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
Transport of Sediments in Rivers

Sand and gravel

- Bed load Transport
  saltating and rolling near the bed of sediments

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.

EDF sediment transport tools
Open Source Telemac 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

\[
\begin{align*}
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} &= 0 \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) &= -gA \frac{\partial Z}{\partial x} - gAJ
\end{align*}
\]

avec :  
A la section mouillée (m²)  
Q le débit (m³/s)  
Z la cote de la surface libre (m)  
J la pente d’énergie déterminée à partir de la relation de Strickler.
Sediment component for SUSPENSION transport (fine sediments):

- Advection dispersion equation for sand and silt (independent)

\[
\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} = \frac{\partial}{\partial x} \left( k_A \frac{\partial C}{\partial x} \right) + E - D
\]

Bed interactions

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

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

- Engelund Hansen Formula for sand transport capacity

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

- Erosion and deposition rates

\[
\begin{cases} 
\text{if } C_{sand} \geq C_{eq} \text{ deposition} \\
\text{if } C_{sand} \leq C_{eq} \text{ erosion}
\end{cases}
\]

\[
D = w_s (C_{sand} - C_{eq}) \quad E = w_s (C_{eq} - C_{sand})
\]

- Bed evolution

\[
\frac{\partial Z_b}{\partial t} = \frac{D}{C_{deposition}} - \frac{E}{C_{layer}}
\]
Sand Deposition test case: Soni experiment

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

- Mesh size $\Delta x=25$ cm
- Friction coefficient $K_s=45$ m$^{1/3}$s$^{-1}$
- Diffusion coefficient $K_x=0.025$ m$^2$ s$^{-1}$
- Non equilibrium coefficient $\alpha=0.54$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flume length $L$</td>
<td>30 (m)</td>
</tr>
<tr>
<td>Flume width $w$</td>
<td>20 (cm)</td>
</tr>
<tr>
<td>Slope $S$</td>
<td>$4.27 \times 10^{-3}$ (cm)</td>
</tr>
<tr>
<td>Discharge</td>
<td>$7.1 \times 10^{-3}$ (m$^3$/s)</td>
</tr>
<tr>
<td>Downstream water depth $H_d$</td>
<td>7.2 (cm)</td>
</tr>
<tr>
<td>Upstream concentration $C_u$</td>
<td>4.88 (g/l)</td>
</tr>
<tr>
<td>Median grain size $d_{50}$</td>
<td>320 (µm)</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flume length</td>
<td>L</td>
<td>9.14</td>
</tr>
<tr>
<td>Flume width</td>
<td>w</td>
<td>30.48</td>
</tr>
<tr>
<td>Slope</td>
<td>S</td>
<td>4.16 \times 10^{-3}</td>
</tr>
<tr>
<td>Discharge</td>
<td></td>
<td>5.66 \times 10^{-3}</td>
</tr>
<tr>
<td>Downstream water depth</td>
<td>Hd</td>
<td>4.1</td>
</tr>
<tr>
<td>Upstream concentration</td>
<td>Cu</td>
<td>0.88</td>
</tr>
<tr>
<td>Median grain size</td>
<td>d_{50}</td>
<td>680</td>
</tr>
</tbody>
</table>

- Mesh size $\Delta x=25$cm
- Friction coefficient $K_s=67$ m$^{1/3}$/s$^{-1}$
- Diffusion coefficient $K_x=1$ m$^2$/s$^{-1}$

Newton experiment, Enguelund Hansen Formula

Newton experiment, Meyer Peter Formula
Sediments in reservoirs

- Japan: sedimentation rate 0.24%/yr
- Switzerland: sedimentation rate 0.20%/yr
- France: sedimentation rate 1.08%/yr
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

[Images: 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)

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** is a convenient way to deal with reservoir operations and prediction of downstream sediment concentration.

  One-dimensional modeling is 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

<table>
<thead>
<tr>
<th>Downstream area</th>
<th>Middle area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>Silt</td>
</tr>
<tr>
<td>C=370 g/l</td>
<td>C=250 g/l</td>
</tr>
<tr>
<td>$d_{10}=5 \mu m$</td>
<td></td>
</tr>
<tr>
<td>$d_{50}=28 \mu m$</td>
<td></td>
</tr>
<tr>
<td>$d_{90}=145 \mu m$</td>
<td>$d_{50}=40 \mu m$</td>
</tr>
<tr>
<td>$% &gt; 40 \mu m = 25 %$</td>
<td></td>
</tr>
<tr>
<td>Organic Matter = 20 %</td>
<td>Organic Matter = 30 %</td>
</tr>
<tr>
<td>Thickness = 1-2 m</td>
<td>Thickness = 30 cm</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand</td>
</tr>
<tr>
<td>$d_{10}=265 \mu m$</td>
<td></td>
</tr>
<tr>
<td>$d_{50}=900 \mu m$</td>
<td></td>
</tr>
<tr>
<td>$d_{90}=2300 \mu m$</td>
<td></td>
</tr>
<tr>
<td>thickness = 1 m</td>
<td>thickness = 1 m</td>
</tr>
</tbody>
</table>
Description of the reservoir for the model

Bed: Bathymetries

Sediment properties

Lack of calibration data ➔ sensitivity analysis

- We choose the worst but physical parameters
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
**Bed evolution**

**Longitudinal bed evolution**

**Initial state**

**Section evolution**

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**EDF**

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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
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

A relaxation solver for the Saint-Venant Exner model
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

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**Dam Break over a moveable bottom**

**Flow over a moveable bump**
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

- How to deal with stochastic properties in numerical modeling?
2013 Cemracs Project

Modeling and simulation of uncertainties in hydraulics and sediment transport

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

\[Q_s = a \sqrt{gRd(\tau^* - \tau_c^*)^{3/2}}\]

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 \(V_y\).

Lajeunessse et al. Journal of Geophysical Research 2010
Thanks for your attention!