Sediment Transport , Numerical Modeling and Reservoir Management

some Concepts and Applications

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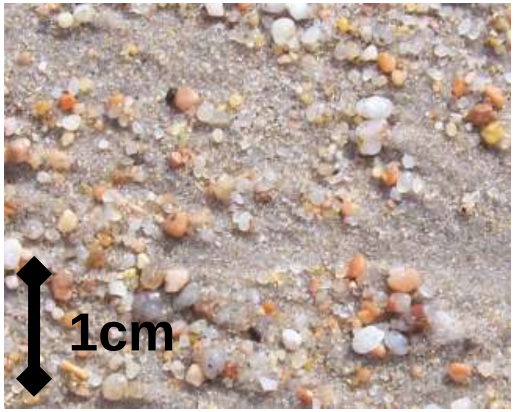
Overview of the presentation

- What is Sediment Transport ?
- Sediment Transport Modeling
- How to Deal with Sediments in Reservoirs ?
- Example : Modeling Reservoir Emptying
- Examples of Current Research : 2011 & 2013 Cemracs Projects

What kind of sediments do we find in rivers ?

- **Granular Material**
  - gravel, sand
  - non cohesive material
  - grain size > 40µm



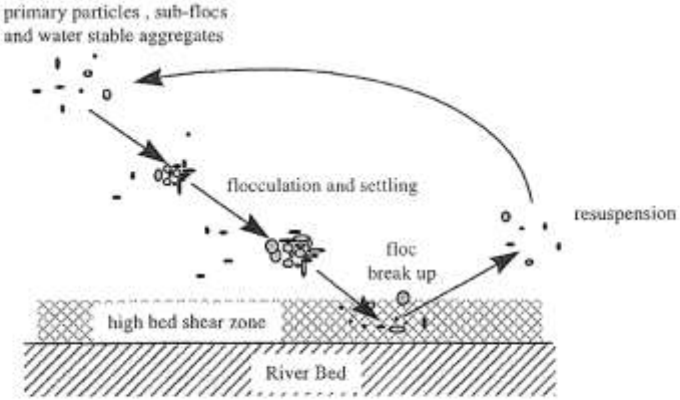
- **Cohesive Material**
  - Silt , clay
  - Grain size < 40µm
  - Strong Interactions between particles

→Cohesion and floculation

- Mixing of gravels and silt :

Cohesive / non cohesive ➔ different physical properties

- Flocculation : cohesive sediments may form aggregates



- Consolidation of cohesive sediments
- Bank stability : different kind of stabilities

Cohesive

Non cohesive

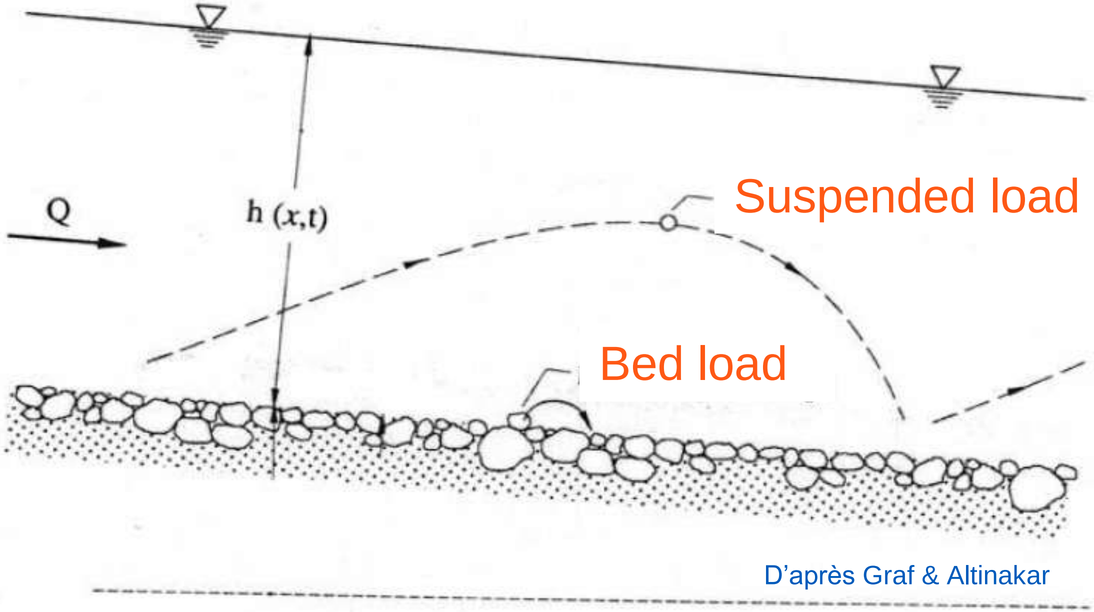
Transport of Sediments in Rivers

Sand and gravel

➔**Bed load Transport**

saltating and rolling

near the bed of sediments



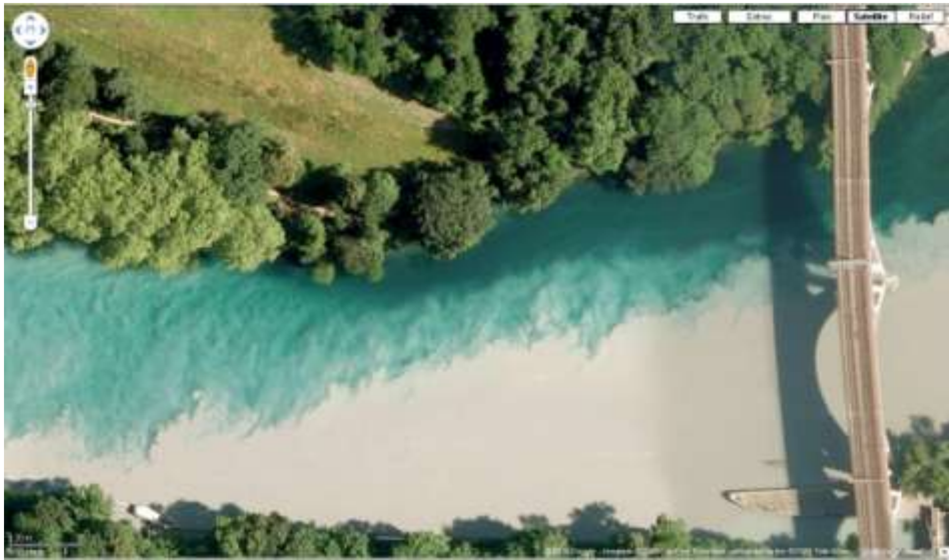
D’après Graf & Altinakar

Fine sediments

➔**Suspended transport**

mixing of sediments in the water

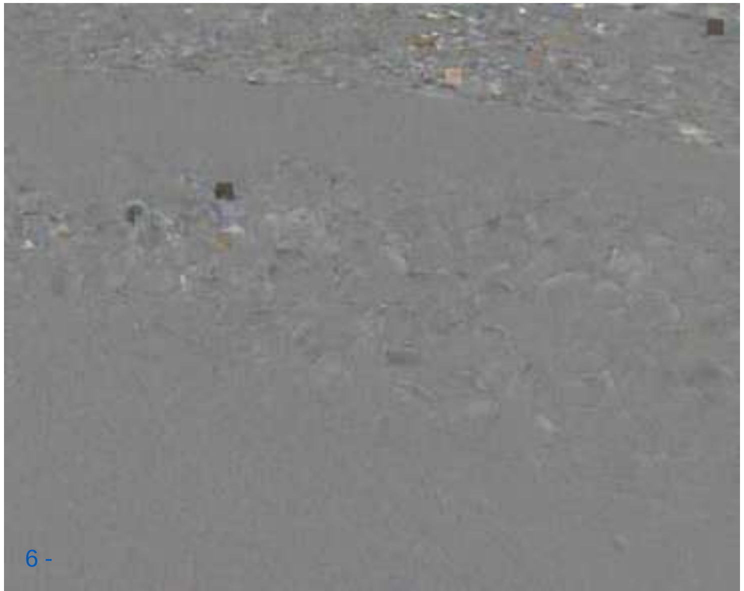
Advection dispersion equation



Transport of Sediments in Rivers

Sand and gravel

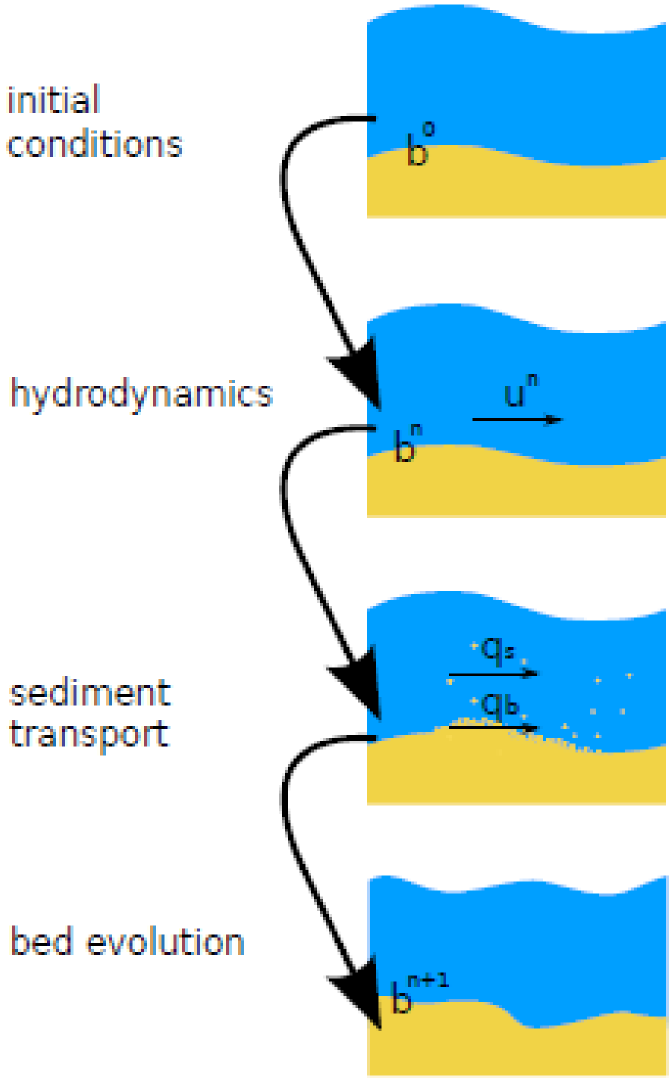
➔Bed load Transport



Fine sediments

➔Suspended transport

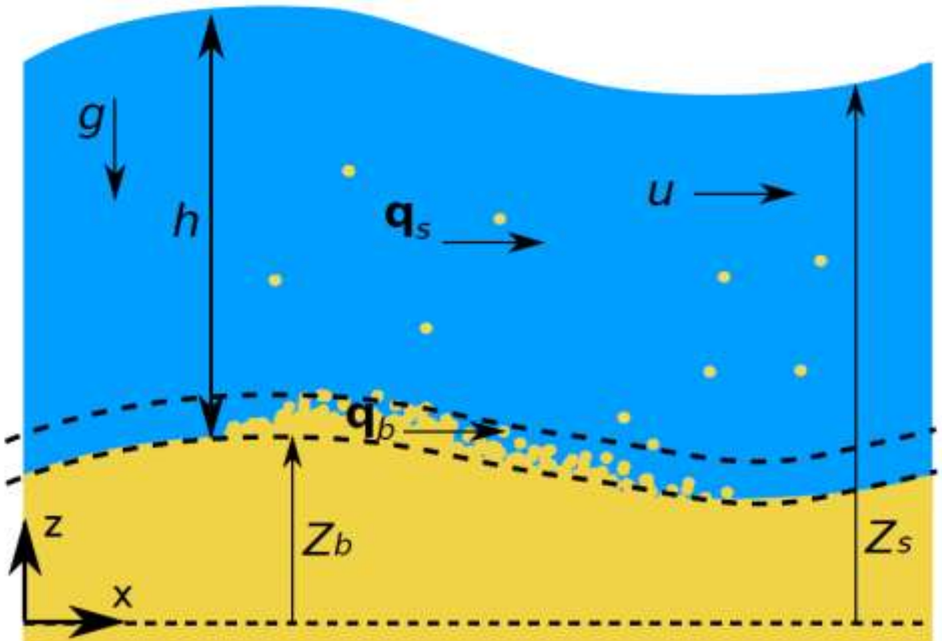
Sediment Transport Modeling : Processes



➔Need of

1. a set of equations for Hydrodynamics
2. a set of equations for Sediment Transport and Bed Evolution

1 & 2 could be splitted



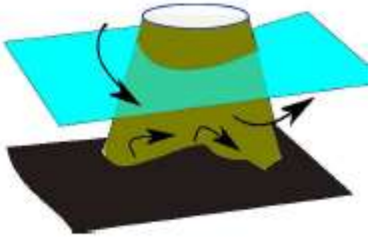
Sediment transport modeling : 3D/2D/1D

- Users have to choose the numerical code depending on the goal of the simulation

- 3D, 2D and 1D simulations are possible

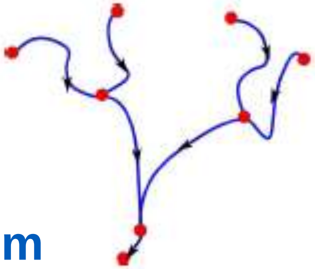
- **Empirical formulae** are used for bed interaction and sediment fluxes

- `Sedi3D:` 3D sediment transport module



- `Sisyphe:` 2D sediment transport module

- `Courlis:` 1D sediment transport module



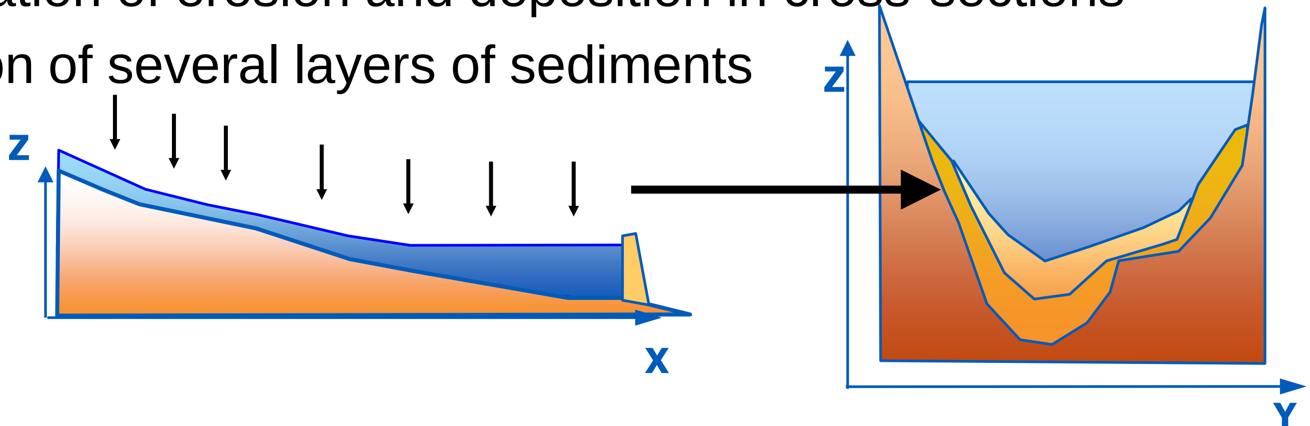
EDF sediment transport tools

Open SourceTelemac Mascaret System

http://www.opentelemac.org/

Example of the 1D sediment transport numerical code

- COURLIS numerical code (Bertier et al 2002)
- One dimensional
- Part of Telemac-Mascaret system (http://www.opentelemac.org/)
- Coupling between 1D shallow water equations (Mascaret, Goutal and Maurel 2002) and sediment component : Splitting approach
- 2D calculation of erosion and deposition in cross-sections
- Description of several layers of sediments



COURLIS (Bertier et al 2002)

Hydrodynamics component : Mascaret

It solves the Shallow Water Equations

Mass continuity equation

Momentum equation

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial Q}{\partial x} = 0 \\ \dfrac{\partial Q}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{Q^2}{A}\right) = -g.A.\dfrac{\partial Z}{\partial x} - g.A.J \end{cases}$$

avec : A la section mouillée (m^2)
Q le débit (m^3/s)
Z la cote de la surface libre (m)
J la pente d'énergie déterminée à partir de la relation de Strickler.

COURLIS (Bertier et al 2002)

Sediment component for SUSPENSION transport (fine sediments) :

- Advection dispersion equation for sand and silt (independent)

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} = \frac{\partial}{\partial x}\left(kA\frac{\partial C}{\partial x}\right) + E - D$$

Bed interactions

- Partheniades and Krone formulae for erosion and deposition of cohesive sediments

$$E = M\left(\frac{\tau}{\tau_{CE}} - 1\right) \qquad D = w_s C\left(1 - \frac{\tau}{\tau_{CD}}\right)$$

- Engelund Hansen Formula for sand transport capacity

$$q_s = 0.05\sqrt{\frac{\delta d^3}{g}}\,\frac{K^2 R_h^{1/3}\,\tau_{eff}}{(\rho_s - \rho)gd} \qquad C_{eq} = \frac{\rho_s q_s}{Q}$$

- Erosion and deposition rates

$$\begin{cases} \text{if } C_{sand} \geq C_{eq} \text{ deposition} & D = w_s\left(C_{sand} - C_{eq}\right) \\ \text{if } C_{sand} \leq C_{eq} \text{ erosion} & E = w_s\left(C_{eq} - C_{sand}\right) \end{cases}$$

- Bed evolution

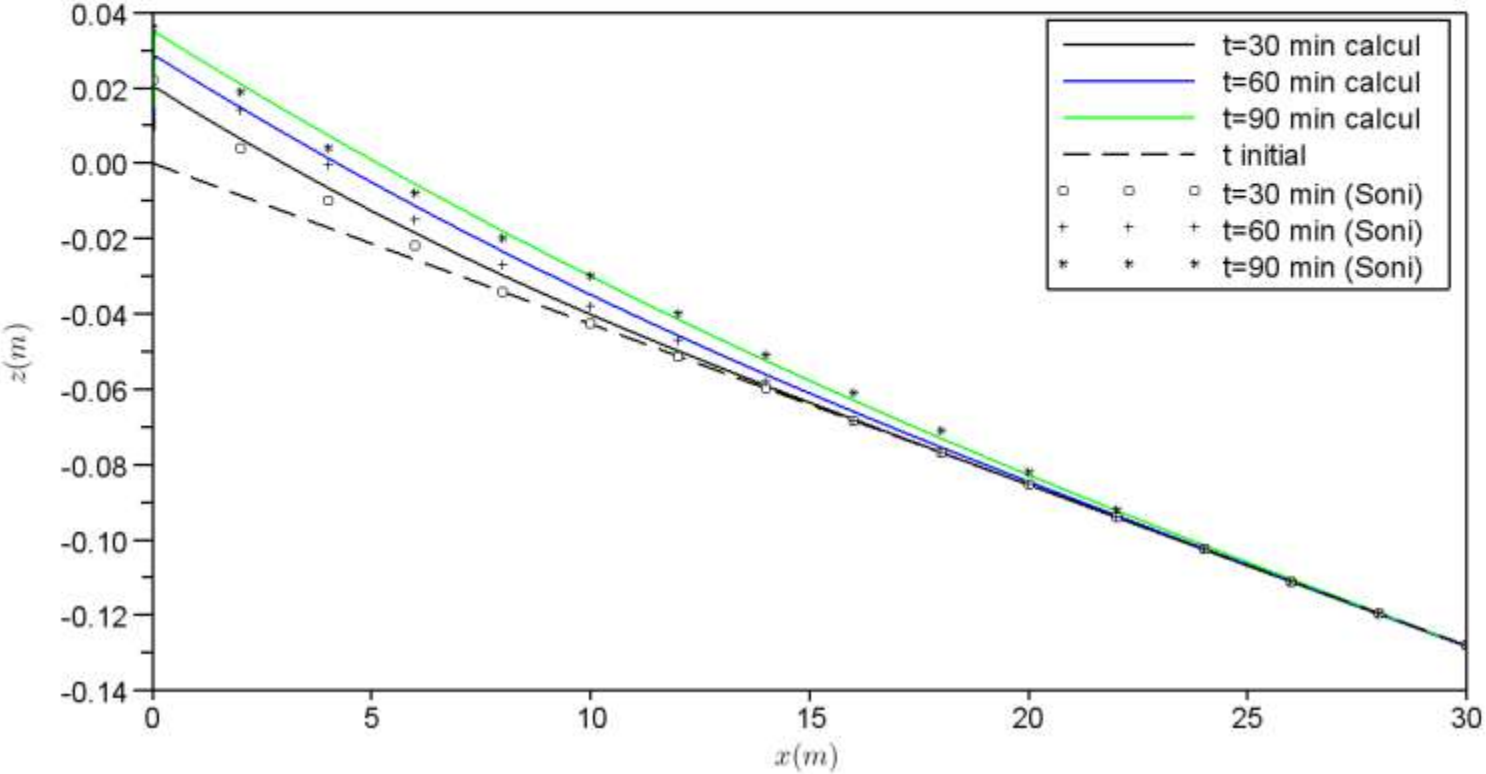
$$\frac{\partial Zb}{\partial t} = \frac{D}{C_{deposition}} - \frac{E}{C_{layer}}$$

Sand Deposition test case : Soni experiment

Soni J.P. Laboratory study of aggradation in alluvial channels, Journal of Hydrology, (49), 1981

- Mesh size Δx=25cm
- Friction coefficient Ks=45 $m^{1/3}s^{-1}$
- Diffusion coefficient Kx=0.025m^2s^{-1}
- Non equilibrium coefficient α=0.54

Flume length	L	30	(m)
Flume width	w	20	(cm)
Slope	S	$4.27\ 10^{-3}$	
Discharge		$7.1\ 10^{-3}$	(m^3/s)
Downstream water depth	Hd	7.2	(cm)
Upstream concentration	Cu	4.88	(g/l)
Median grain size	d_{50}	320	(µm)

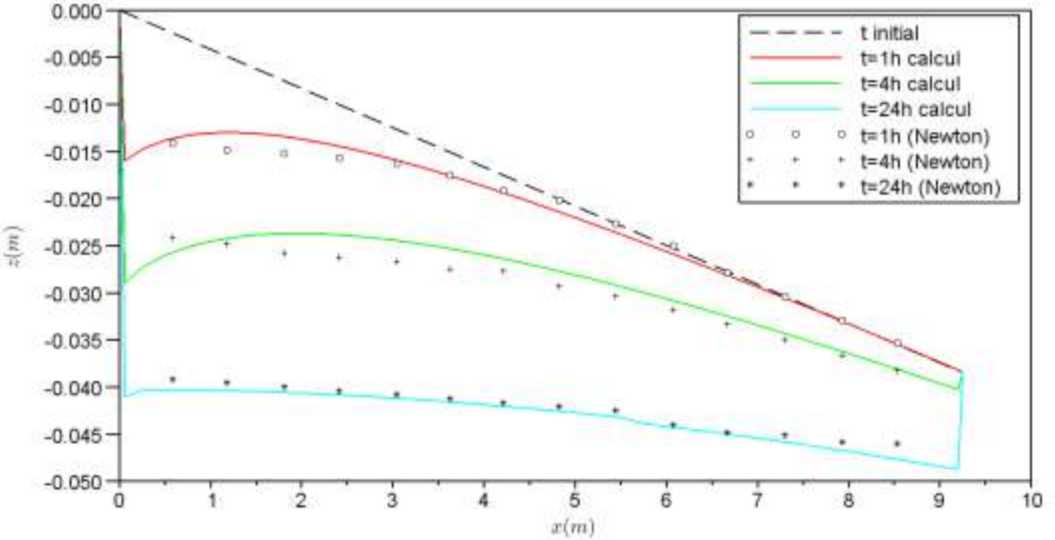


Sand Erosion test case : Newton Experiment

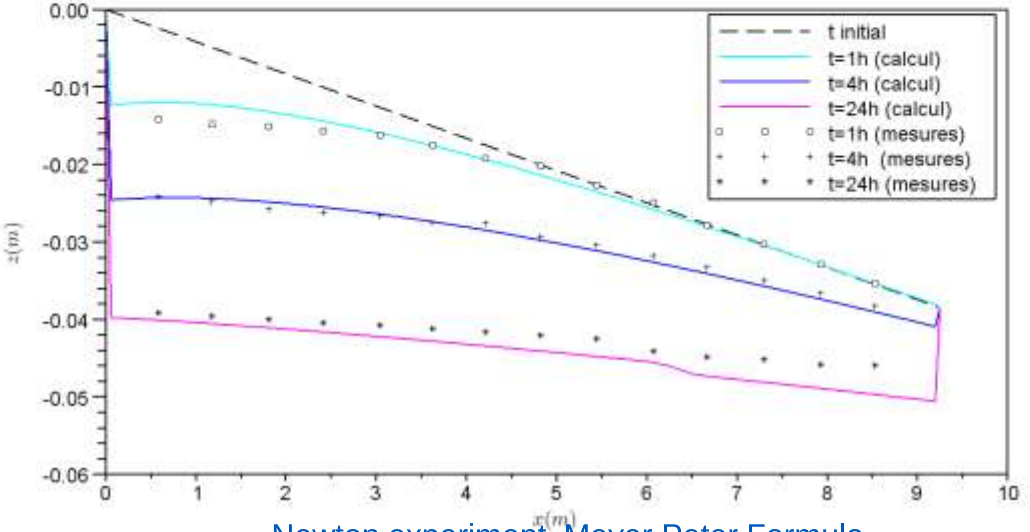
Newton C.T. An experimental investigation of bed degradation in an open channel. Technical report, Boston Society of Civil Engineers, 1951

Flume length	L	9.14	(m)
Flume width	w	30.48	(cm)
Slope	S	$4.16\ 10^{-3}$	
Discharge		$5.66\ 10^{-3}$	(m^3/s)
Downstream water depth	Hd	4.1	(cm)
Upstream concentration	Cu	0.88	(g/l)
Median grain size	d_{50}	680	(µm)

- Mesh size Δx=25cm
- Friction coefficient Ks=67 $m^{1/3}s^{-1}$
- Diffusion coefficient Kx=1m^2s^{-1}

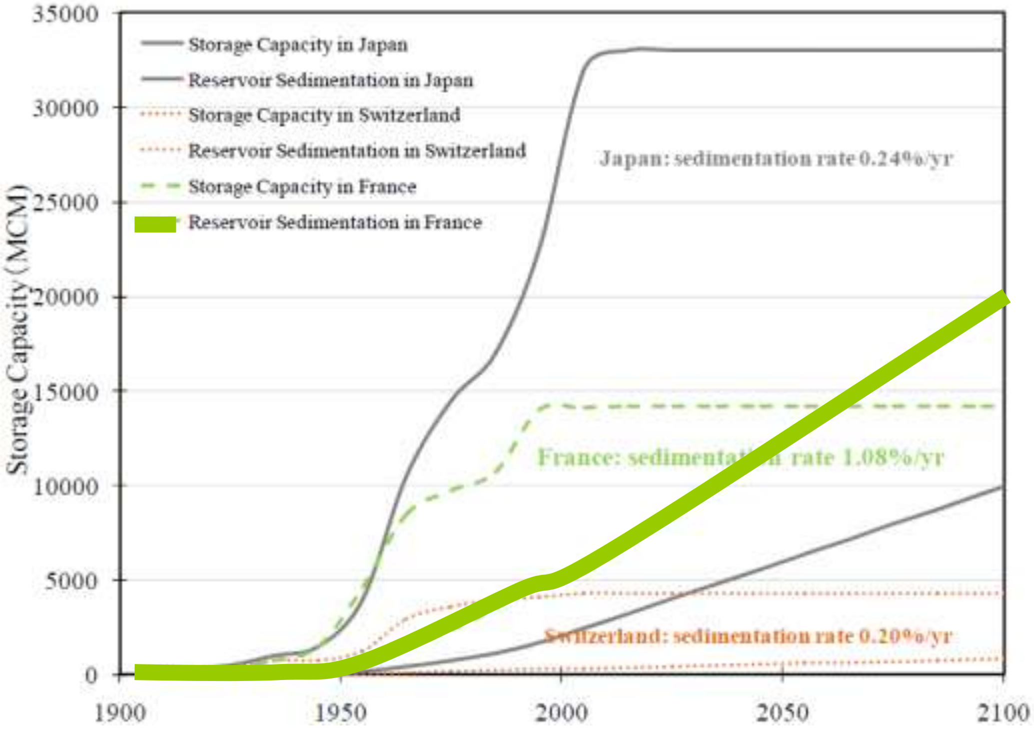


Newton experiment, Enguelund Hansen Formula



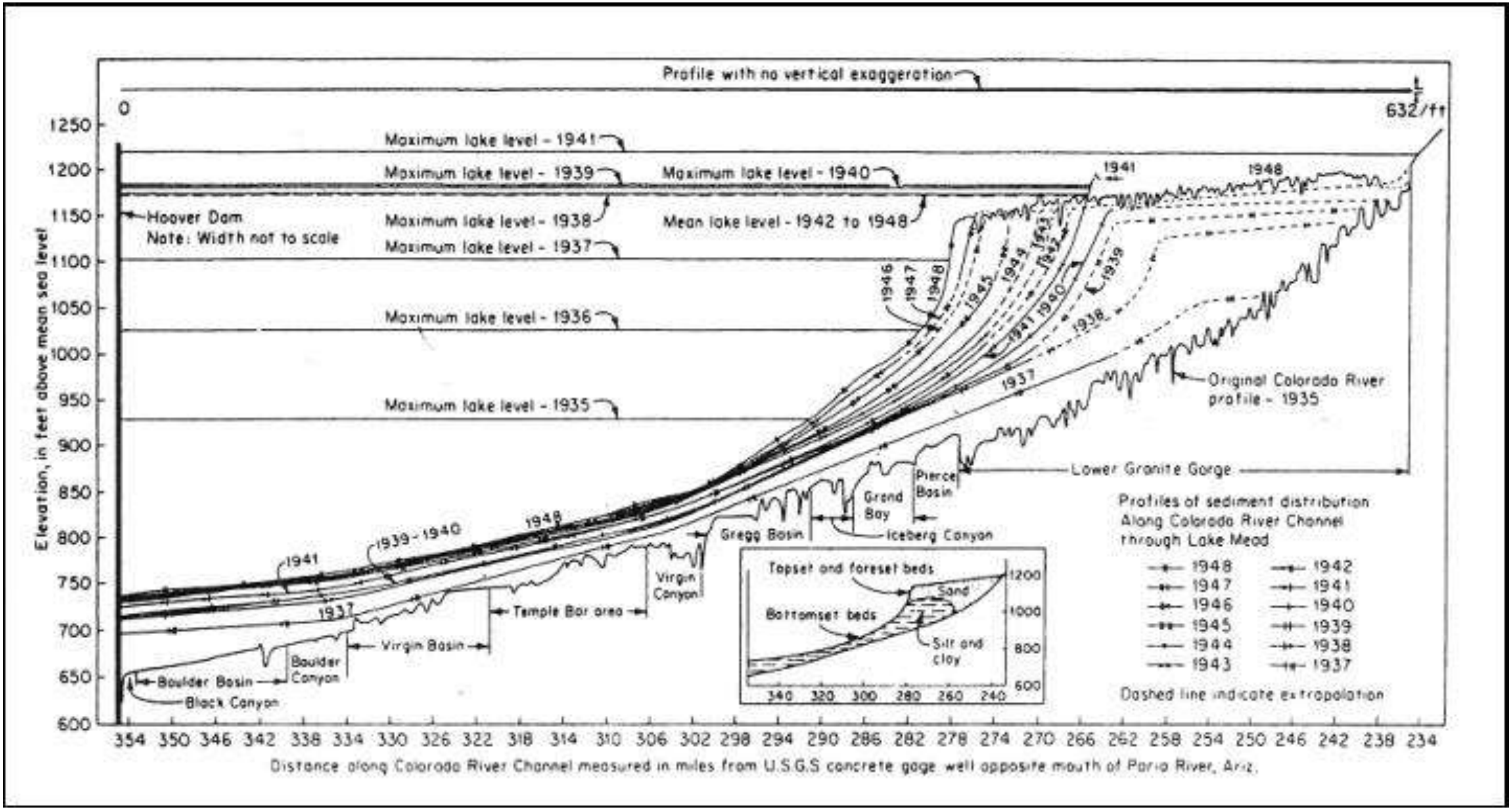
Newton experiment, Meyer Peter Formula

Sediments in reservoirs



Sediments in reservoirs

Lac Mead, US (Smith 1954)



How to deal with reservoir sedimentation ?

- EDF manage more than 400 reservoirs
- **Reservoir emptying** is performed regularly to control the state of dams or to perform works
  - Large quantities of eroded sediments
  - Need to predict downstream impacts (water quality)
- **Reservoir flushing** is performed to stop reservoir sedimentation
  - Need to know how to manage the flushing
  - Need to forecast downstream transport of sediment
- **Numerical modeling** a convenient way to deal with these questions


Emptying of Riou reservoir


Swiss Reservoir, picture from T. Bertolcht

Example :Emptying Tolla Reservoir

Tolla Reservoir (South Corsica) :

- emptying in order to perform works on the dam
- mitigate water quality degradation
- Not so many options : dilution using tributaries, settling tank, time during the year, speed of lowering and minimal elevation
- Downstream water intake for drinking water supply for Ajaccio city (53 000 inhabitants)

Tolla last Emptying1981

Use of numerical modeling

- to estimate the quantities of eroded sediments
- To test different scenarios of emptying
- **Use of a one dimensional model to simulate the downstream concentrations**

What kind of modeling ?

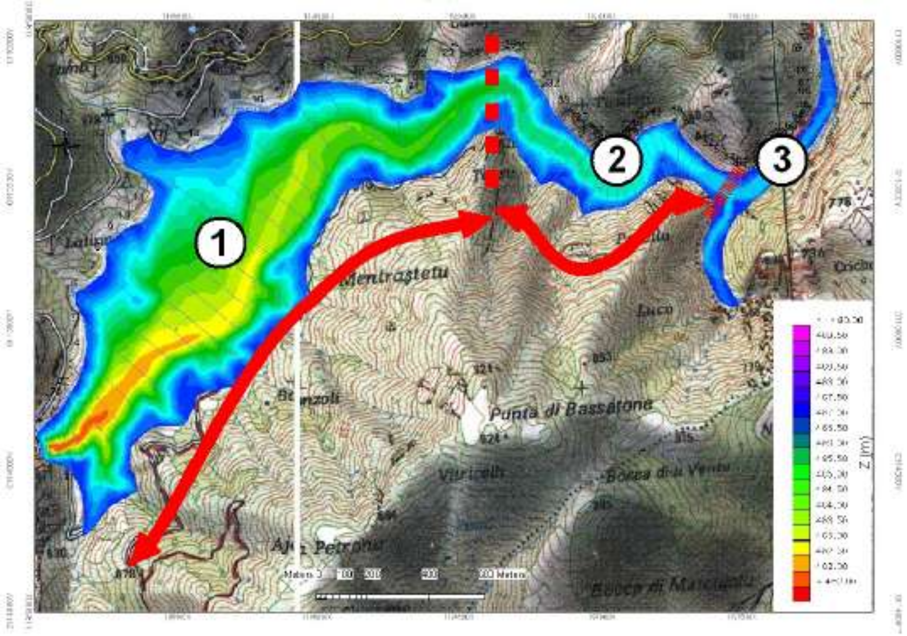
- **Numerical modeling** a convenient way to deal with reservoir operations and prediction of downstream sediment concentration

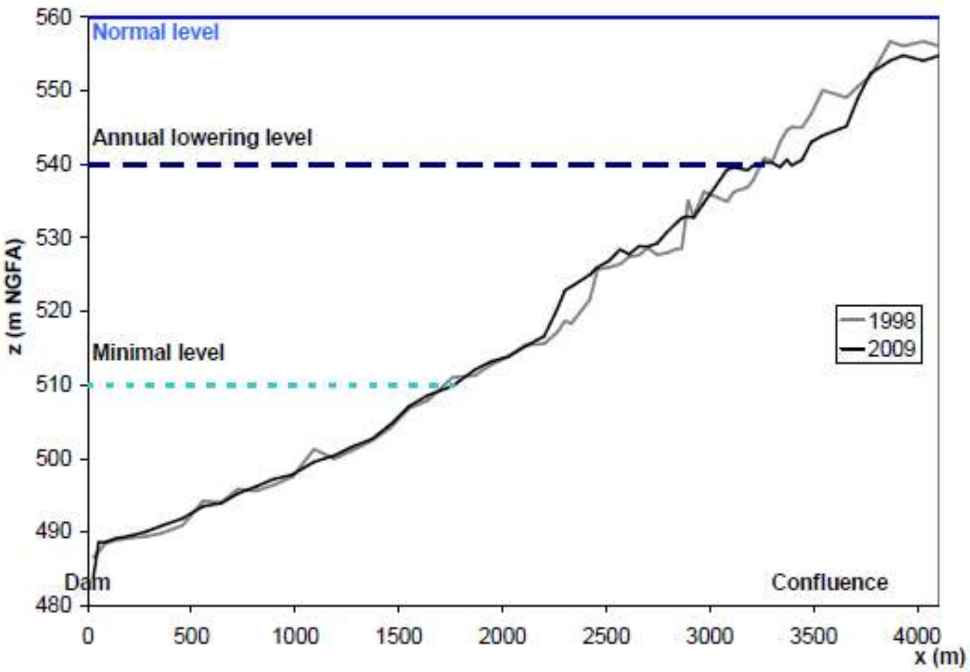
One dimensional modeling well suited in many cases

- Depends on the geometry of the reservoir
- No need to reproduce in detail flow and sediment transport patterns in the reservoir
- Very good results for engineering studies on previous cases :
  - St Egreve Reservoir, Valette ICSE 2012,
  - Grangent Reservoir, Bertier River Flow 2012

Sediment and Morphology of Tolla Reservoir

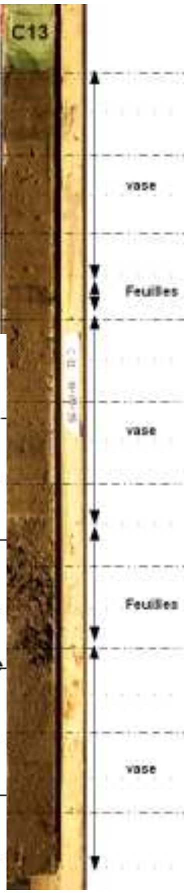
- 2 bathymetries (1998-2009)
- Old small dam near the main dam
- Steep slope x~2200m + upstream confluence

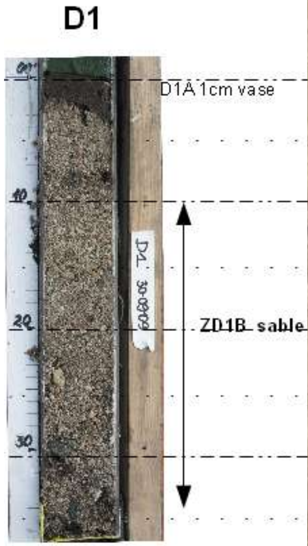


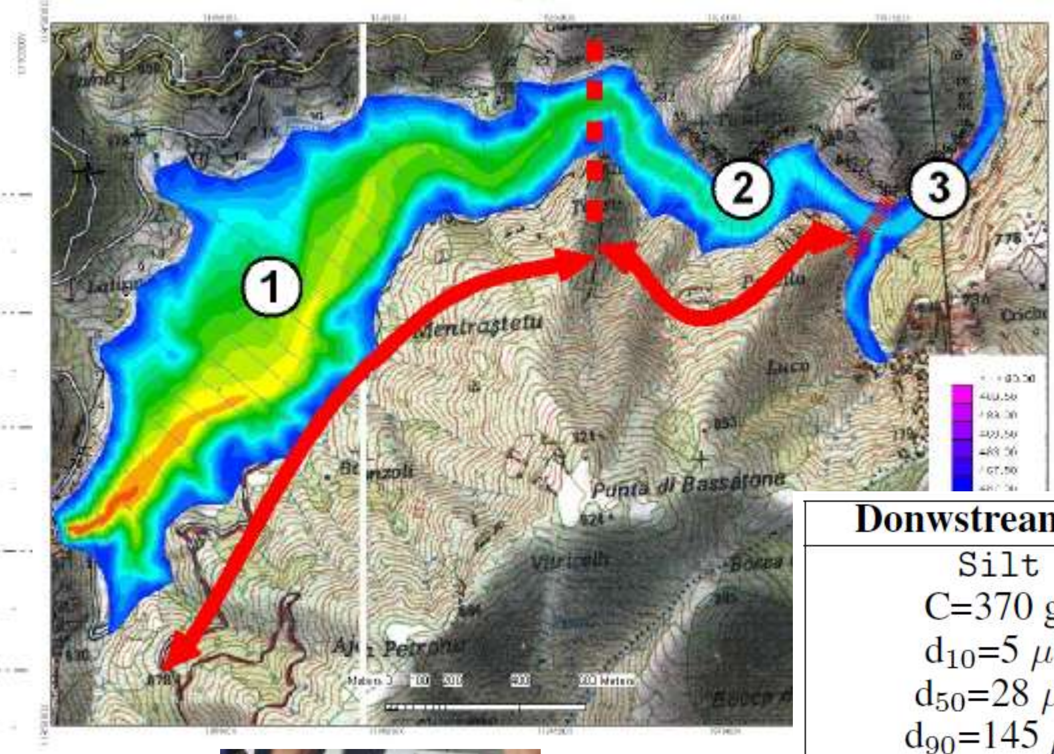


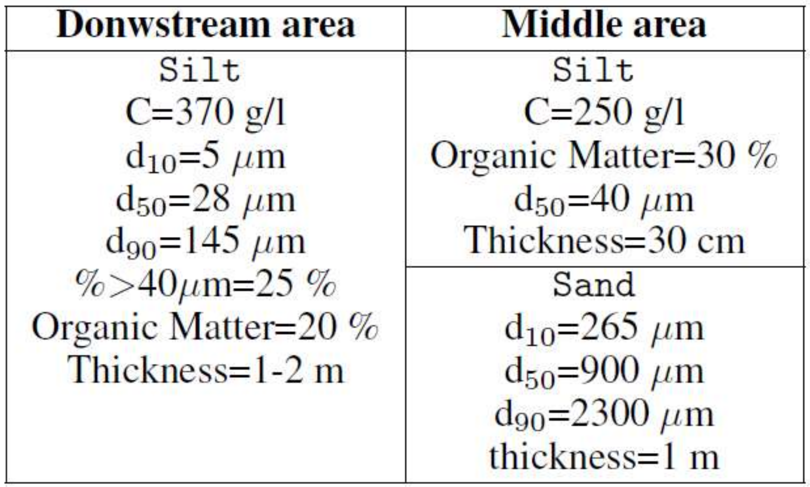
Sediment properties from sampled cores

- Silt in the downstream area (1) and sand upstream (2)
- + leaves
- Upstream area (3): not modeled









Donwstream area	Middle area
Silt C=370 g/l d_{10}=5 μm d_{50}=28 μm d_{90}=145 μm %>40μm=25 % Organic Matter=20 % Thickness=1-2 m	Silt C=250 g/l Organic Matter=30 % d_{50}=40 μm Thickness=30 cm Sand d_{10}=265 μm d_{50}=900 μm d_{90}=2300 μm thickness=1 m

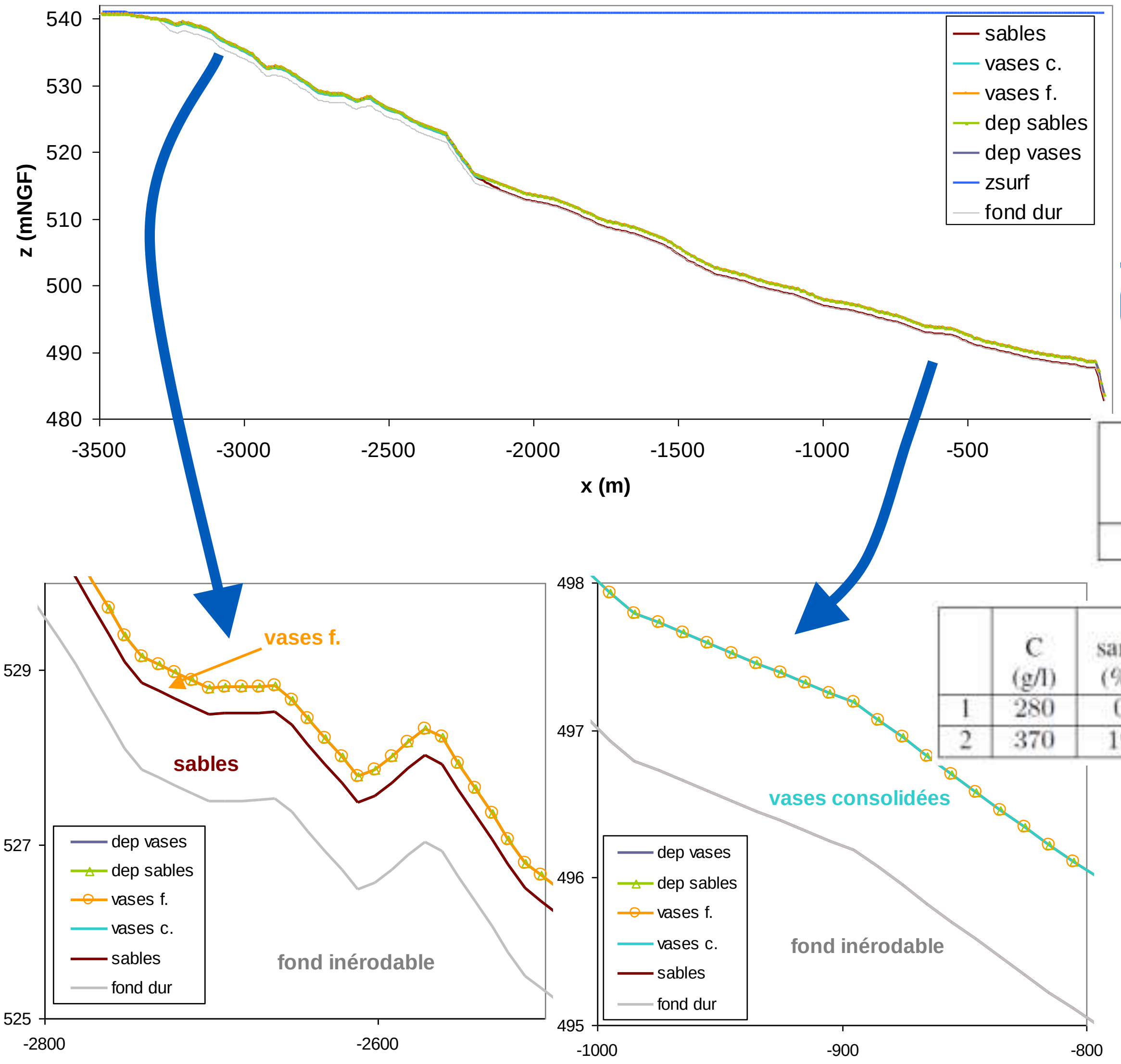
Description of the reservoir for the model

bed : Bathymetries

Sediment properties

Lack of calibration data ➔ **sensitivity analysis**

➧ **we choose the worst but physical parameters**

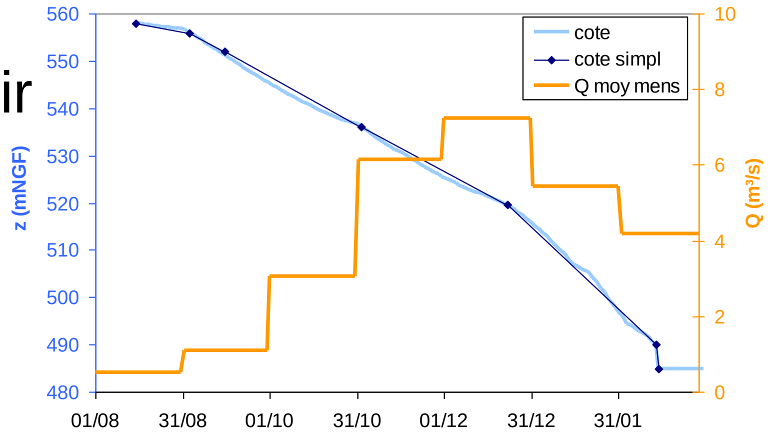


	C (g/l)	Sand parameters			
		sand (%)	d_{50} (μm)	w_s (m/s)	K_p ($m^{1/3}s^{-1}$)
sand	1400	90	90	7.10^{-3}	$75 - 95$

	C (g/l)	sand (%)	Silt parameters			
			τ_{ce} (Pa)	M ($kgs^{-1}m^{-2}$)	w_s (m/s)	τ_{cd} (Pa)
1	280	0	$0.1 - 1$	$0.01 - 0.02$	$2.10^{-3} - 10^{-2}$	$0.01 - 0.1$
2	370	19	$0.5 - 2$	$0.01 - 0.02$	$2.10^{-3} - 10^{-2}$	$0.01 - 0.1$

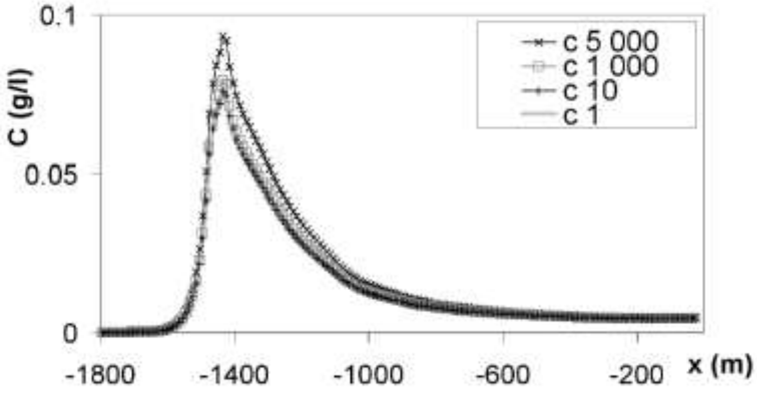
Initial conditions and limit conditions

- Downstream condition : emptying scenario
- Upstream : incoming discharge
- Initial : steady state of the full reservoir



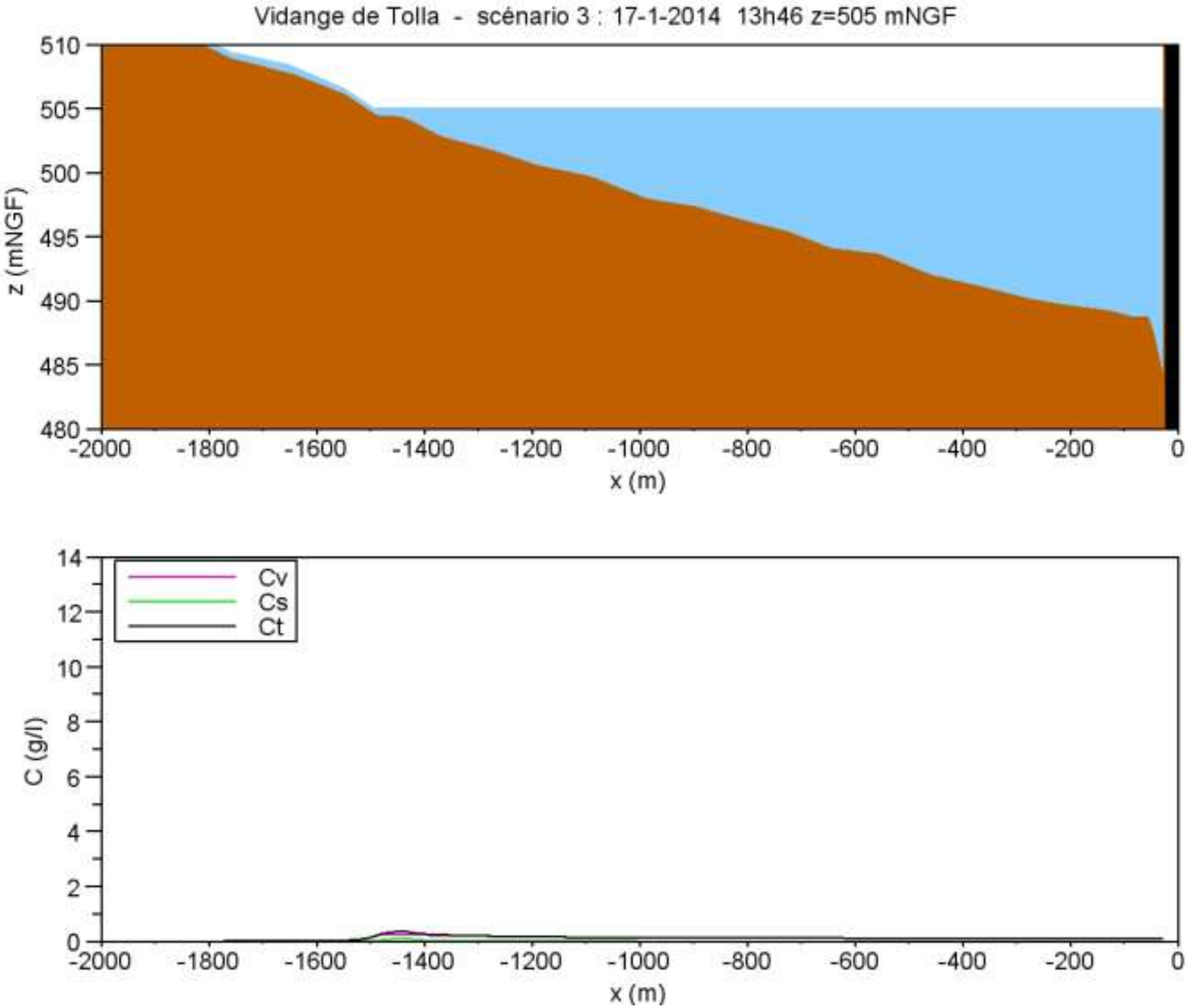
Numerical parameters

- Vertical and longitudinal meshes
- Numerical schemes (supercritical flows)
- Coupling time step $\left(u+\sqrt{gh}\right)\frac{\Delta t}{\Delta x}<1$



- Chosen to obtain reliable results with smallest calculation times as possible

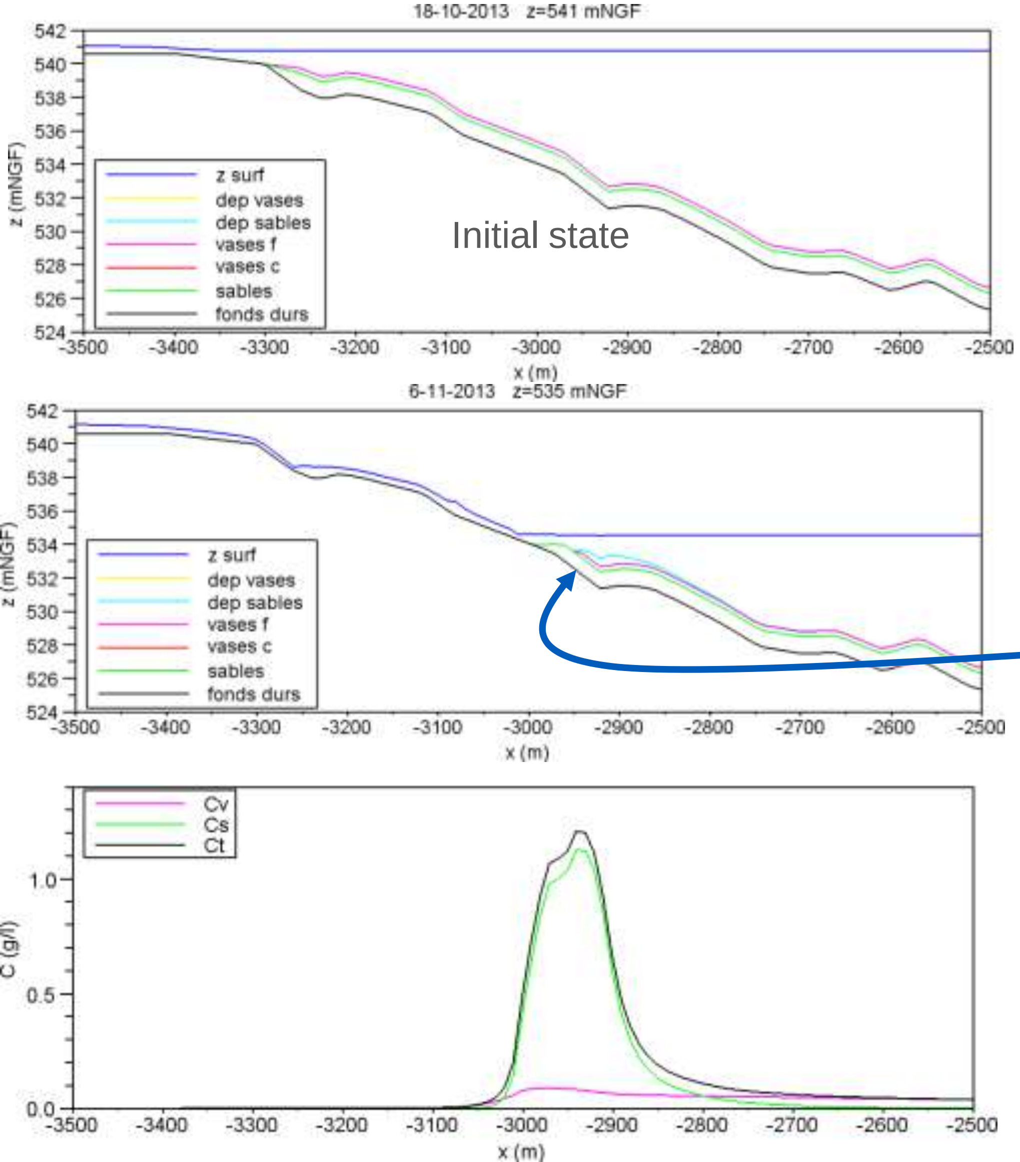
Results



Vidange de Tolla - scénario 3 : 17-1-2014 13h46 z=505 mNGF
z (mNGF)
510
505
500
495
490
485
480
-2000
-1800
-1600
-1400
-1200
-1000
-800
-600
-400
-200
0
x (m)
C (g/l)
14
12
10
8
6
4
2
0
Cv
Cs
Ct
-2000
-1800
-1600
-1400
-1200
-1000
-800
-600
-400
-200
0
x (m)

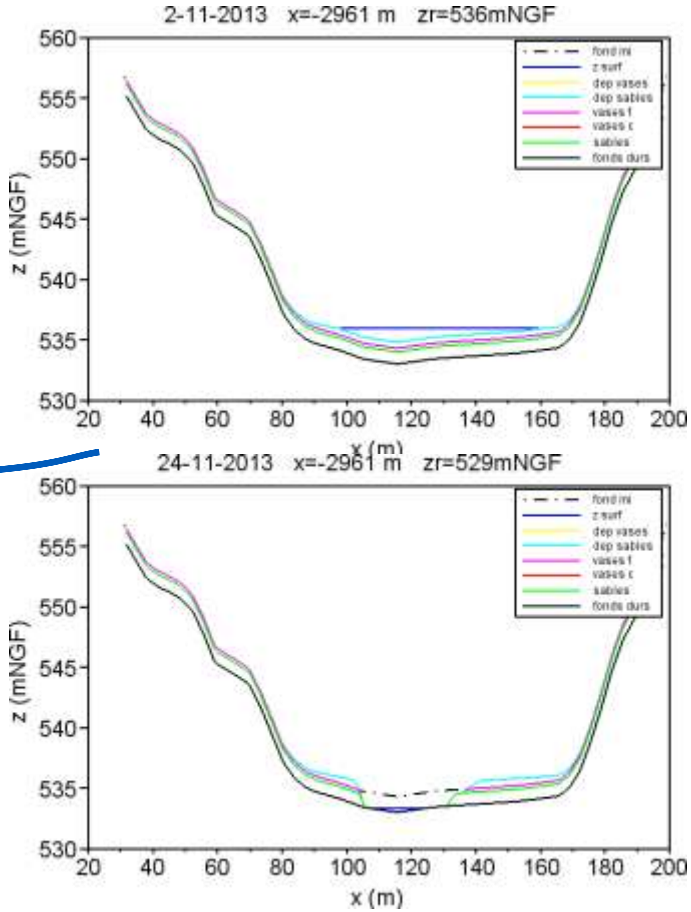
Bed evolution

Longitudinal bed evolution

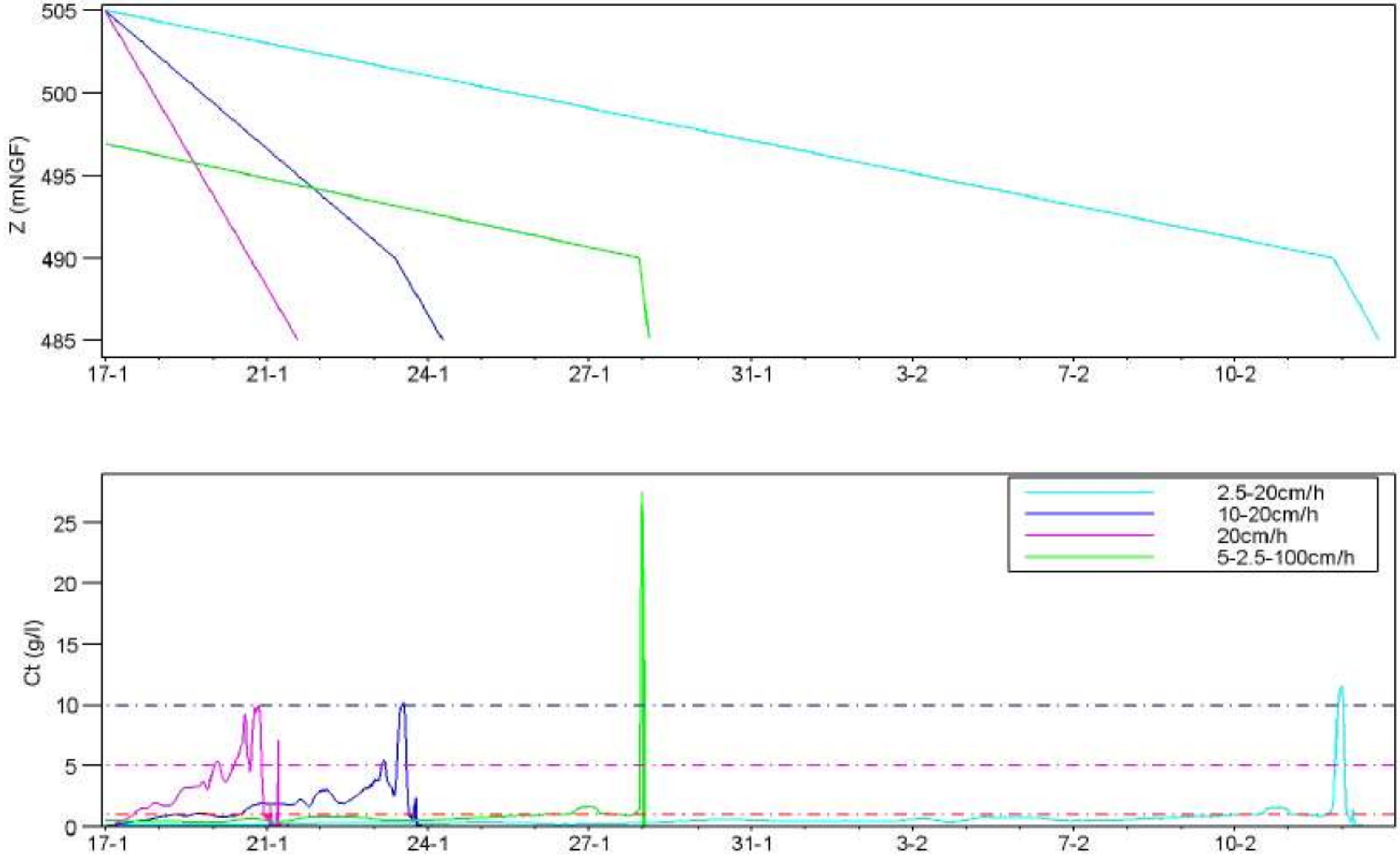


Initial state

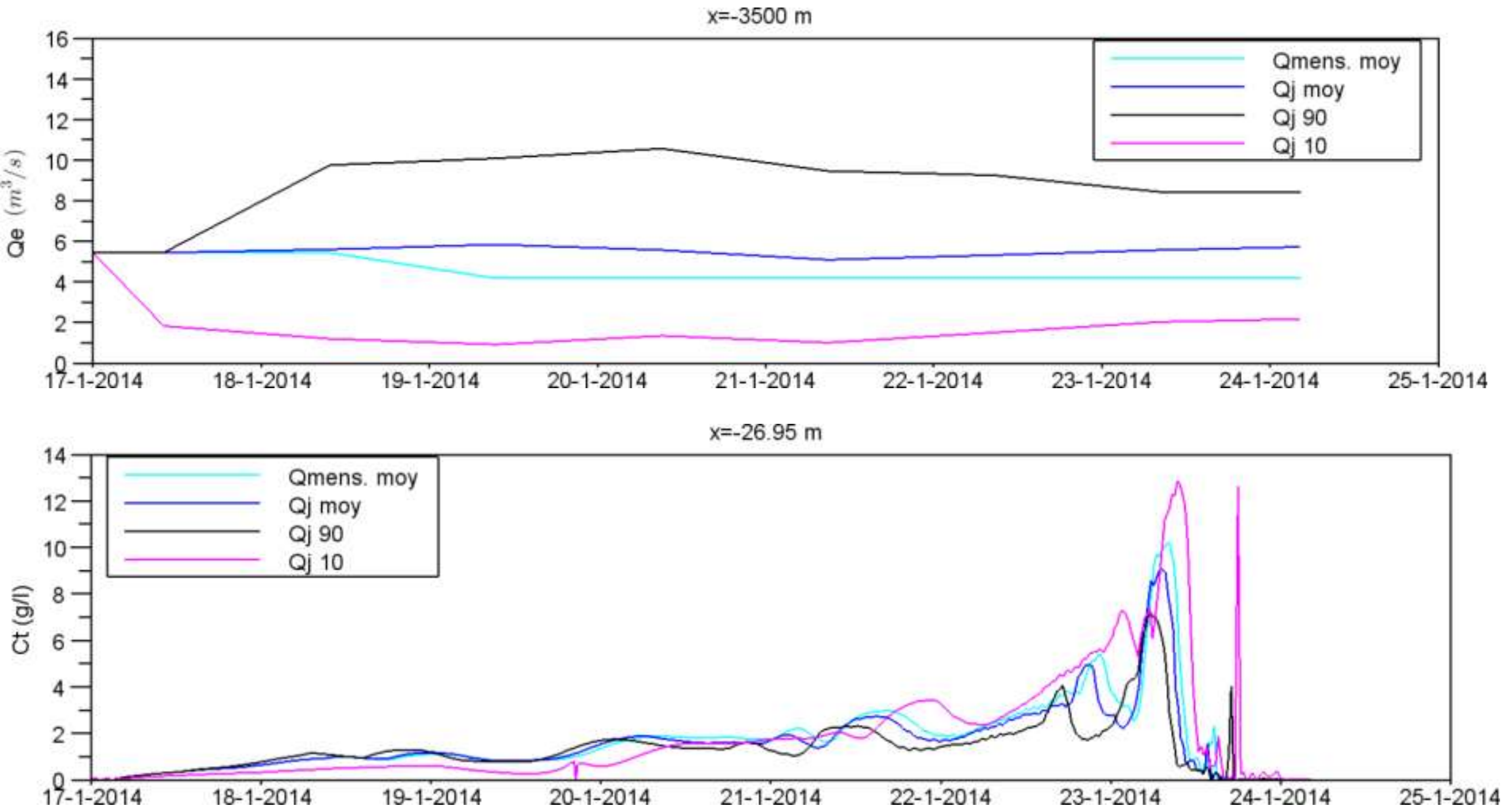
Section evolution



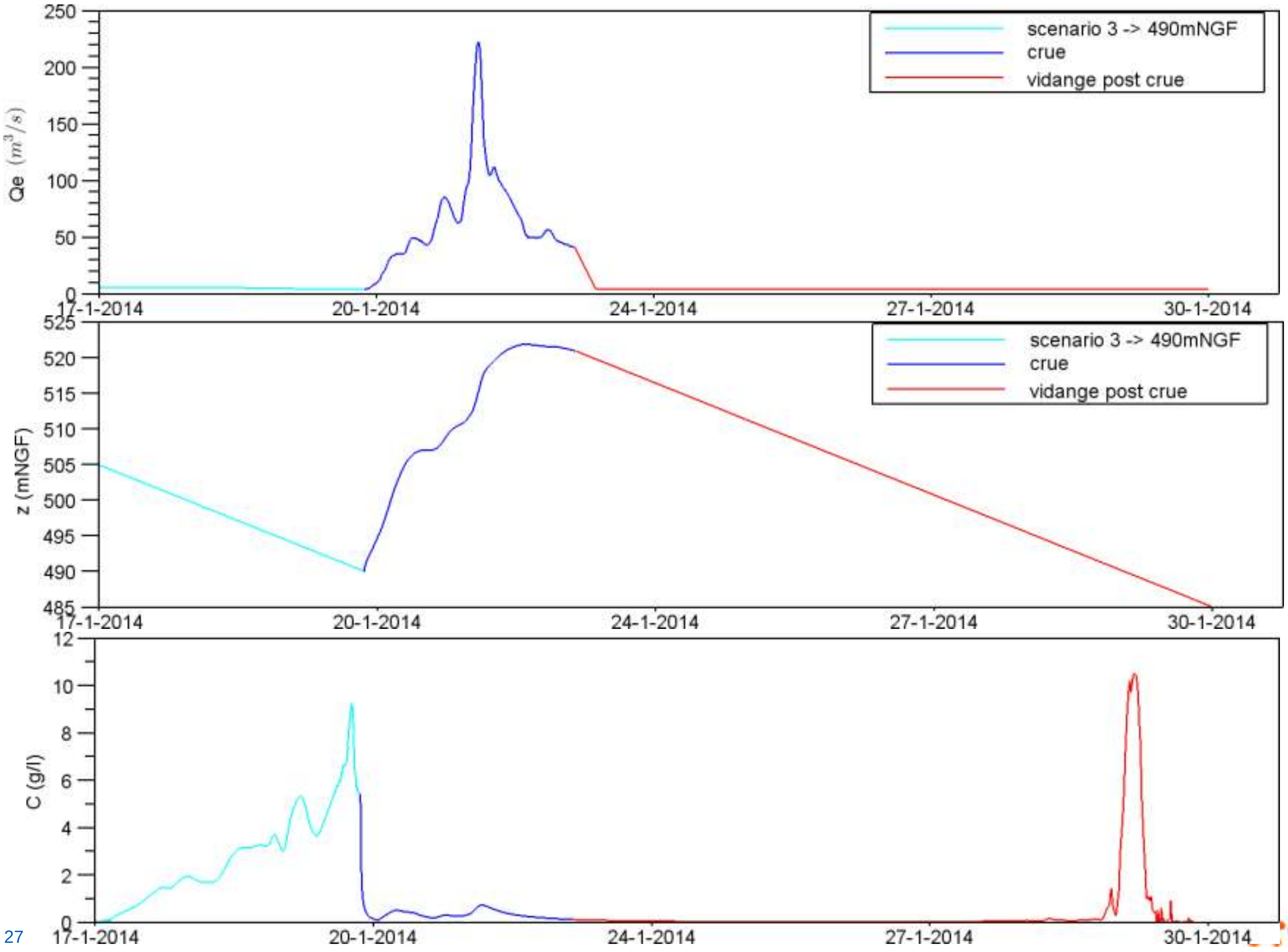
Emptying scenario: Comparing speed of lowering



Upstream discharge : no possible in situ control



What happens if there is a flood ?



Examples of current research

- 2011 & 2013 Cemracs Projects

2011 Cemracs Project

- Sediment transport modeling : **relaxation schemes for Saint-Venant Exner** and three layer models

Emmanuel Audusse, Christophe Chalons, Olivier Delestre, Nicole Goutal, Magali Jodeau, Jacques Sainte-Marie, Jan Giesselmann and Georges Sadaka

EDF, INRIA, UNIV P6

- SHALLOW WATER AND EXNER EQUATIONS

$$\begin{aligned}
\frac{\partial H}{\partial t} + \frac{\partial Q}{\partial x} &= 0, \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{H} + \frac{g}{2}H^2\right) &= -gH\frac{\partial z_b}{\partial x}, \\
\rho_s(1-p)\frac{\partial z_b}{\partial t} + \frac{\partial Q_s}{\partial x} &= 0,
\end{aligned}$$

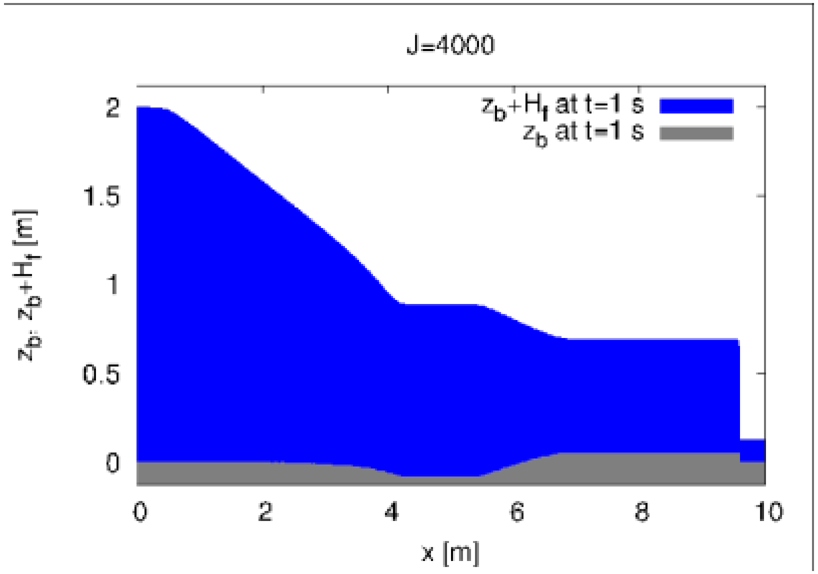
- A RELAXATION SOLVER FOR THE SAINT-VENANT EXNER MODEL

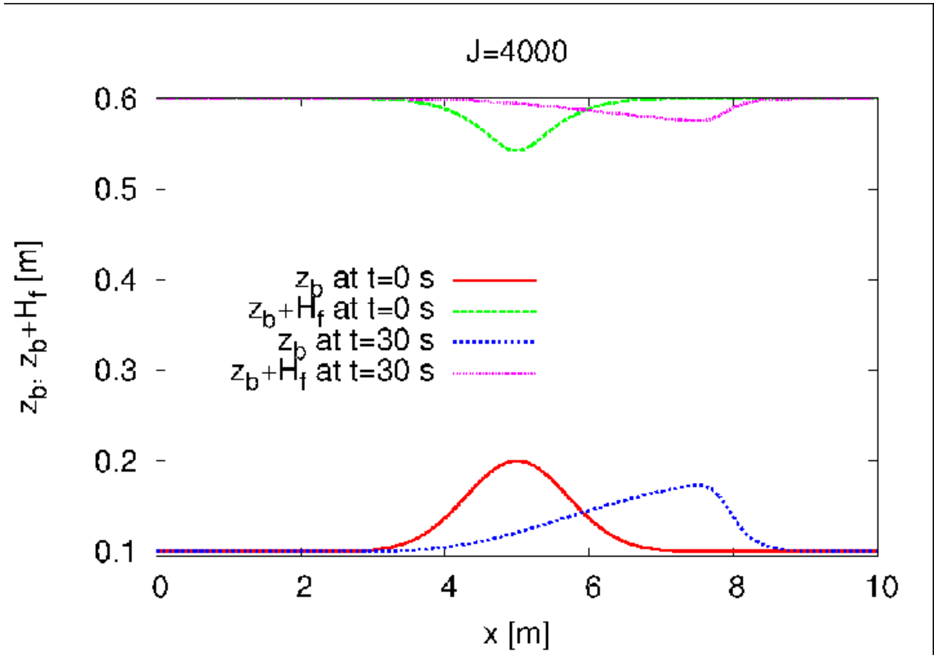
$$\begin{aligned}
\frac{\partial H}{\partial t} + \frac{\partial Hu}{\partial x} &= 0 \\
\frac{\partial Hu}{\partial t} + \frac{\partial}{\partial x}(Hu^2 + \Pi) &= -gH\frac{\partial z_b}{\partial x} \\
\frac{\partial \Pi}{\partial t} + u\frac{\partial \Pi}{\partial x} + \frac{a^2}{H}\frac{\partial u}{\partial x} &= \frac{1}{\lambda}(\Pi - \frac{gH^2}{2}) \\
\frac{\partial z_b}{\partial t} + \frac{\partial \tilde{Q}_s}{\partial x} &= 0 \\
\frac{\partial \tilde{Q}_s}{\partial t} + \left(\frac{b^2}{H^2} - u^2\right)\frac{\partial z_b}{\partial x} + 2u\frac{\partial \tilde{Q}_s}{\partial x} &= \frac{1}{\lambda}(\tilde{Q}_s - Q_s)
\end{aligned}$$

2011 Cemracs Project

- sediment transport modelling : **relaxation schemes for Saint-Venant Exner** and three layer models

- A RELAXATION SOLVER FOR THE SAINT-VENANT EXNER MODEL : SOME RESULTS



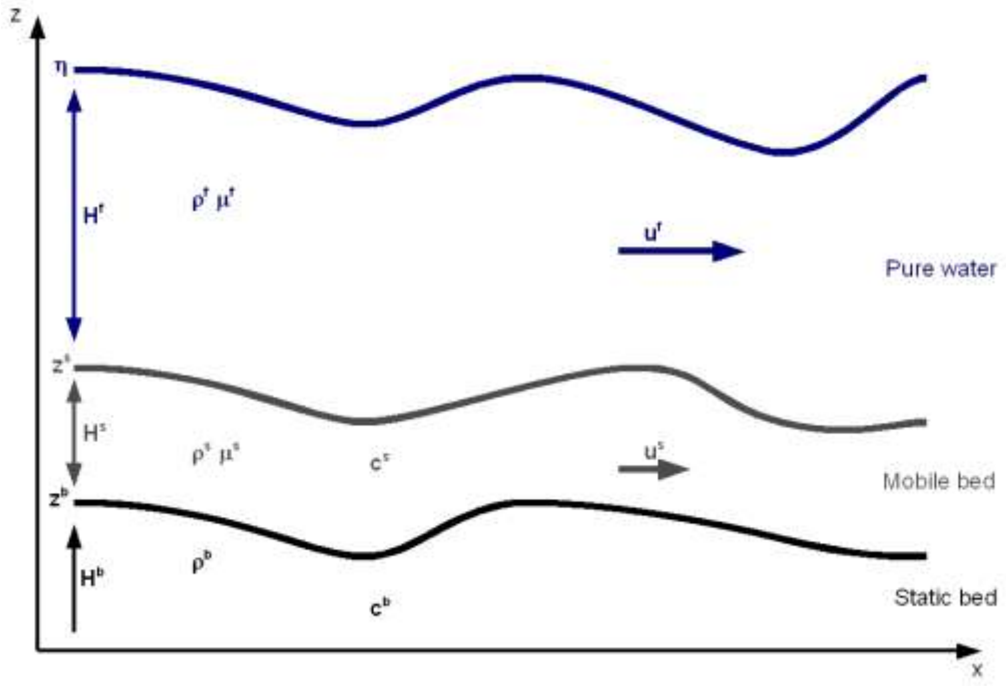


Flow over a moveable bump

Dam Break over a moveable bottom

2011 Cemracs Project

- sediment transport modelling : relaxation schemes for Saint-Venant Exner and **three layer models**



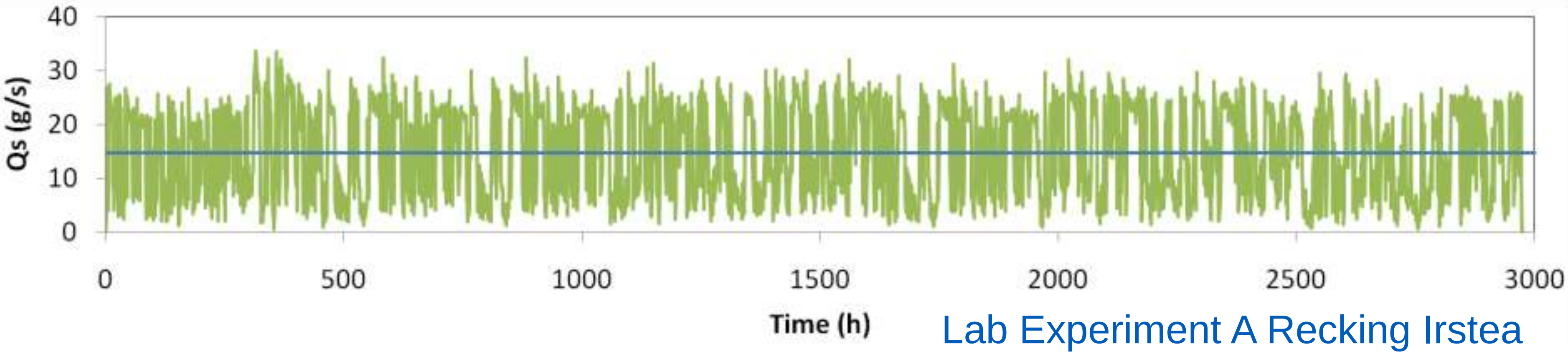
Three Layer Model

2013 Cemracs Project

- Modeling and simulation of uncertainties in hydraulics and sediment transport

Emmanuel Audusse, Sébastien Boyaval, Yueyan Cao, Nicole Goutal, Magali Jodeau, Philippe Ung
EDF, UNIV P13, LABORATOIRE ST VENANT

- Sediment transport is a stochastic process



Lab Experiment A Recking Irstea

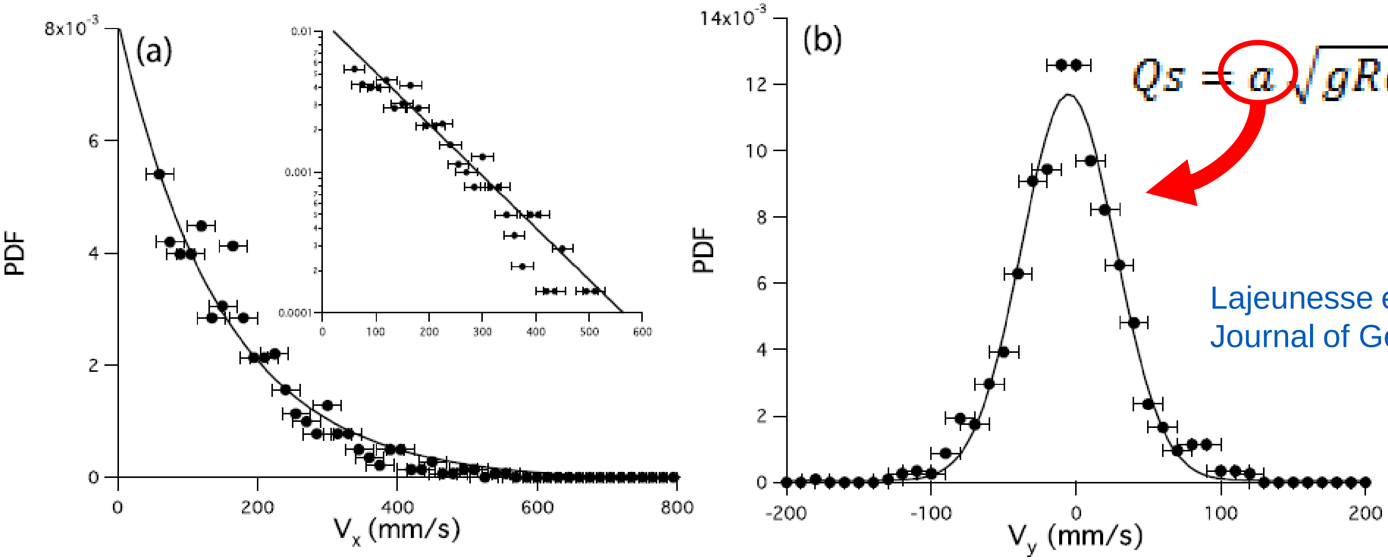
- How to deal with stochastic properties in numerical modeling ?

2013 Cemracs Project

- Modeling and simulation of uncertainties in hydraulics and sediment transport

$$
\begin{aligned}
\frac{\partial H}{\partial t} + \frac{\partial Q}{\partial x} &= 0, \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{H} + \frac{g}{2}H^2\right) &= -gH\frac{\partial z_b}{\partial x}, -gHJ \\
\rho_s(1-p)\frac{\partial z_b}{\partial t} + \frac{\partial Q_s}{\partial x} &= 0,
\end{aligned}
$$

$$Qs = \boxed{a}\sqrt{gRd}(\tau^* - \boxed{\tau_c^*})^{3/2}$$



Lajeunesse et al.
Journal of Geophysical Research 2010

Figure 6. (a) Experimental probability density functions (PDFs) of V_x for $\tau^* = 0.103$, $Re_s = 426$, $H/D = 5$, and $S = 0.042$. Inset shows the same data represented on a semilog plot. (b) Corresponding PDFs of V_y.

Thanks for your attention !

Sylvain C.