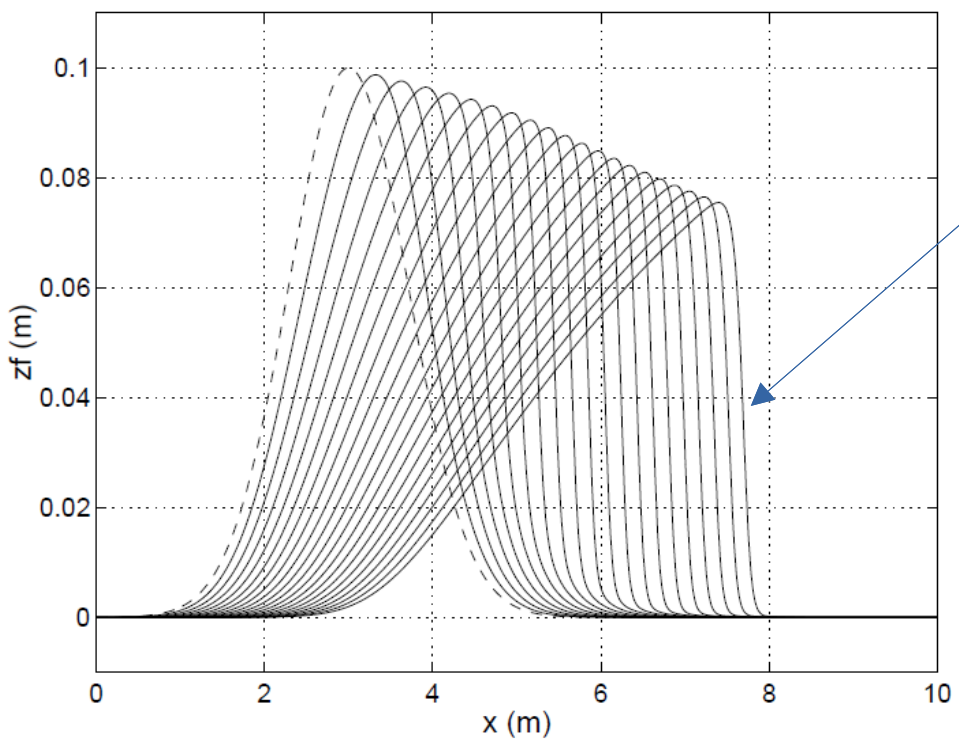
- Attention! In practical use (numerical modelling), term adding diffusion that stabilize calculations. L_a function of the mesh size

Need of diffusion…

- Importance of diffusion to avoid chock → physical?!
  - Adaptation length
  - Slope effect

$$q_s^* = q_s\left(1 - \beta \frac{\partial z_b}{\partial s}\right)$$

Local slope



Dune front
Avalanche transport:
q_s = f(slope,$q_{s,up}$)

Representation of a sediment mixture

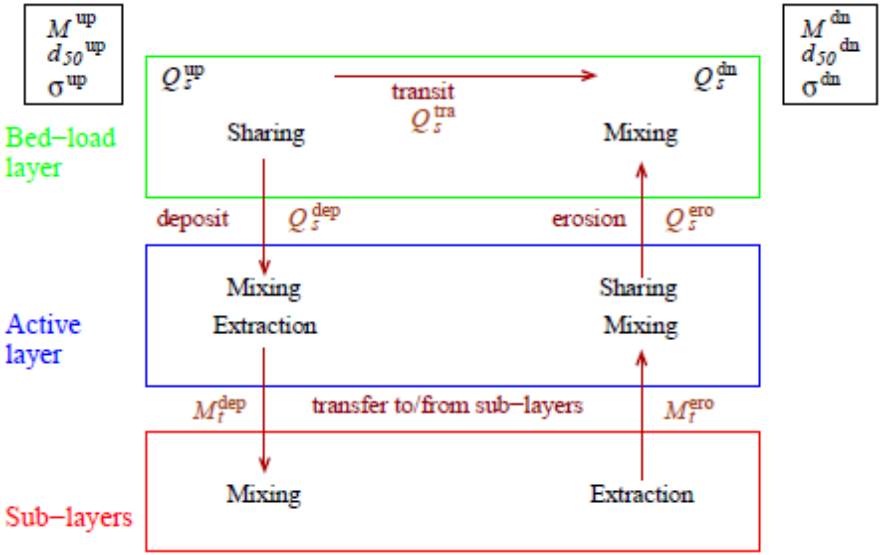
- Most models assumed a single grain size
- Two schools for taking into account a sediment mixture with a poorly sorted grain size distribution (GSD)
  - Description of the GSD in multi-classes ;

    calculation of sediment transport for each class taking into account their content and potential interactions between classes (masquage, surexposition)
  - Description of the GSD using 2 parameters: D_{50} et σ

    hypothesis of a log-normale distribution ; need of semi-empirical laws for the evolution of D_{50} et σ

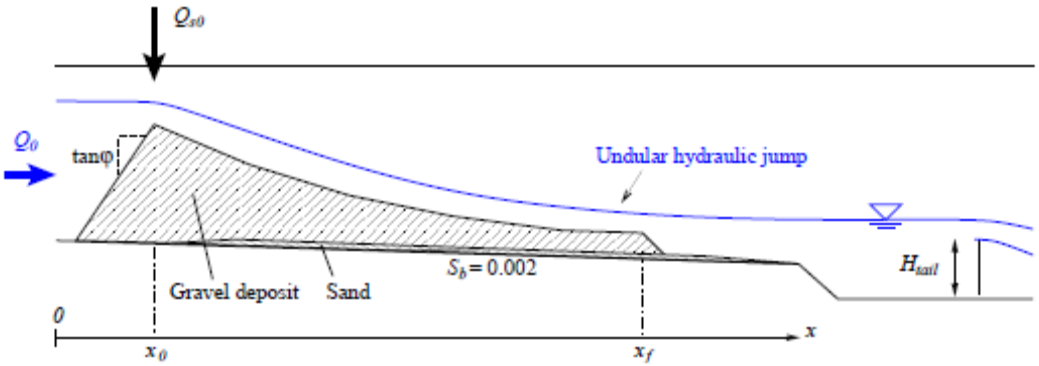
Bed evolution module

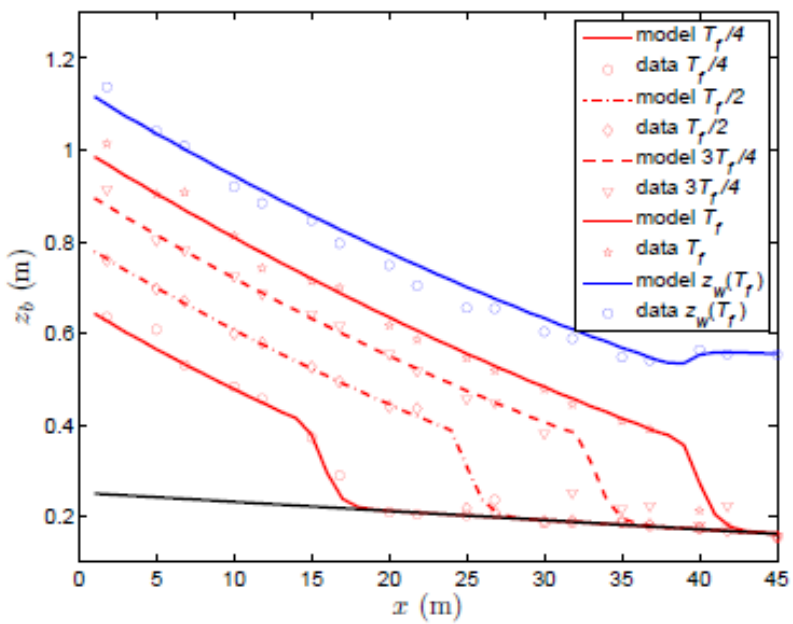
- Most complex part of a morphodynamic model
  - Need to deal with a sediment time step that is different from the hydraulic time step, possible input or output of sediments (or a mixture of sediments), different sediment layers etc. for each cell and each time step.
  - Introduction of the active layer concept to link transport layers to bed layers (Hirano, 1971)



Bed level and grain size evolutions

- Example of a downstream fining experiment (Camenen et al., 2017) using the RubarBe code (INRAE RiverLy, A. Paquier)





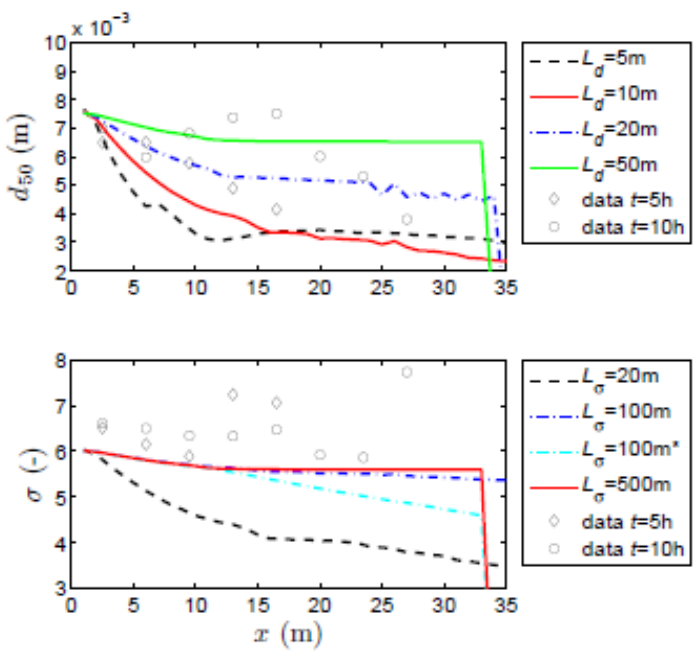
No big issue for the bed level evolution

$$\Delta x = 1 \text{ m}$$

$$L_a = 2 \text{ m}$$

Bed level and grain size evolutions

- Example of a downstream fining experiment (Camenen et al., 2017) using the RubarBe code (INRAE RiverLy, A. Paquier)
- GSD evolution:
  - Mixing process $d_{50} = d_{50a}^{Ma/(Ma+Mb)} d_{50a}^{Mb/(Ma+Mb)}$
  - Sharing process $d_{50f/c} = d_{50} \exp\left[-/+ \frac{\Delta x}{L_d} \frac{\sigma - 1}{\sigma} \frac{M - M_{f/c}}{M} \right]$

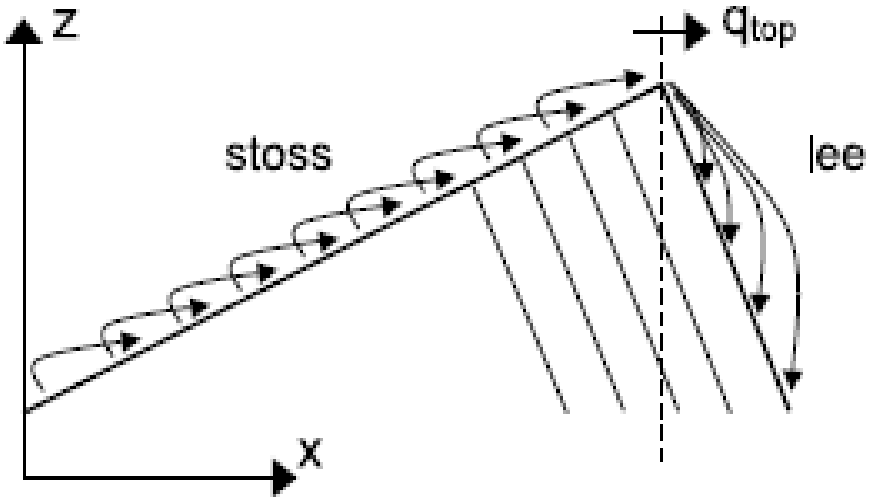


L_d and L_σ proportional to the equilibrium reach length

Correct behaviour but mass conservation for each class not necessarily conserved

Limits of the Hirano concept

- A system of bed layers physical? Active layer thickness?
- Issue for vertical sediment fluxes with no net aggradation or degradation (infiltration, sorting)
- Fail to describe vertical sorting fluxes through bed form migration



Blom & Parker (JGR 2004)

Limits of the Hirano concept

- Equilibrium sorting model (Blom & Parker, JGR 2004)
  - Framework for sediment continuity (Parker et al., JHE 2000) with introduction of a probability density function (PDF) of bed surface elevations, p_e:

$$(1-p)P_s\frac{\partial F_i}{\partial t}+(1-p)F_i\frac{\partial P_s}{\partial t}+(1-p)F_i p_e\frac{\partial \eta}{\partial t}=D_i-E_i$$

    - F_i: volume fraction content of size fraction i at elevation z
    - $P_s=1-\int_{-\infty}^{z} p_e\,dz$
  - Einstein step length formulation + lee sorting function + account for the variability in bed form trough elevation

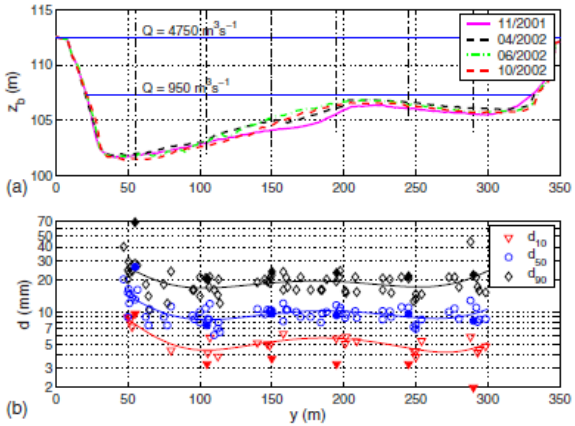
    → computation of the vertical sorting profile in case of dunes
  - Issues in predicting probability distribution of bed elevation and elevation-specific densities for erosion and deposition

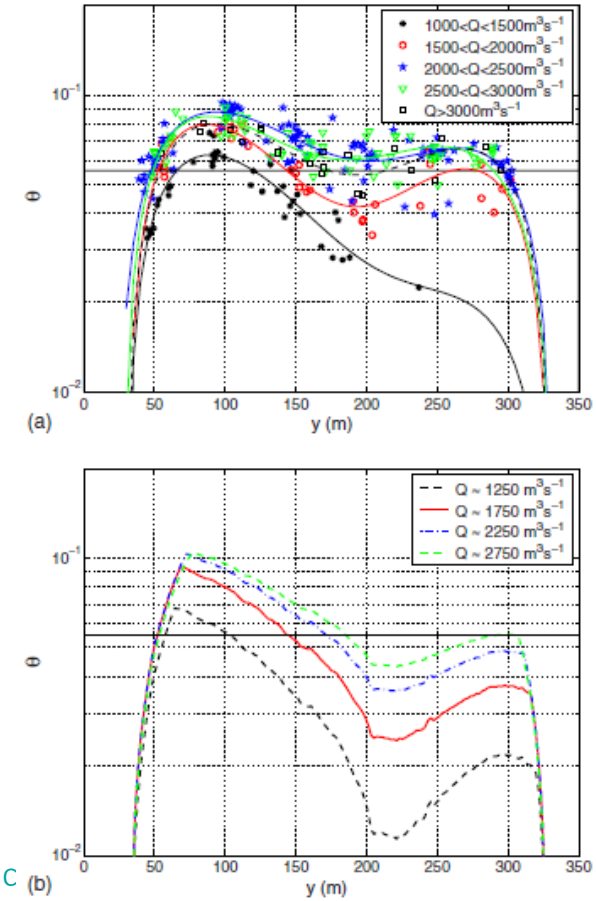
Limits of 1D modelling

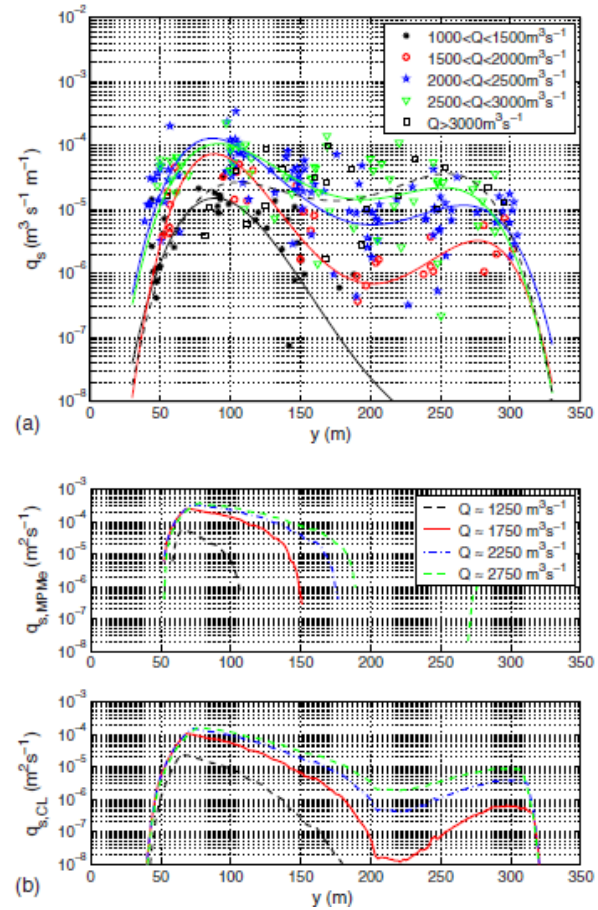
- Based on section-averaged values
  - Water depths and bed shear stress do vary throughout the river section and sediment transport is highly non-linear
  - Bed evolution non-uniform over a river cross-section
- No description of 2D and 3D phenomena
  - Main channel from left to right side of the river → transverse flows liked to transverse channel or transverse slopes)
  - Effects of a 3D flow (curve) on sediment transport

Toward a 1D1/2 modelling

- Distribution of bed shear stress throughout a river section (± proportional to the water depth)
- Example of the Danube River in Slovakia (Camenen et al., 2011)



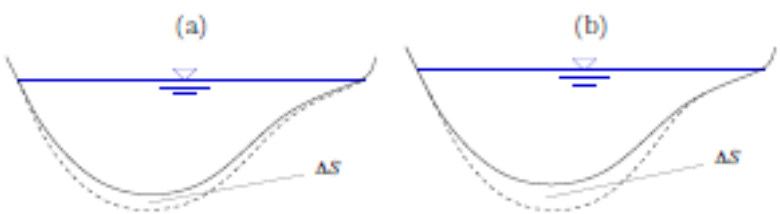




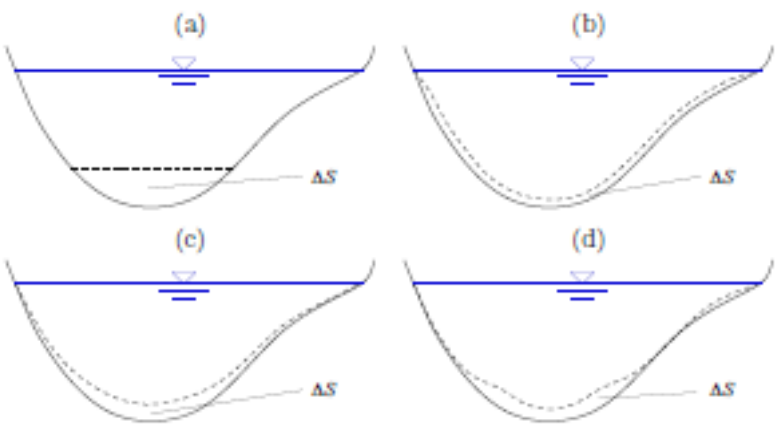
Toward a 1D1/2 modelling

- Distribution of erosion/deposition volumes throughout the river cross-section
  - Function of the bed shear stress (water depth)
  - Different distribution depending on erosion/deposition?
    → more realistic but less stable
  - Modelling strategy depending on the river, difficult to validate!

erosion



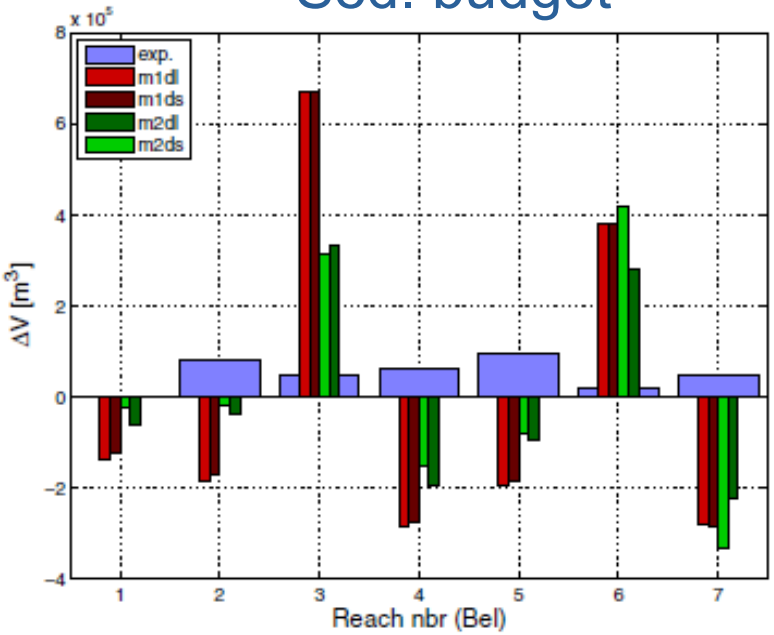
deposition



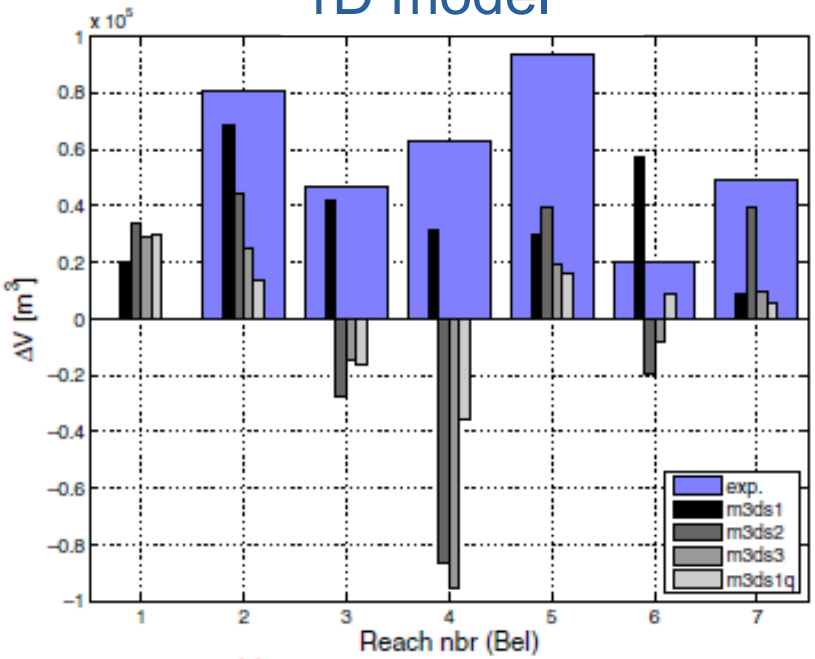
Application of 1D modelling for sediment budget

- Sediment budget on several reaches of the Loire River at Belleville, comparison simplified sediment budgets and 1D modelling (Camenen et al., 2015)

Sed. budget



1D model



- Importance of unsteadiness and diffusion

Modelling of the fine sediment dynamics

- Advection-Dispersion equation

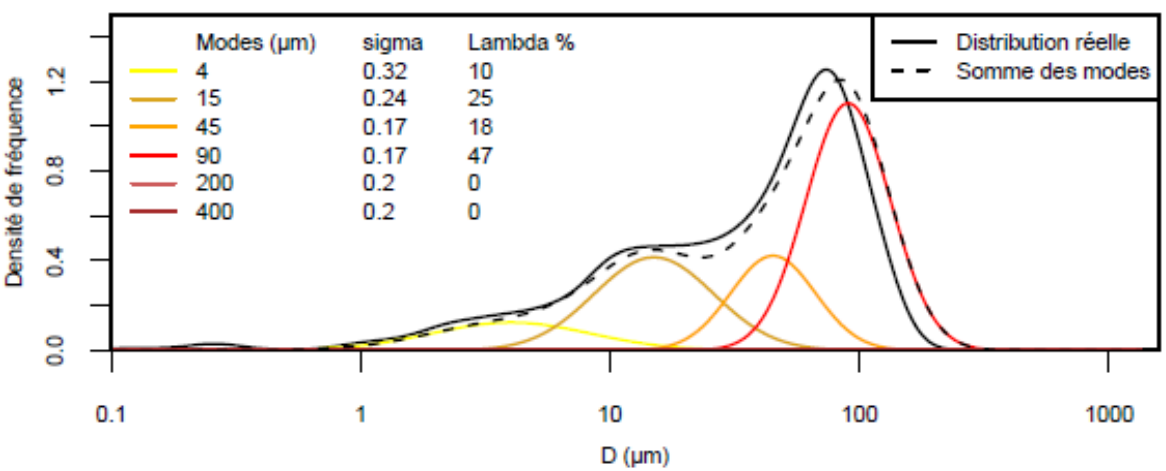
$$\frac{\partial(S_w C)}{\partial t}+\frac{\partial(QC)}{\partial x}-\frac{\partial}{\partial x}\left(D_f S_w \frac{\partial C}{\partial x}\right)=(E-D)W+q_{Lat}C_{Lat}$$

Advection *Dispersion* *Source terms*

- Implicitly assumed that concentration is homogeneous over the vertical (2D) or the cross-section (1D)
  - OK for fine sediments
  - Wrong for sand
- In case of a 1D (or 2D) model, a concept of mean concentration (over vertical or over the river section) can be used → equilibrium with hydraulic forces

Modelling of the fine sediment dynamics

- Importance of the description of the GSD
  - GSD poorly sorted for fine sediments
  - Vertical equilibrium and bed exchanges very sensitive to the settling velocity, so to the grain size
  - Estimation of main modes of a suspension using data from a laser diffraction siever (Guertault, PhD 2015)



nom	d_{50} (µm)	σ
argile	4	0,32
limon fin	15	0,24
limon gros	45	0,17
sable très fin	90	0,17
sable fin	200	0,2
sable moyen	400	0,2

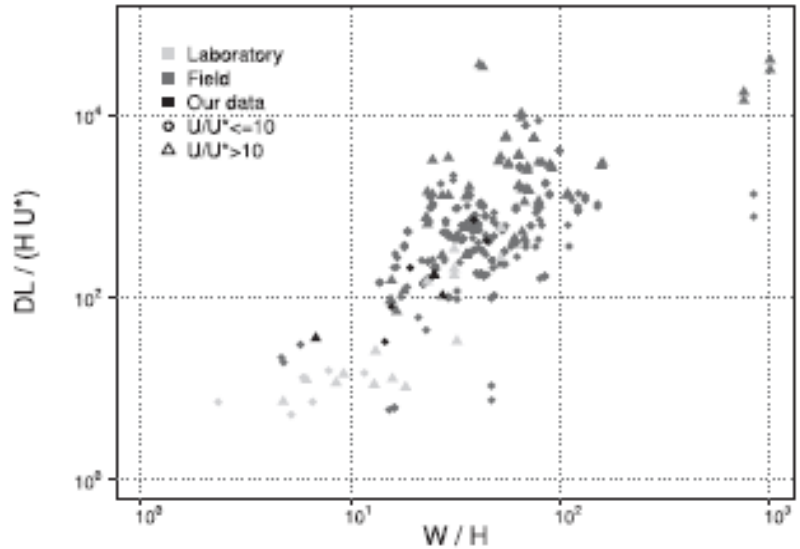
Longitudinal dispersion

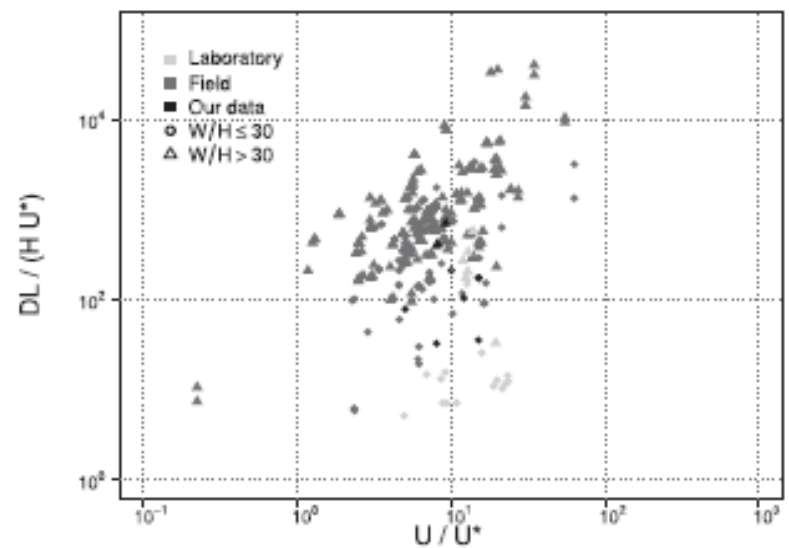
- Many semi-empirical formulations:

$$D_f = a\left(\frac{U}{u_*}\right)^b\left(\frac{W}{H}\right)^c$$

- Correct results obtained for Meribel-Jonage with the Iwasa & Aya (1991) formula (Launay et al. 2014) :

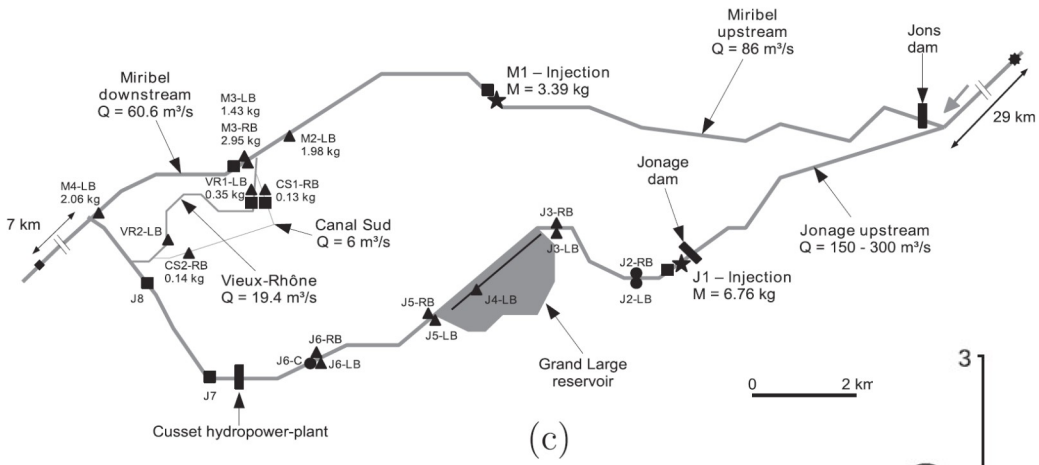
$$a=2 \ ; \ b=0 \ ; \ c=1.5$$



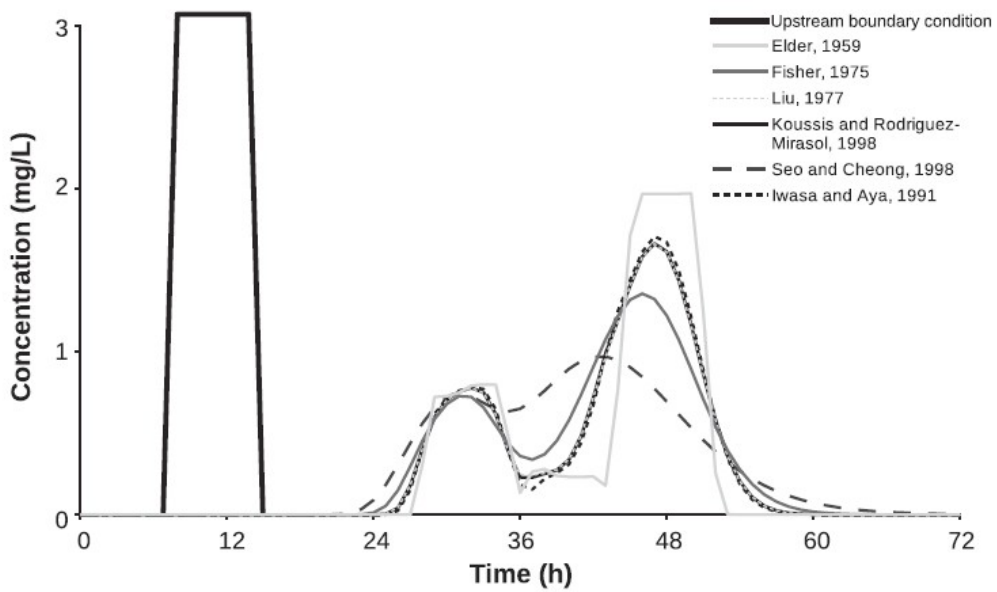


Longitudinal dispersion

- Example of Miribel-Jonage to evaluate the impact of the choice of the longitudinal dispersion formula (Launay et al., 2014) (injection of Rhodamine WT in 2011)



Simulation with Mage- AdisTS (INRAE RiverLy, J.-B. Faure)



1D modelling of the Rhône River

Rhône model

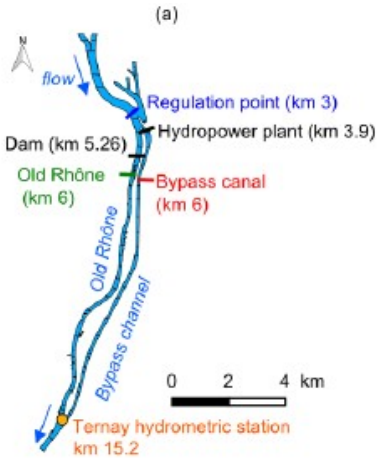
Observatoire des Sédiments du Rhône (OSR)

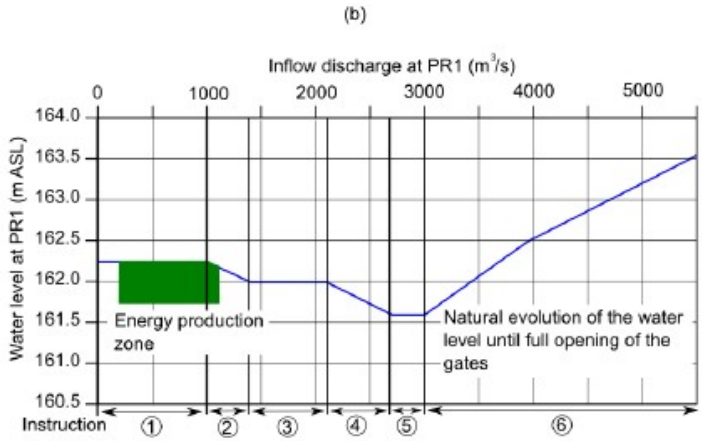
Mage-AdisTS

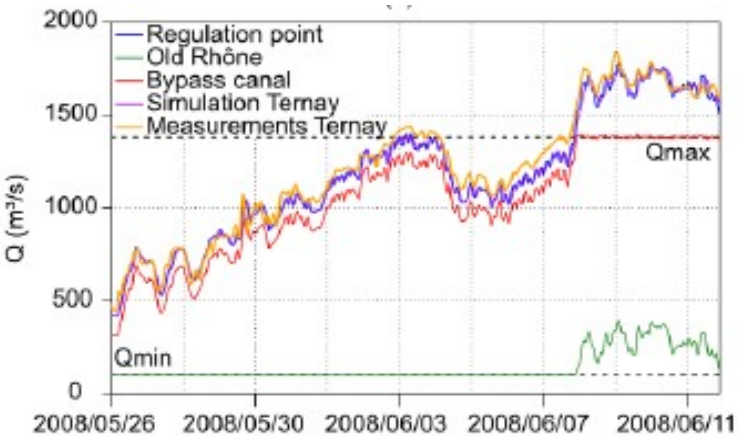
INRAE

1D modelling of the Rhône River

- Regulation of hydro-electric dams (hydraulic laws)
- Additional regulation
  - Discharge regulation du débit entre le between Old-Rhône (compensation water) and headrace (max turbinated water)
  - Water level to maintain in the reservoir (navigation)
- Exemple de Pierre-Bénite (Dugué et al., 2008)



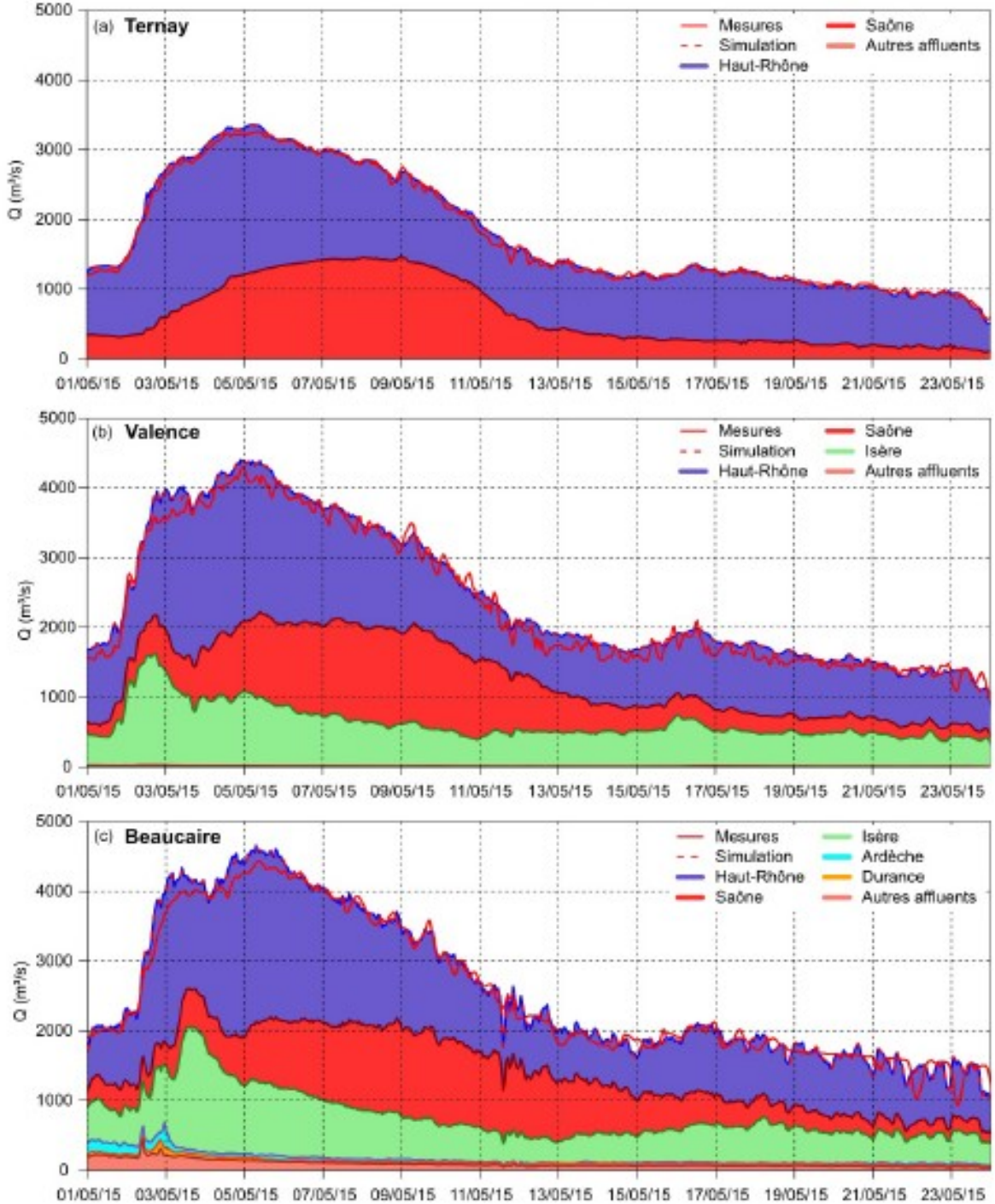




INRAE

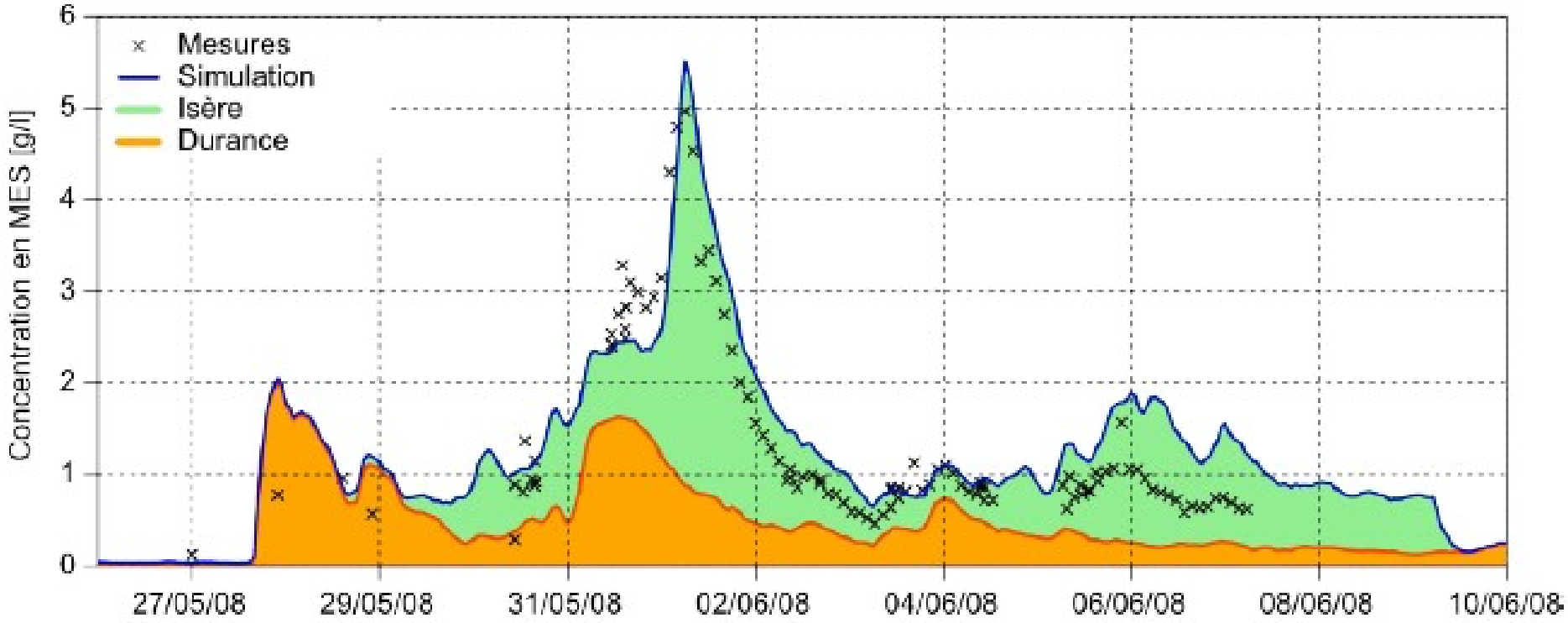
Application of Mage-AdisTS on the Rhône River

- Possibility to quantify each tributary input of water at Beaucaire



Application ofMage-AdisTS on the Rhône River

- Suspended Sediment Matter (SSM) flux on the Rhône River at Beaucaire following 2008 floods of the Isère and Durance River (Launay et al., Stoten 2019)



Source terms

- Erosion (Partheniades, 1965)

$$E = M\left(\frac{\tau}{\tau_{cr}} - 1\right)$$

  - *M*: [kg/m²/s] erosion coefficient, τ : bed shear stress [N/m2], and τ_{cr} : critical bed shear stress (may vary with time for cohesive sediments → consolidation)

- Deposition (Krone, 1962)

$$D = C\,W_s\left(1 - \frac{\tau}{\tau_{cr,sed}}\right) \qquad \tau_{cr,sed} = \infty\,?$$

  - Debate on the existence of a critical be shear stress for sedimentation (settling flux whatever the bed shears stress)
  - In case of a 3D model, use of a concentration close to the bed

Source terms (AdisTS)

- Combination of the erosion (Partheniades, 1965) and deposition (Krone, 1962) source terms

$$E - D = a_{pd} W_s \left(C_{eq} - C \right)$$

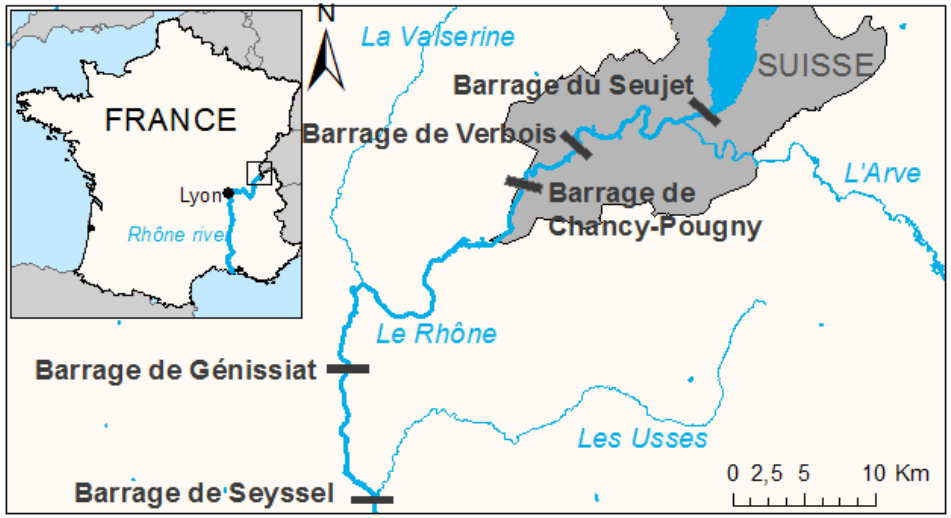
$$C_{eq} = C_0 \left(\frac{\tau}{\tau_{cr}} - 1 \right)$$

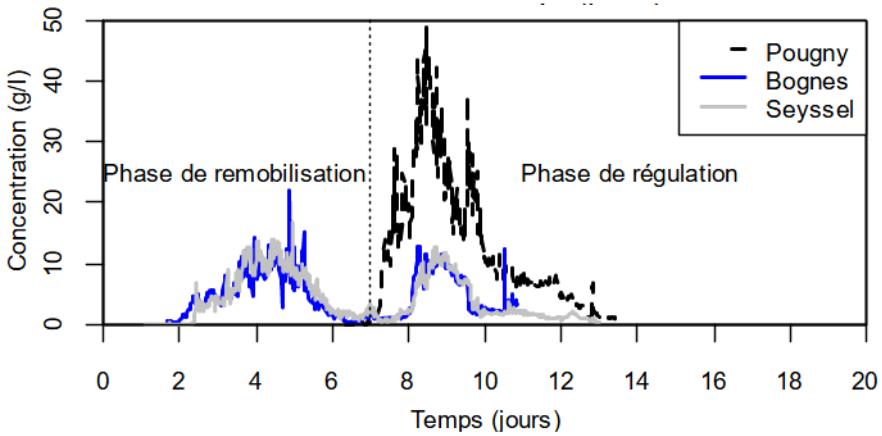
$$(1-p) \frac{\partial S_s}{\partial t} = (E - D) W$$

- a_{pd} =1 (settling flux not disturbed)
- C_0 function of the grain size from 1 (clay) to 0.2 (sand) (Guertault et al., JHE 2016)
- Bed shear stress estimated from a 1D model (evaluation in the main channel and in the active flood plain)

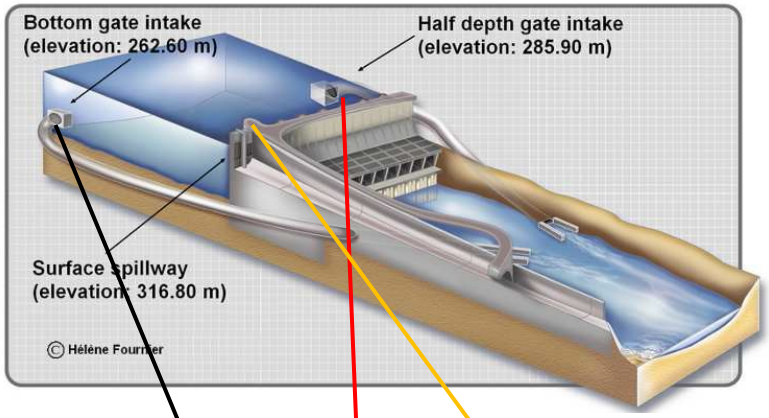
Flushing operation in the Haut-Rhône

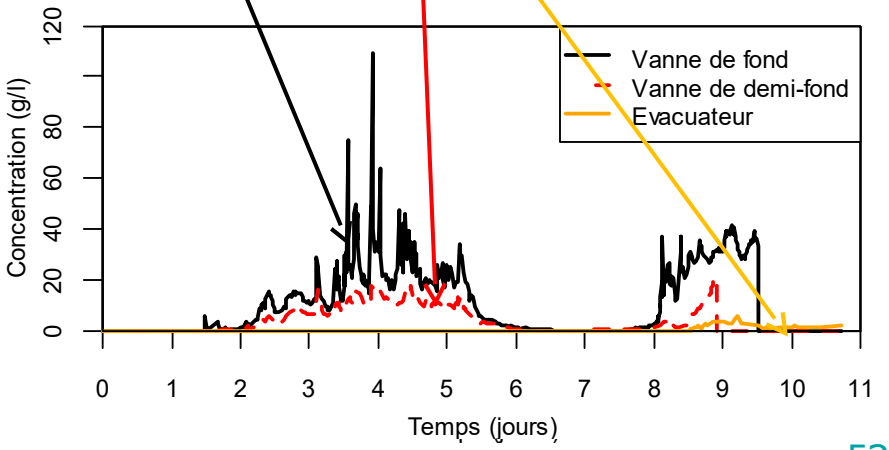
- Flushing of Verbois and Chancy-Pougny dams
- Companion operation for Génissiat and Seyssel dam





Dilution capacity of Génissiat dam

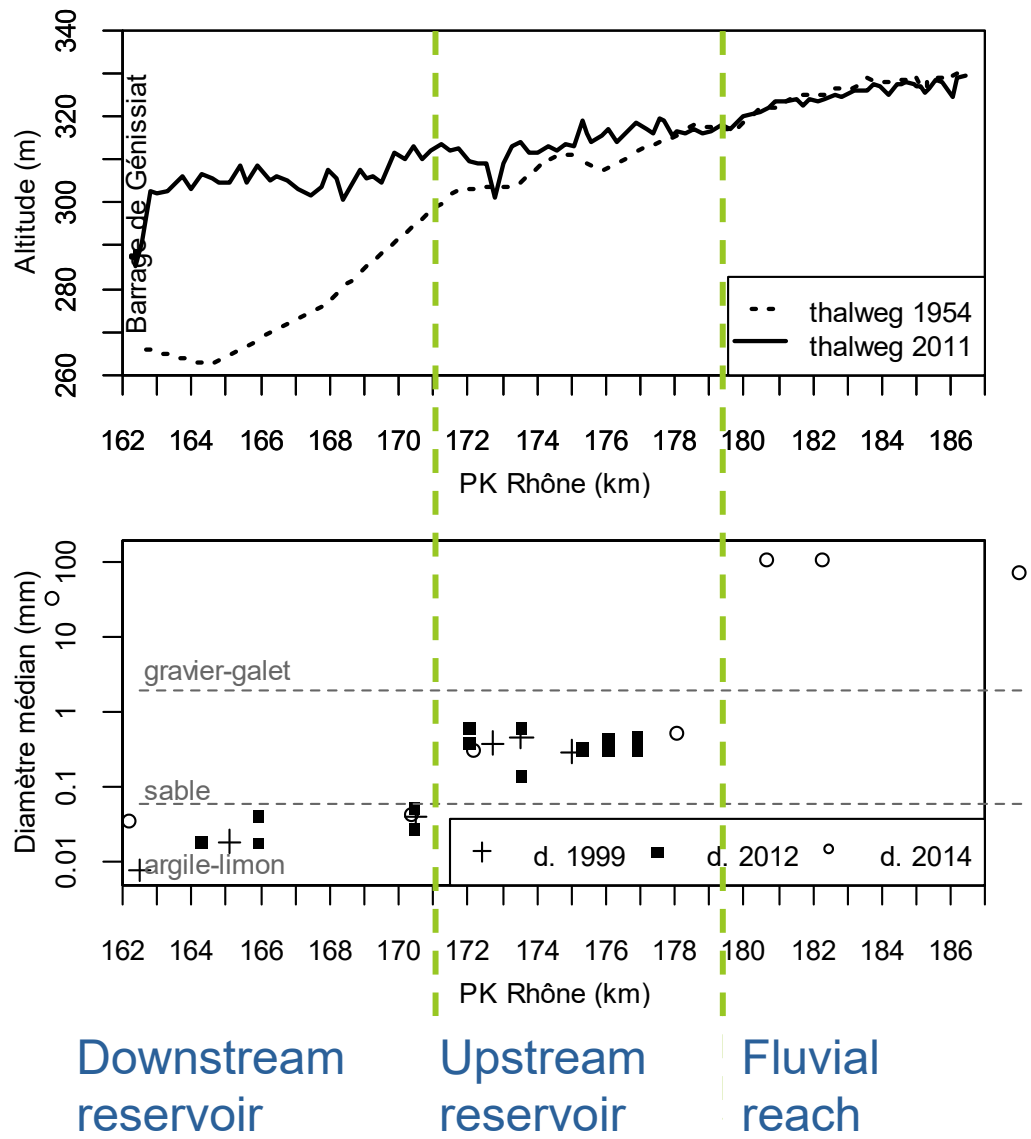




Flushing operation in the Haut-Rhône

- Génissiat dam reservoir:
  - 14 millions m³ deposits (25% volume)
  - Augmentation of deposit thickness downstream
  - Downstream fining of the grain size

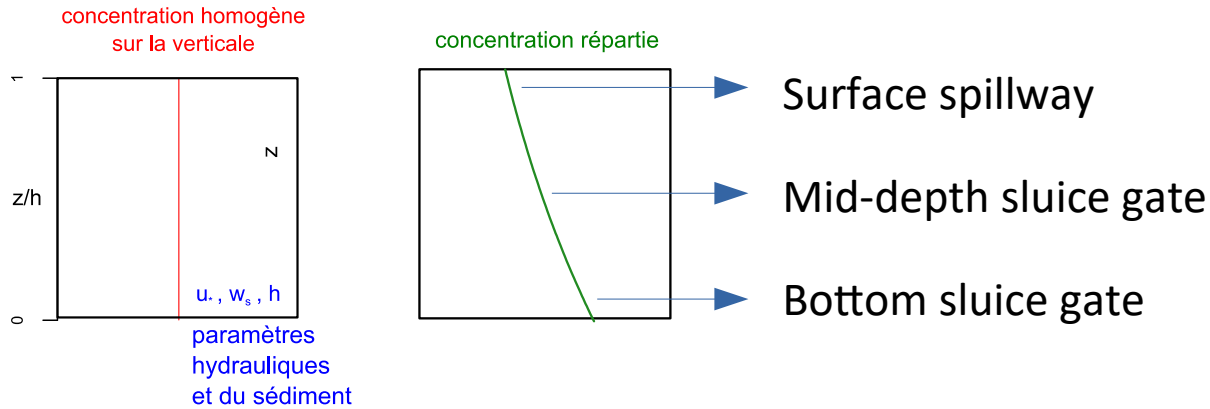
(Guertault et al., ESPL 2017)

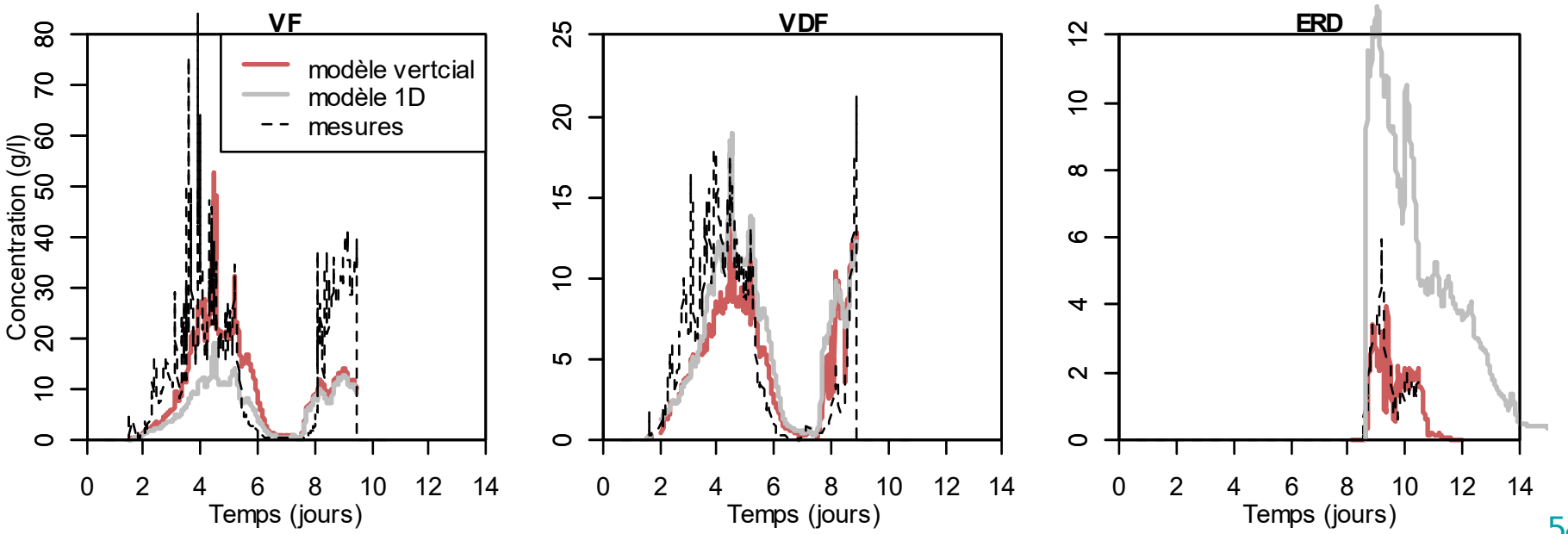


Downstream reservoir | Upstream reservoir | Fluvial reach

Application of AdisTS on Génissiat dam reservoir

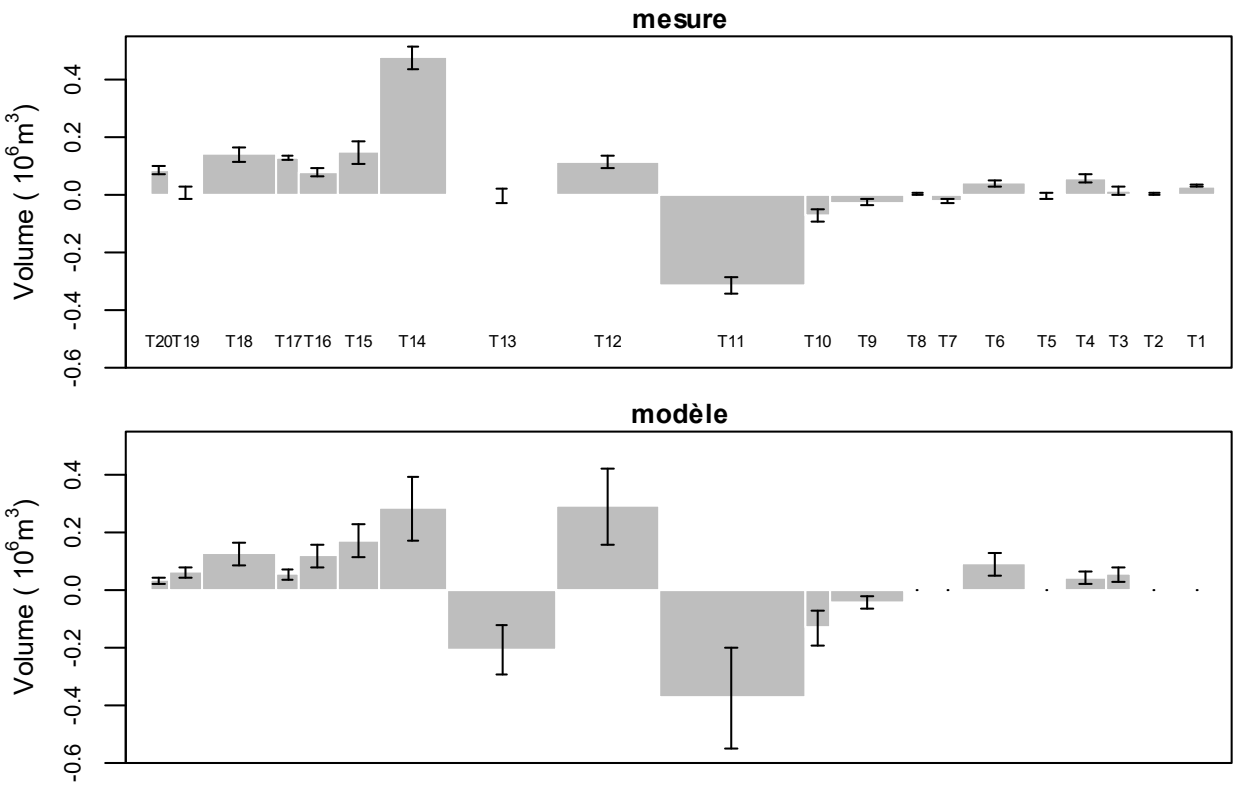
- Module for concentration repartition in different works





Application of AdisTS on Génissiat dam reservoir

- Estimation of morphological evolution in the dam reservoir e (1984 flush operation)



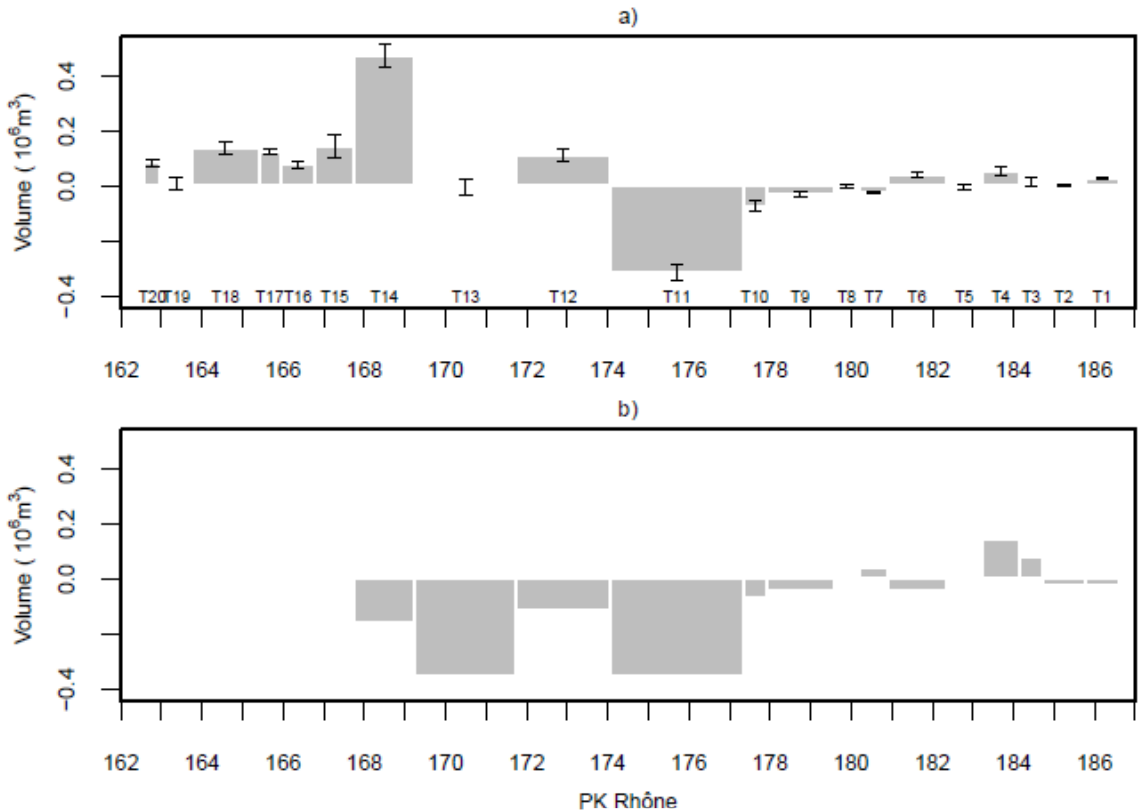
Deposits of fines downstream

Sand erosion

INRAE

Application of RubarBE on Génissiat dam reservoir

- Estimation of morphological evolution in the dam reservoir e (1984 flush operation) using sediment transport capacity



Fines not taken into account

Large sand erosion

Problems due to sediment mixture

- Modelling of coarse sediments (bedload) together with fine sediments (suspended load)

  → coupling of the Exner equation and advection-dispersion equation for each class of sediment *i*:

$$(1-p)\frac{\partial S_s}{\partial t}+\sum_i \frac{\partial Q_{si}}{\partial x}=\sum_i (E_i-D_i)W$$

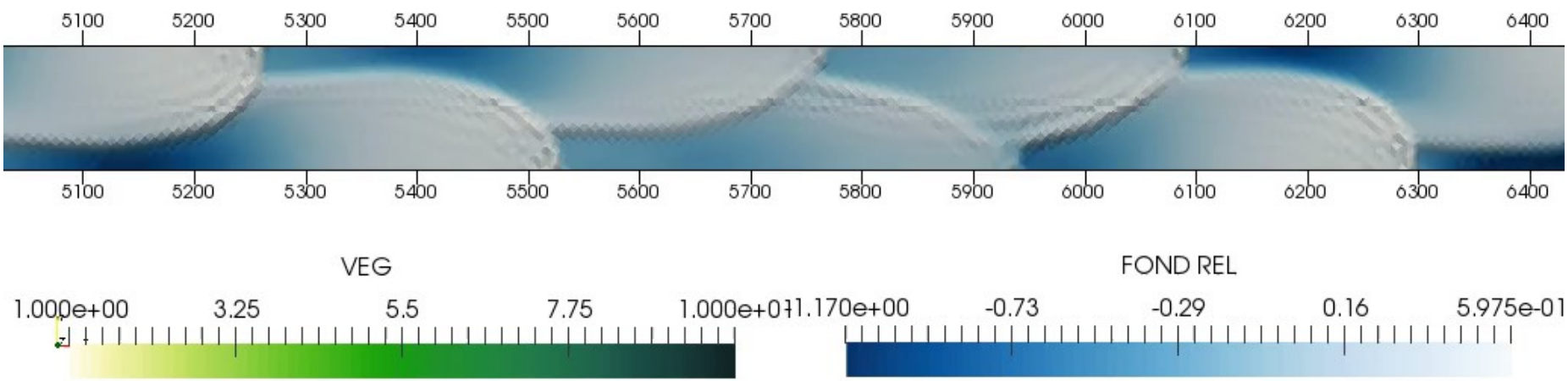
- Fine sediment impacts
  - Consolidation effects (soil mechanics)
  - Varying porosity of the bed (compaction, infiltration)
  - How to deal with sediment layers?

2D morphodynamic modelling

- Main issues
  - Slope effects on bedload transport
    - Correction of the magnitude
    - Correction of of the direction

    → creation of macro-bedform (alternate bars)

$$q_s^* = q_s \left(1 - \beta \frac{\partial z_b}{\partial s} \right)$$



Jiaze Li (PhD, 2019-2022)

2D morphodynamic modelling

- Main issues
  - Slope effects on bedload transport
  - Roughness
    - Bed roughness + drag roughness (vegetation)
    - Spatially distribution
    - Temporal distribution (bedforms, vegetation)

    → significant impact on the distribution of the flow and so on the morphodynamics

2D morphodynamic modelling

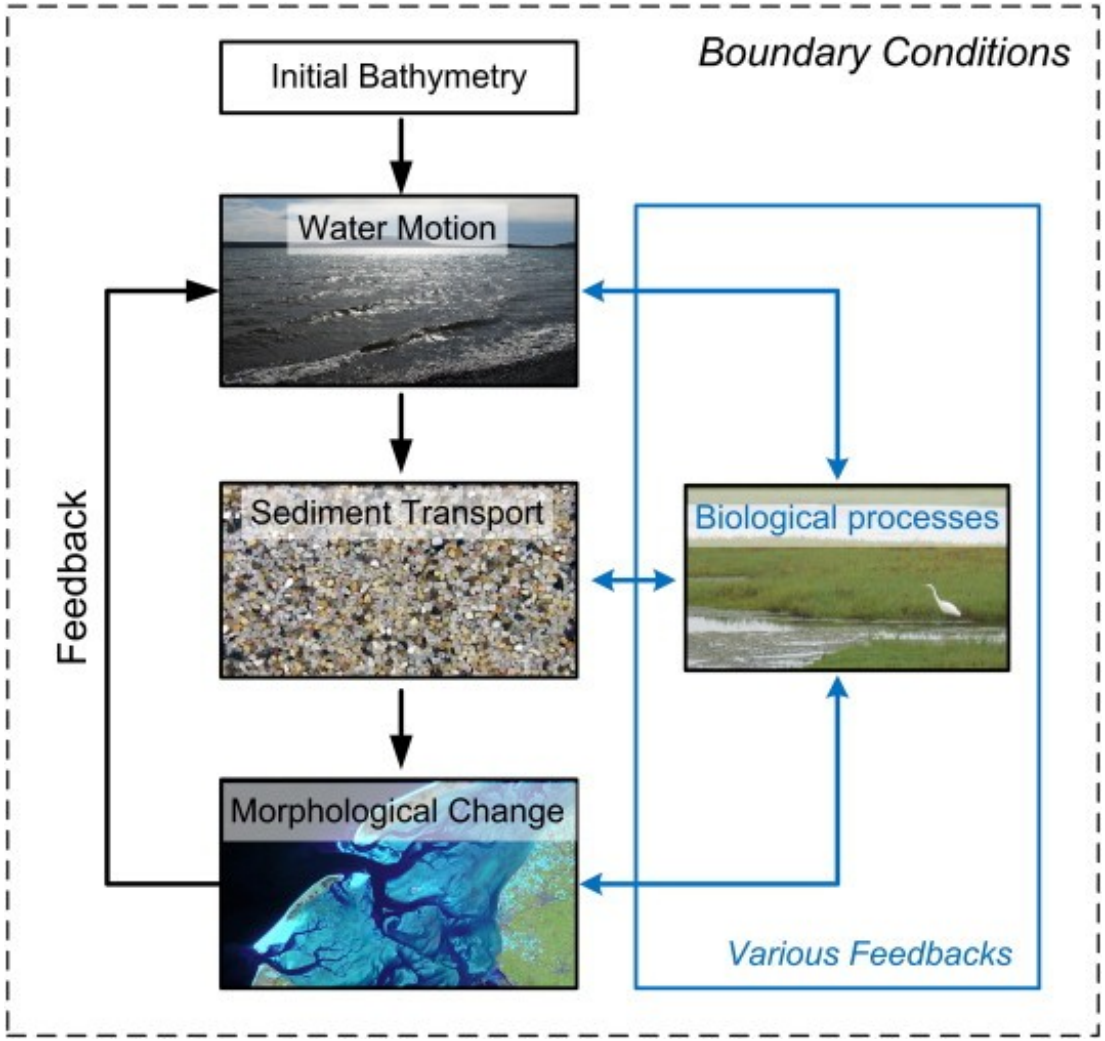
- Main issues
  - Slope effects on bedload transport
  - Roughness
  - Turbulence model
    - « classical » models generally used
      → K-epsilon model

2D morphodynamic modelling

- Main issues
  - Slope effects on bedload transport
  - Roughness
  - Turbulence model
  - Sediment transport formulation (multi-class)

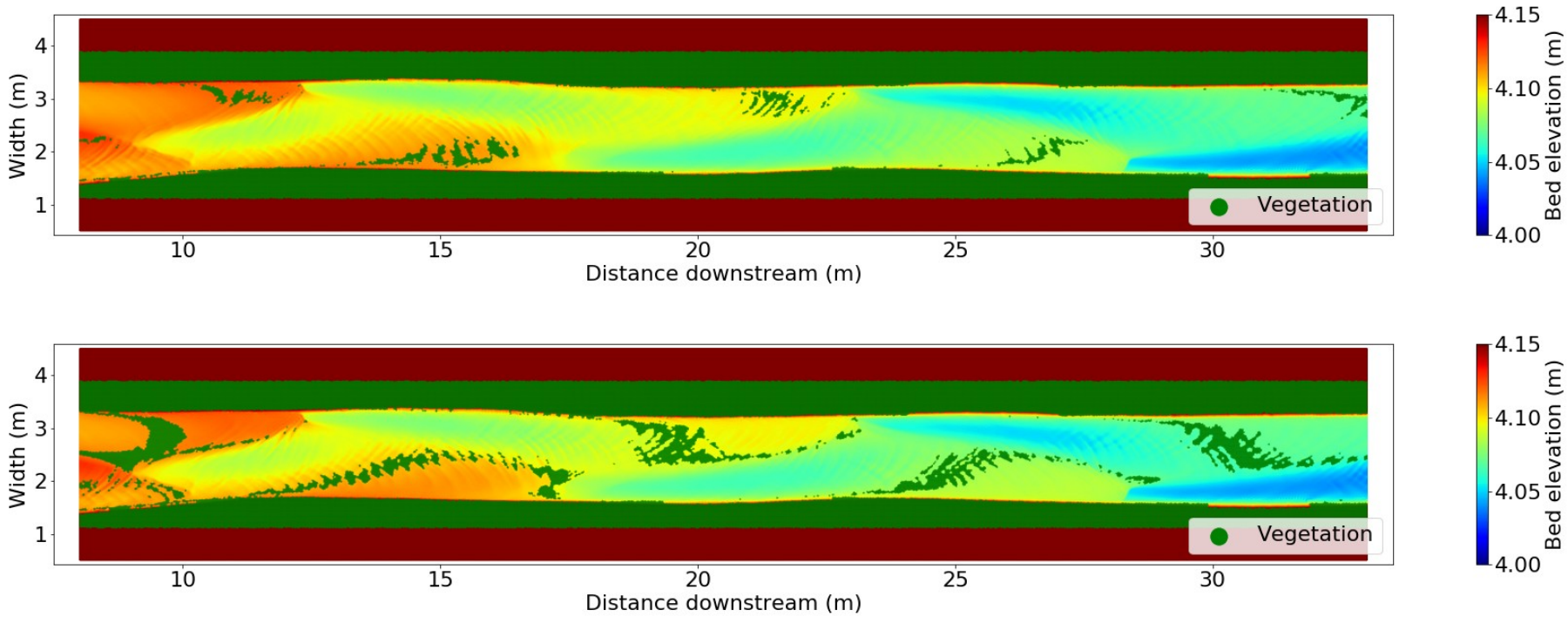
2D morphodynamic modelling, impact of vegetation

Jiaze Li (PhD, 2019-2022)



2D morphodynamic modelling, impact of vegetation

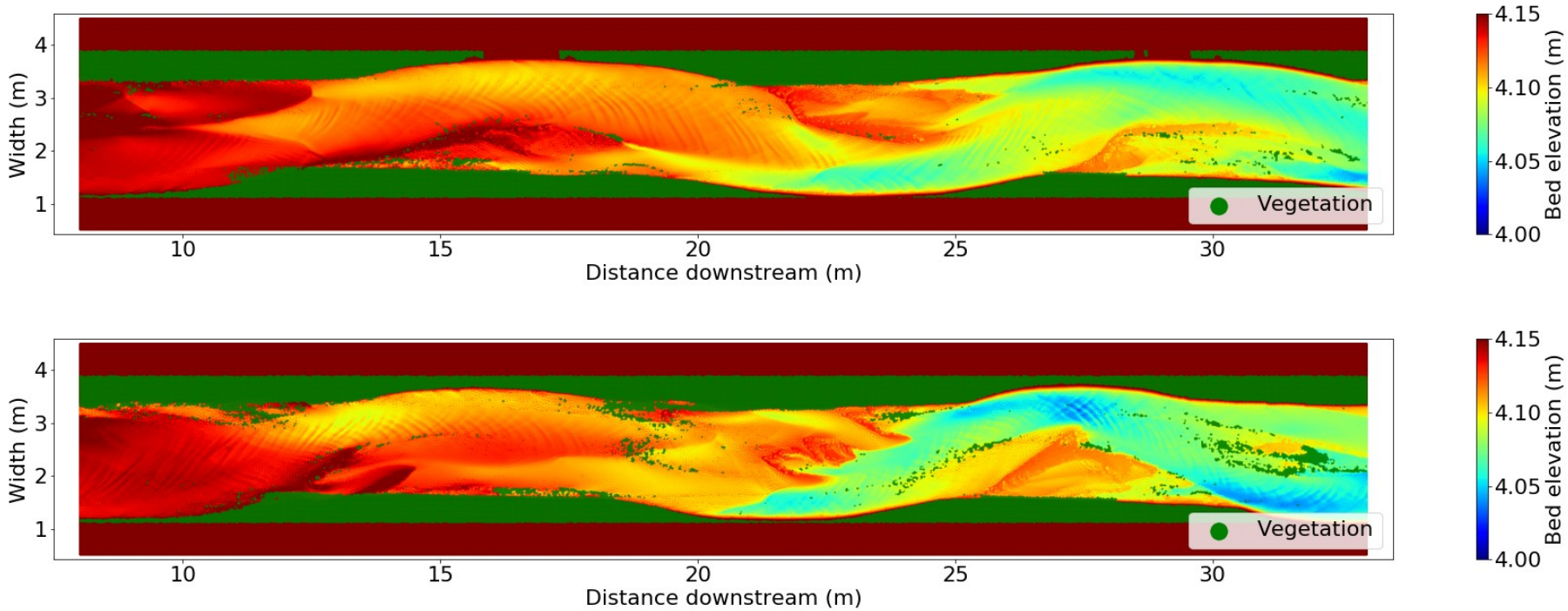
- Impact of the vegetation growth



Jiaze Li (PhD, 2019-2022)

2D morphodynamic modelling, impact of vegetation

- Impact of the vegetation growth



Jiaze Li (PhD, 2019-2022)

Conclusion and perspectives

- Classic approaches (1D, 2D) commonly used for engineering issues with robust results for both hydraulics and bed evolution
- Strong interest in computation efficiency to do long term modelling of large domains (prospective calculations with an estimation of uncertainties)
- How to manage large data set (input, output)?
- Needs in coupling different models (hydrology, hydraulics, geotechnics, ecology, etc.)
- For morphodynamical modelling, sediment mixture remains an issue (varying porosity, sediment layers, etc.) as well as vegetation

INRAE

- Thanks for your attention !