A modeling system handling the wide range of time scales involved in sediment transport

Presented by Dr **Benjamin J. Dewals**[1,2]
Co-authors: Dr Sébastien Erpicum[1], Dr Pierre Archambeau[1] & Prof. Michel Pirotton[1]

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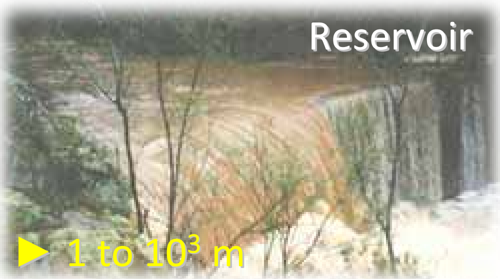
[2] Post-doctoral researcher of the Belgian Fund for Scientific Research F.R.S. – FNRS

DEMANDS FOR MODELLING IN FLUVIAL (AND COASTAL) MORPHODYNAMICS

- Different scales in space and time
- Different transport mechanisms
  (bed load, suspended load, mud; cohesive / non-cohesive…)



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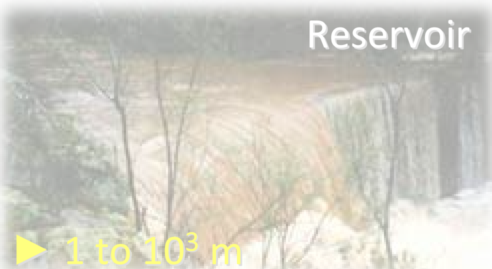

Sedimentation during months, years or decades

Flushing operations planned for a couple of days or week(s)

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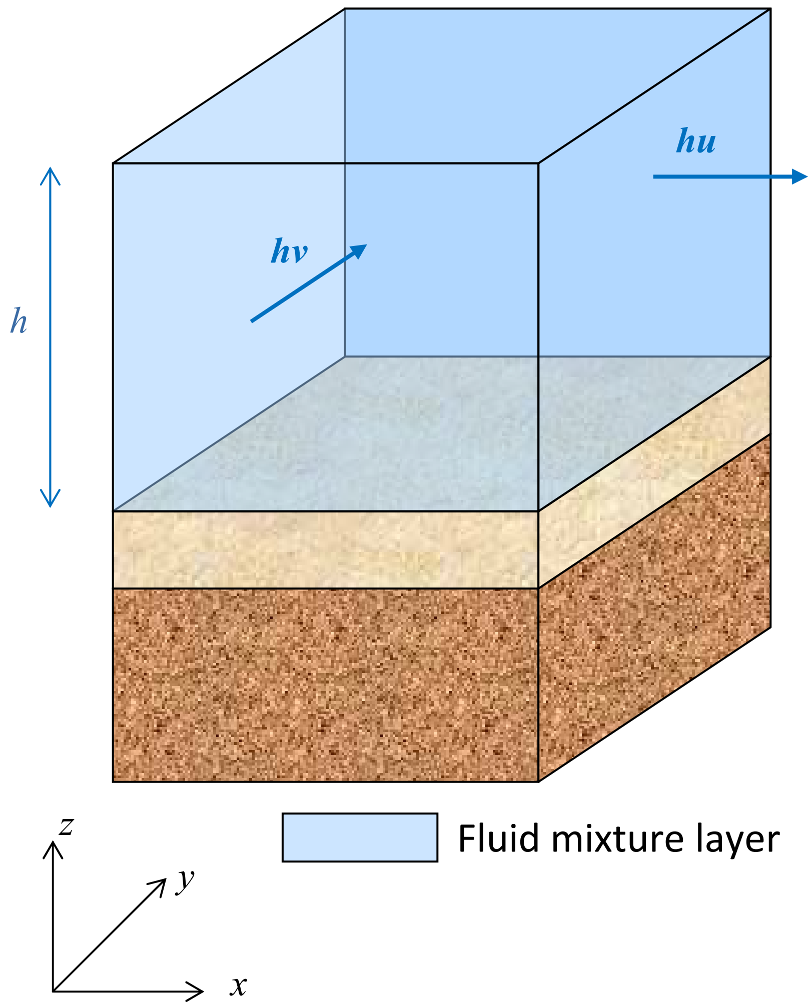
CONCEPTUAL MODEL: 2DH → **MATHEMATICAL MODEL**



- 2DH model: still appealing for a number of engineering applications (*cf* scarcity of 3D input and validation data, and sensitivity with respect to IC and BC)

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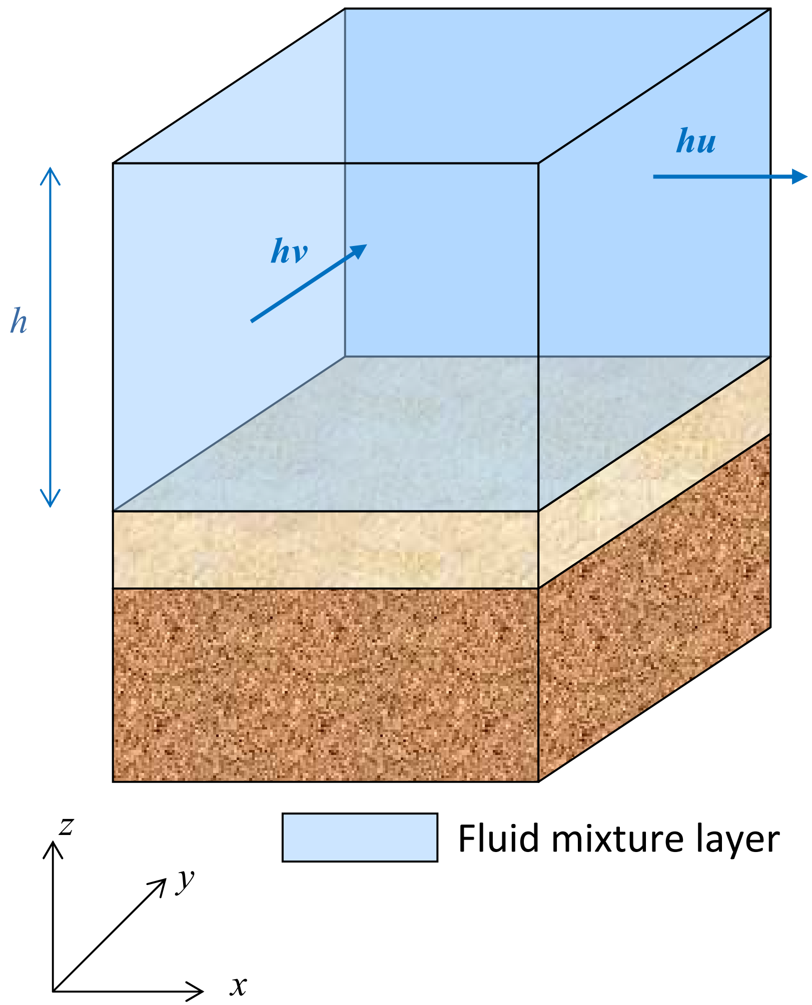

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- Includes wall-friction & turbulence modelling (two-length-scale depth-averaged k-ε model)

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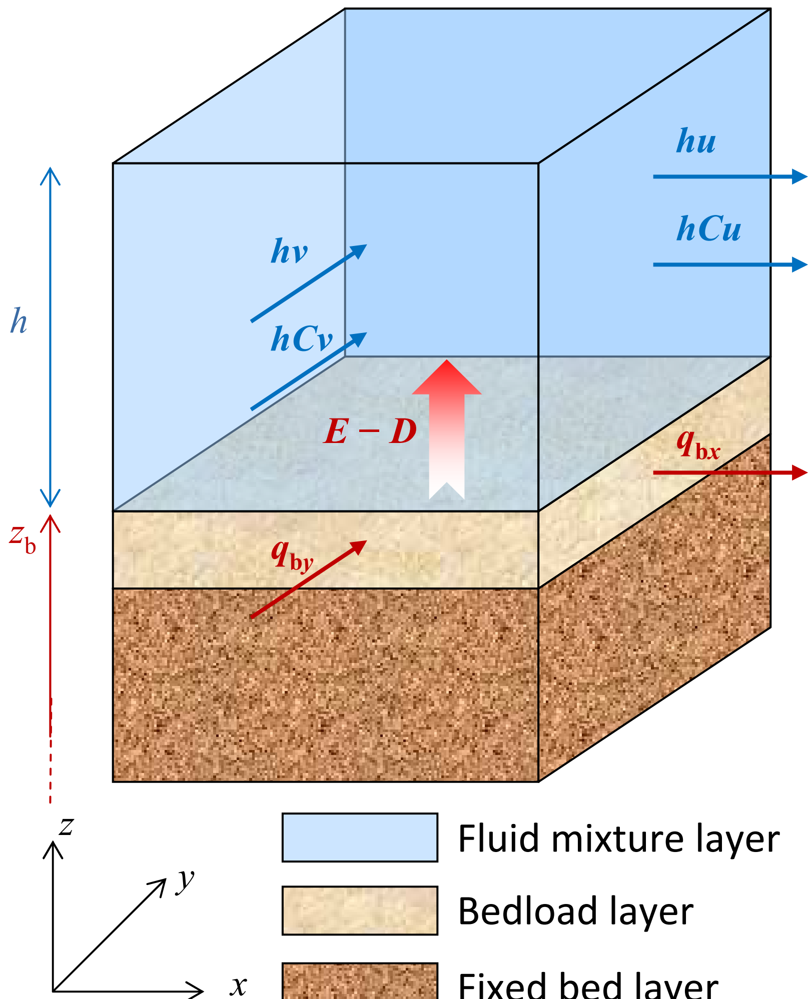

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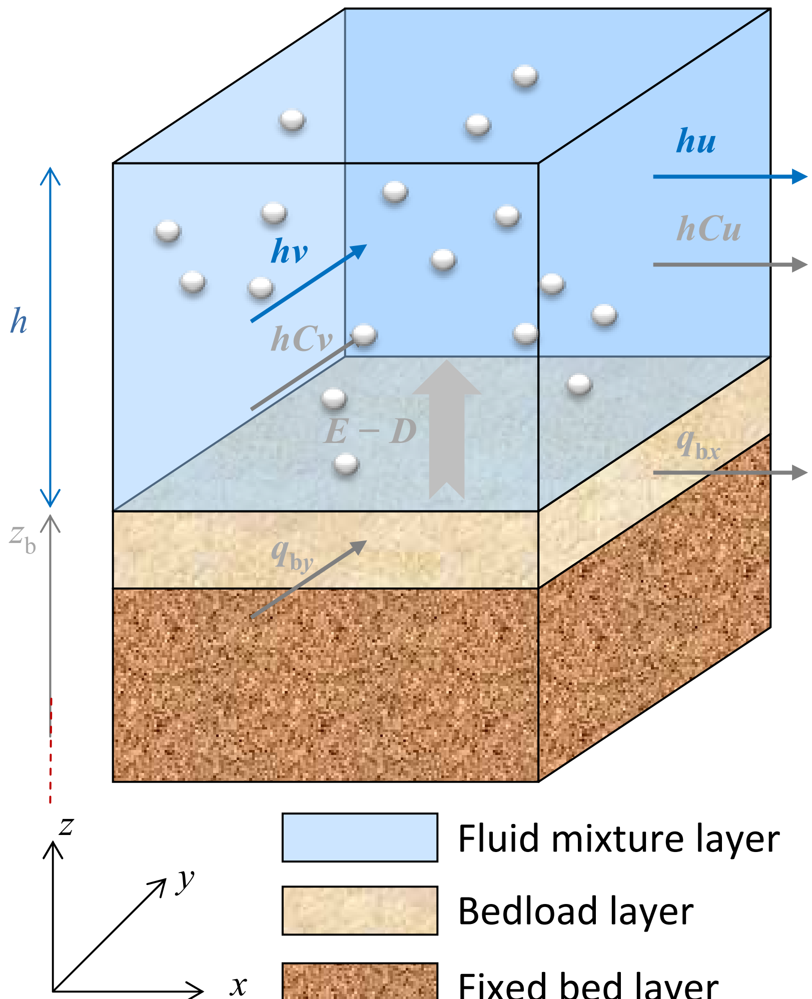
Eulerian
mass balance for suspended load

- Mass balance for bedload or total load (solid discharge = local instant. transport capacity)

e.g. MPM, Ackers & White, Rickenmann, …

CONCEPTUAL MODEL: 2DH

MATHEMATICAL MODEL



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Eulerian mass balance for suspended load

Lagrangian force balance for suspended sediments

- Mass balance for bedload or total load (modelled as equilibrium sediment transport)

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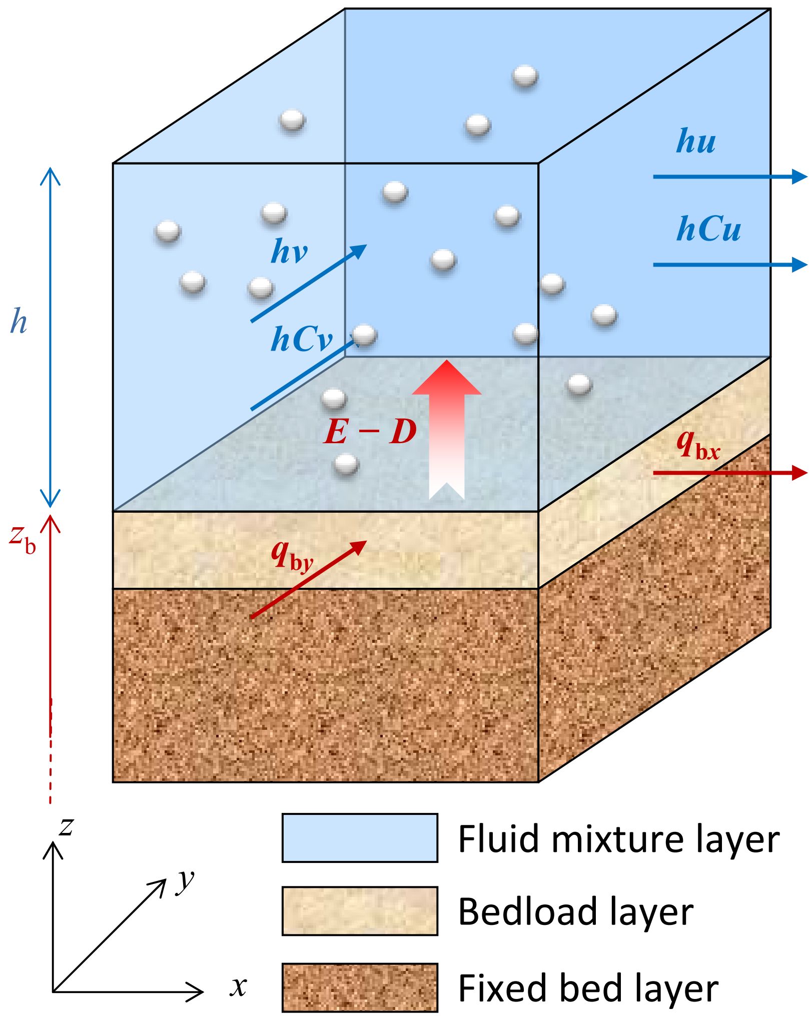

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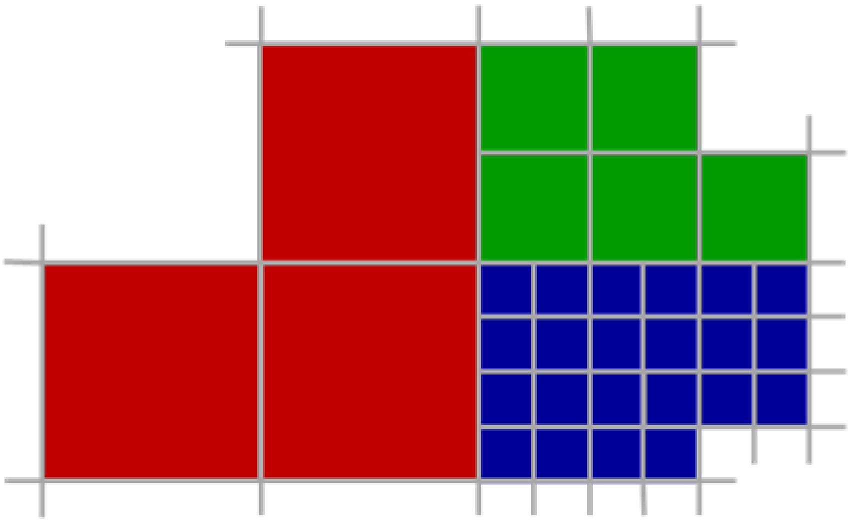
- Finite volume technique
- Modelling system *WOLF*
- Existing academic code
- Entirely developed in the research group

CHARACTERISTICS OF THE DEPTH-AVERAGED FLOW MODEL

- ▶ Multiblock grids

  + 1D branches



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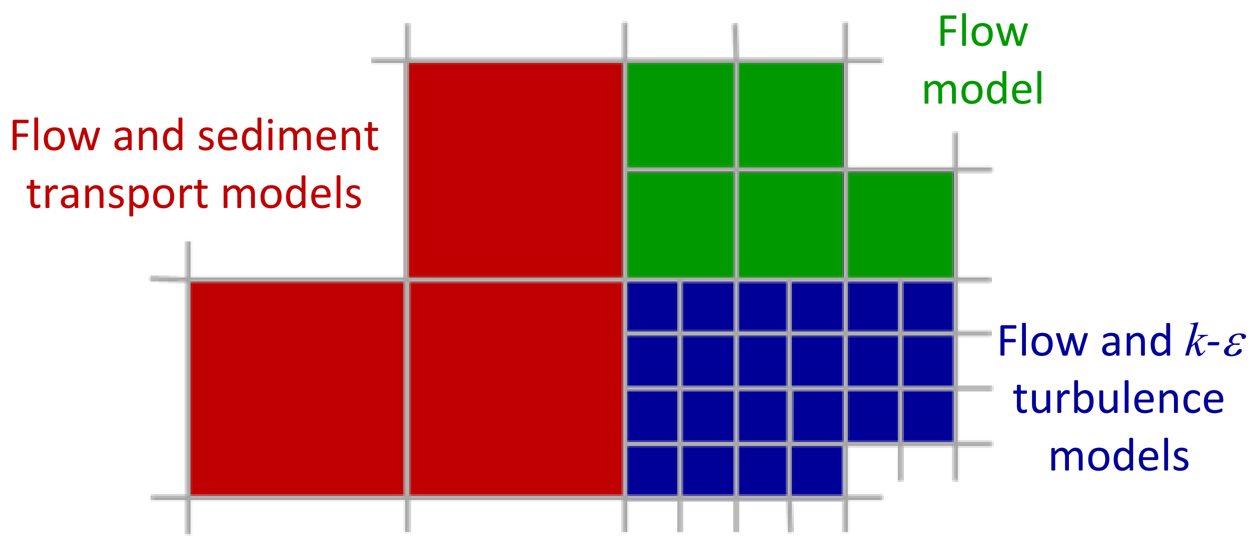

CHARACTERISTICS OF THE DEPTH-AVERAGED FLOW MODEL

- ▶ Multiblock grids

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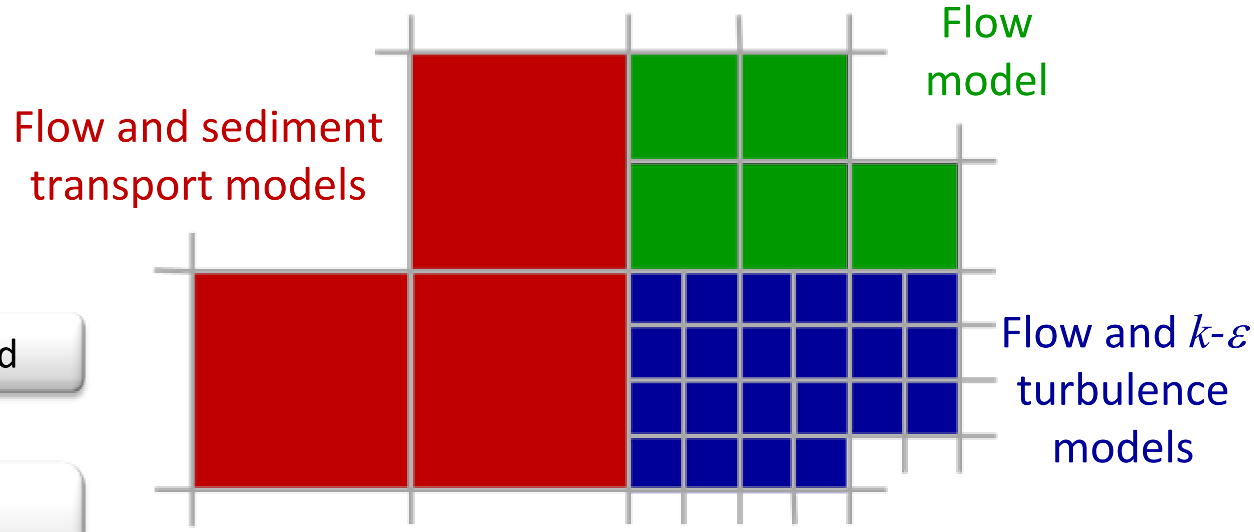
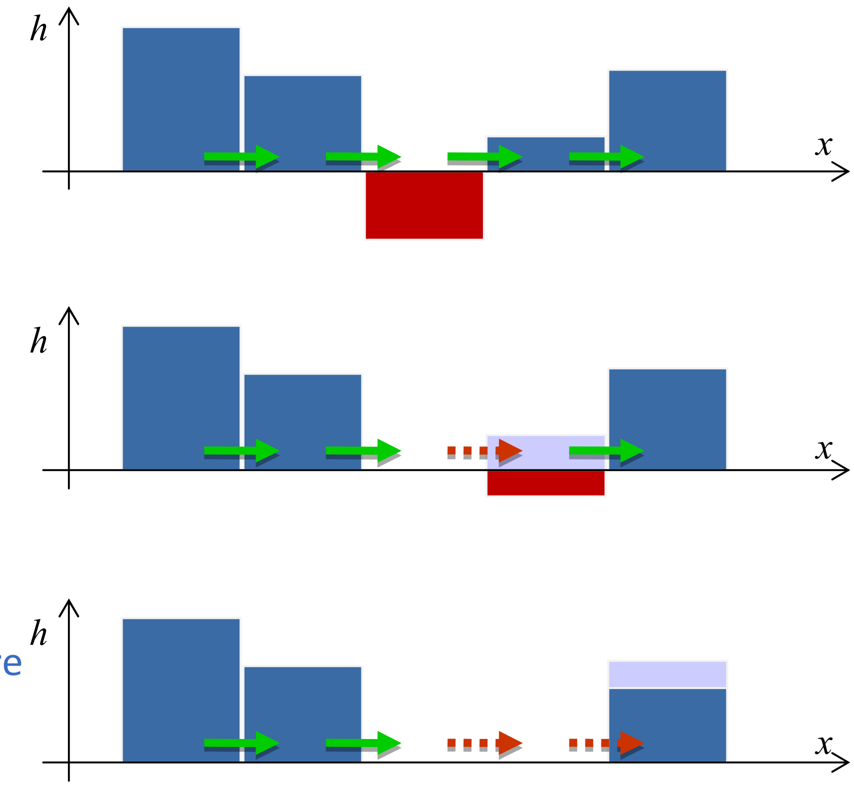
- ▶ Multimodel system
- ▶ Adaptive computation grid
- ▶ Drying of cells free of mass conservation error



CHARACTERISTICS OF THE DEPTH-AVERAGED FLOW MODEL

Example on a flat topography:



- ▶ Multiblock grids

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- ▶ Multimodel system

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- ▶ Drying of cells free of mass conservation error

Iterate until *h* >= 0 everywhere

Solve the continuity equation

In cells where h < 0, limit outward fluxes

Solve the momentum equations

← ITERATIVE PROCESS AT EACH TIME STEP

EFFICIENT BECAUSE RESTRICTED TO “DRYING CELLS”

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EFFICIENT BECAUSE RESTRICTED TO "DRYING CELLS"

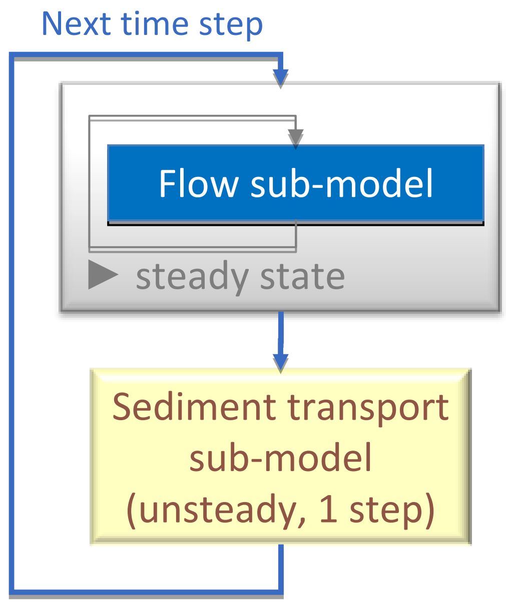
Extensively validated flow model

- Erpicum, Dewals *et al.* (2009), *Engineering Applications of Computational Fluid Dynamics*
- Roger, Dewals *et al*. (2009), *J. Hydraul. Res.*
- Dewals , Kantoush *et al.* (2008), *Env. Fluid. Mech.*
- Erpicum, Meile *et al.* (2008), *Int. J. Numer. Methods Fluids*
- Dewals , Erpicum *et al.* (2006), *J. Hydraul. Res.*
- Erpicum, Dewals *et al.* (in press)*, J. Comput. Appl. Math.*
- Kerger, Archambeau *et al*. (accepted), *Int. J. Numer. Methods Fluids*
- …

EULERIAN MODEL: MULTI-SCALE IN TIME

▶ THREE LEVELS OF COUPLING BETWEEN SUB-MODELS

Model A	Model B	Model C
« coupled »	*« semi-coupled »*	*Iterative process*



- Cost-effective
- Opportunities for coupling (e.g. MPI Interface)

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Model A

Next time step

Flow sub-model
(unsteady, 1 step)

Sediment transport
sub-model
(unsteady, 1 step)

- ▶ Demanding in compu-tational resources
- ▶ Needs a specific stable numerical scheme

Model B

Next time step

Flow sub-model

▶ steady state

Sediment transport
sub-model
(unsteady, 1 step)

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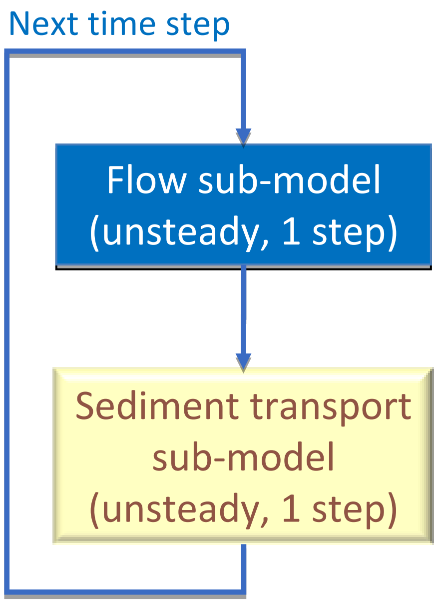

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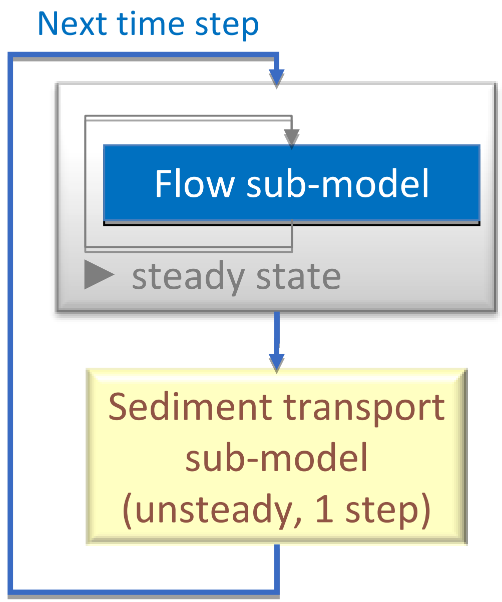
Model B

« semi-coupled »

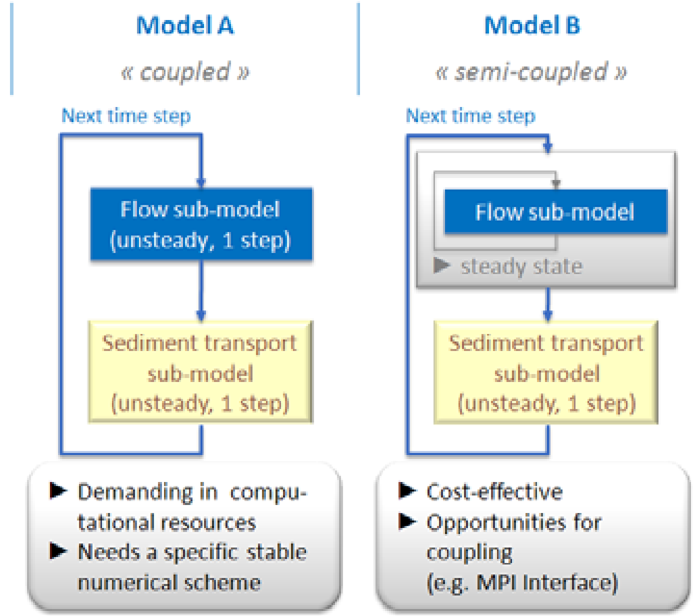


- Cost-effective
- Opportunities for coupling (e.g. MPI Interface)

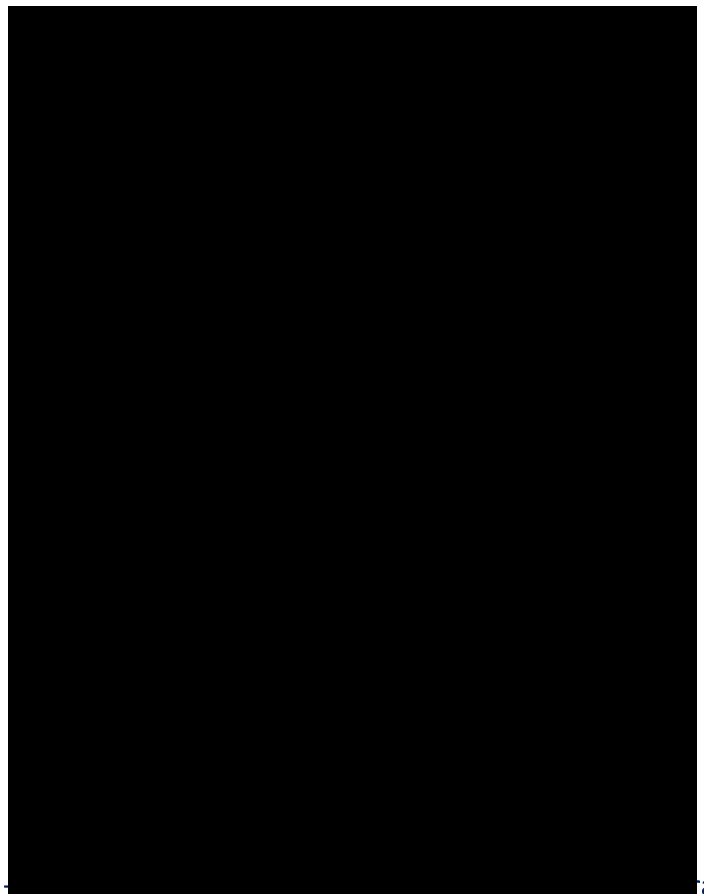
- Accounts for rigid bottoms, free of mass conservation error (iterative process)
- Accounts for slope failures (simple geometrical approach), free of mass conservation error

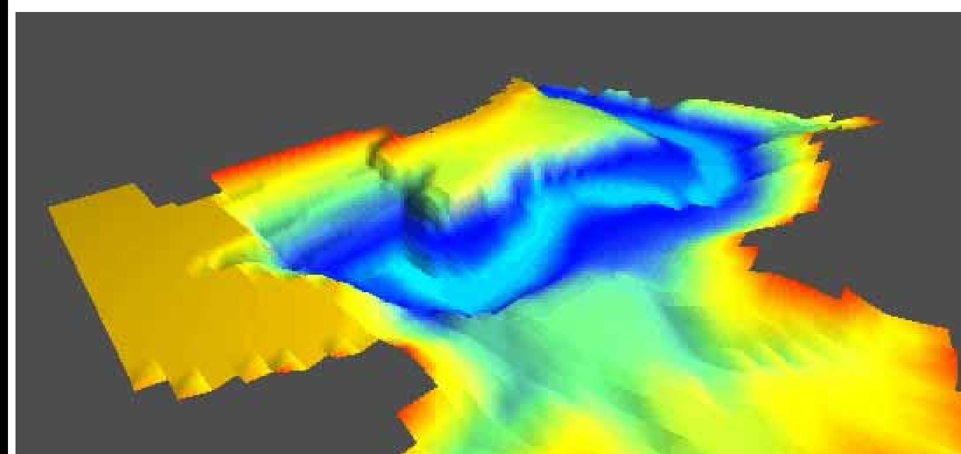
EULERIAN MODEL: MULTI-SCALE IN TIME

▶ **COMPLEMENTARITY OF THE COUPLED AND SEMI-COUPLED MODELS: RESERVOIR SEDIMENTATION AND SEDIMENT FLUSHING**



Flushing operations (**model A**, ***1 week***)





Reservoir sedimentation
(**model B**, ***20 years***)

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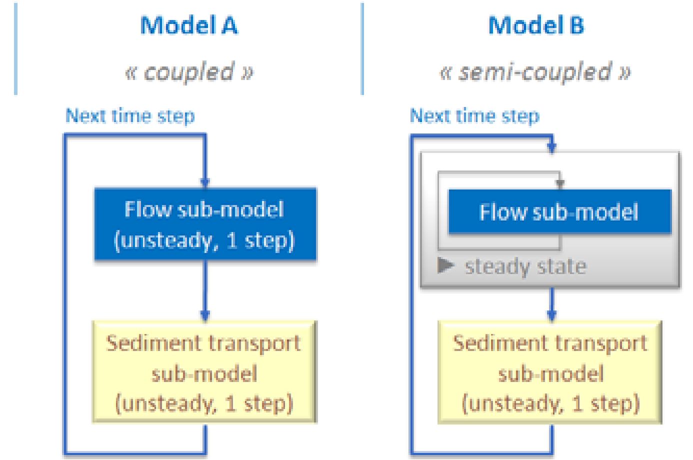

- Demanding in computational resources
- Needs a specific stable numerical scheme

- Cost-effective
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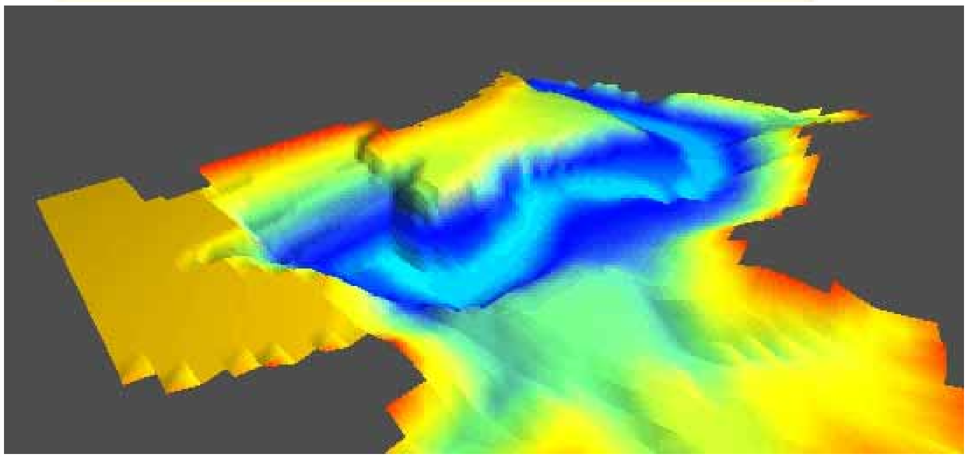
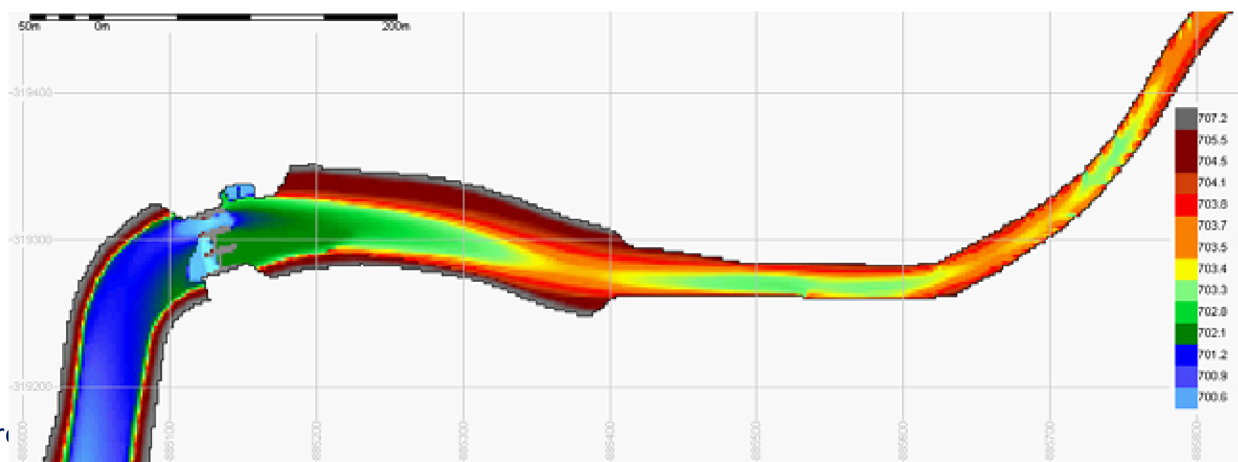


Reservoir sedimentation (**model B**, ***20 years***)

Flushing operations (**model A**, ***1 week***)



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Sediment transport sub-model (unsteady, 1 step)

- Demanding in computational resources
- Needs a specific stable numerical scheme

Model B

Next time step

Flow sub-model

▶ steady state

Sediment transport sub-model (unsteady, 1 step)

- Cost-effective
- Opportunities for coupling (e.g. MPI Interface)

Model C

Next iteration

Flow sub-model

▶ steady state

Sediment transport sub-model (steady approach)

- Extremely cost-effective
- No time evolution of bottom elevation

STEADY FLOW AND EQUILIBRIUM BED PROFILE

▶ MATHEMATICAL BACKGROUND

Based on an obvious analogy between:

- steady flow continuity equation
- steady continuity equation

$$\frac{\partial}{\partial x}(hu)+\frac{\partial}{\partial y}(hv)=0 \qquad \frac{\partial q_{\mathrm{bx}}}{\partial x}+\frac{\partial q_{\mathrm{by}}}{\partial y}=0$$

- Solid unit discharges proportional to flow unit discharges

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- Solid unit discharges proportional to flow unit discharges
- Use of a transport capacity law

$$\alpha\, q = q_{\mathrm{b}} = f(s, d, g, n, q, z_{\mathrm{s}} - z_{\mathrm{b}})$$

- Correct the bottom elevation and update the flow field

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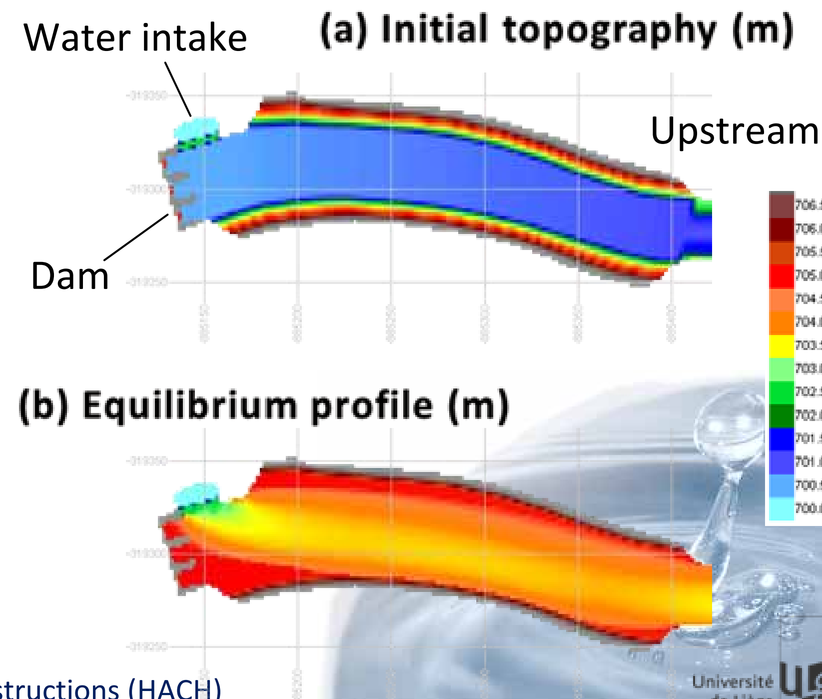
▶ STABILITY ANALYSIS

$$\mathrm{Fr} < \frac{\sqrt{2}}{2} \approx 0.7$$

Dewals, Erpicum *et al.* (2008), *Houille Blanche – Rev. int.*
Dewals, Erpicum *et al.* (2009); *SHF workshop*



LAGRANGIAN MODEL FOR NON-EQUILIBRIUM SEDIMENT TRANSPORT

▶ PRINCIPLE AND MATHEMATICAL BACKGROUND (INCL. STOCHASTIC COMPONENT)

- Conceptual model: momentum equation for particles

$$\frac{du_p}{dt} = F_D(u - u_p) + g_x\left(\frac{\rho_p - \rho}{\rho_p}\right) + F_x$$

Drag | Gravity and Buoyancy | Lift, …

- Simplified approach:

$$\mathbf{v}_s = \left(u + \varsigma_x \tilde{u}\right)\mathbf{e}_x + \left(v + \varsigma_y \tilde{u}\right)\mathbf{e}_y + \left(-w_s + \varsigma_z \tilde{u}\right)\mathbf{e}_z$$

$\mathbf{v}_s$ = particle velocity
$\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ = unit vectors along *x*, *y* and *z* ;
ζ_x, ζ_y, ζ_z, = random variables between 0 and 1
$\tilde{u}$ and $\tilde{w}$ = characteristic fluctuating velocity along horizontal and vertical
(deduced from de k if a k-ε model is used, otherwise from the shear velocity $u_* = (\tau_b/\rho)^{0.5}$

▶ Output: location of deposits
▶ No feedback on flow field

LAGRANGIAN MODEL FOR NON-EQUILIBRIUM SEDIMENT TRANSPORT

▶ APPLICATION SETTLING BASINS

Inlet into a storm tank

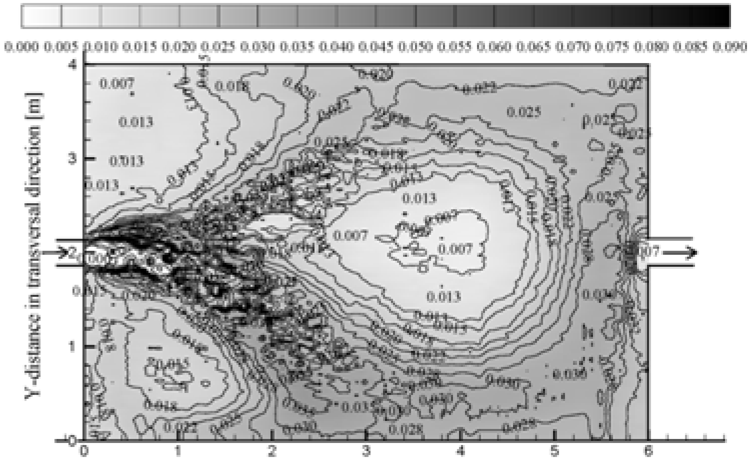
Storm tank of Rosheim (Alsace, France)

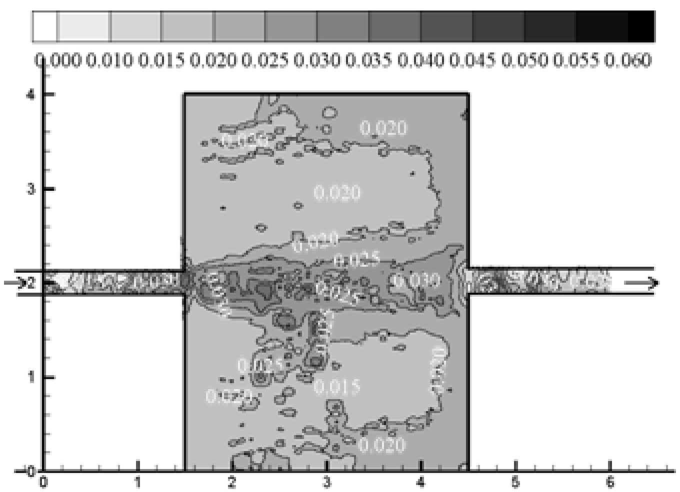
▶ Common structures but … complex flow and deposits patterns

- Sedimentation must be either **maximized** (settling basins) or **minimized** (storage facilities)
- Existing empirical knowledge for deposits ***quantities*** (trapping efficiency ...)
- Predicting deposits ***location*** needed for optimal reservoir operation and maintenance

Available data for validation of sediment deposition

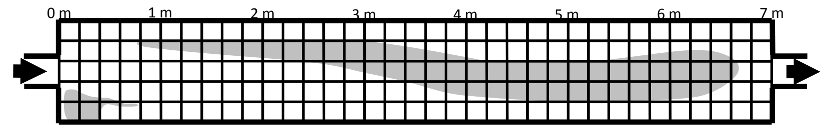
Kantoush (2008), PhD thesis, EPFL



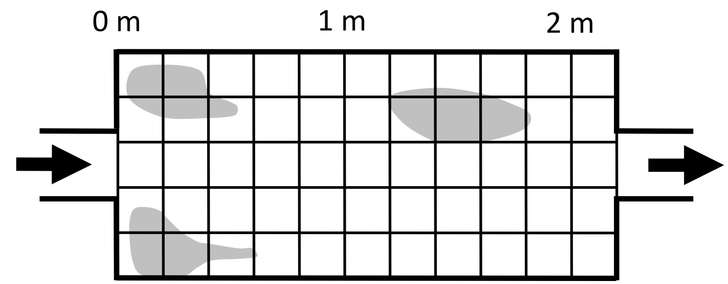


Material = walnut shell
ρ_s = 1.5 d_{50} = 50 µm w_s = 1 mm/s
C_{in} = 3.0 g/l Mostly suspended load

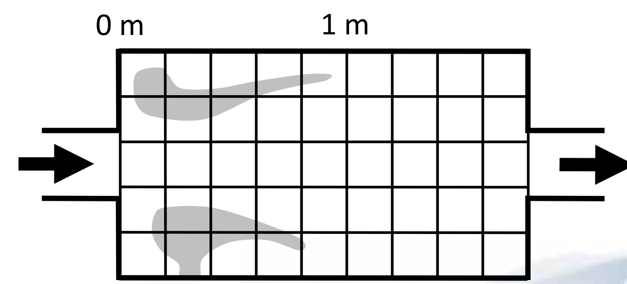
Dufresne, Dewals et al. (submitted), J. Hydraul. Eng.-ASCE



Experiment ST1-a



Experiment ST2-b

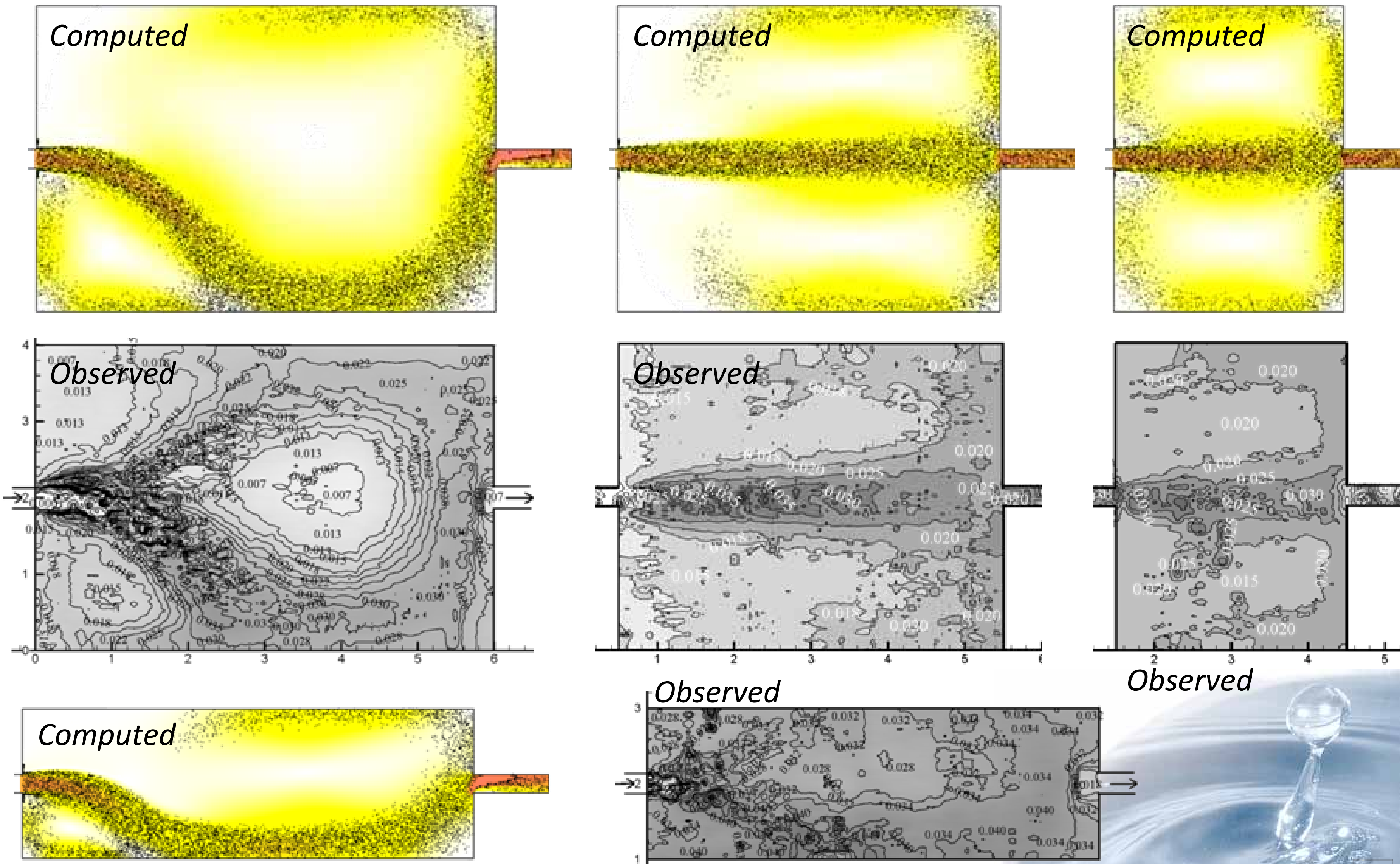


Experiment ST3-a

Material = Granular plastic (Styrolux 656 C)
ρ_s = 1.020 d_{50} = 2.5 mm w_s = 25 mm/s
C_{in} = 0.5 g/l Mainly bedload

Numerical modelling of sediment deposition

→ Dewals *et al.* (2008), Env. Fluid Mech.



Dewals, Erpicum *et al.* (2009), *SHF workshop*

CONCLUSIONS

- ► Constraint for modelling: multiscale in space and time, accounting for different transport mechanisms
- ► 2D depth-averaged modelling, still an appealing compromise

- ► Work in progress:
  - implementation of sediment transport model within 2DV/3D flow models (developed by our research group)
  - non-Newtonian constitutive laws for the fluid-sediment mixture in case of high concentration in solid particles