What problems can be solved by a 1–D river sediment transport model? An example of RubarBE software

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English summary

With a 1-D sediment transport model, various problems can be investigated. The most obvious one is to estimate the amount of sediment transported, which can be found by balancing inputs, outputs and exchanges with the river bed. Sediment transport during floods can be high and, particularly in mountain rivers, one flood may significantly alter the morphology of the river bed. It implies that the model should integrate uneven flow and be able to describe the changes to the shape of the cross sections. Cemagref developed RubarBE to include these two last aspects, concentrating on one single type of sediment found in the bed material load. An example of application of RubarBE to the River Isère is provided.

Résumé français : *Quels problèmes résoudre par un code 1D de transport de sédiments en rivière? Exemple du logiciel RubarBE*

Avec un modèle unidimensionnel de transport de sédiments, plusieurs problèmes peuvent être approchés. Le plus évident est l'estimation de la quantité de sédiments transportés en faisant le bilan entre apports, sorties et échanges avec le fond. Un fort transport de sédiments se produit pendant les crues et, particulièrement en rivières de montagne, une crue peut modifier la morphologie d'un lit de rivière notablement. Ceci implique que le modèle doit intégrer le régime transitoire et pouvoir décrire l'évolution de la forme des sections en travers. Le Cemagref a développé RubarBE pour inclure ces deux derniers aspects en se concentrant sur un seul type de sédiments supposé constituer le matériau du lit. Un exemple d'application de RubarBE à l'Isère est présenté.

Streszczenie polskie: ***Możliwości zastosowania jednowymiarowego modelu matematycznego transportu rumowiska. Przykład: Rubarbe software***

Przepływ w korycie cieku opisywany jest zwykle jednowymiarowym modelem matematycznym. Jednym z podstawowych zastosowań tego typu modelu, jest możliwość określania ilości transportowanego rumowiska oraz związanych z nią zmian koryta w profilu podłużnym. Podczas przepływu wód powodziowych występuje intensywny ruch rumowiska wleczonego. Często dochodzi do znacznej zmiany jego granulacji., czego następstwem jest wystąpienia dużych zmian w konfiguracji dna Rubarbe umożliwia obliczenia w warunkach ruchu zmiennego opisując jednocześnie zmiany w przekrojach poprzecznych. Program Rubarbe powstał w instytucie badawczym Cemagref. Przykładem zastosowania programu Rubarbe są obliczenia prowadzone na rzece Isere.

1. Introduction

Sediment transport is one of the main process that should be considered in studying "natural" rivers. Even if the sediment load is low, exchanges are always occuring between the banks, the bottom and the flow. This process, that is at the origin of the morphology of the rivers, is still acting and may have huge consequences on human activities or the environment. This paper recalls the problems that may appear and the main processes and parameters that are concerned. Then the sediment transport software RubarBE is described and its use on the River Isere is detailed.

2. The questions linked with sediment transport

Except the cases of the very concentrated sediment loads that change the properties of water, the main questions concern the evolution of the depositions or the erosions that occur along the river. If the problem is integrated for a long period, the volume of sediment for one stretch of river has to be assessed. More generally, the question of the evolution of the bed and the banks at any moment, and its effects on the flow features, should be answered.
Typical problems can be emphasized. Flood risk is directly linked to the level of water in the river in relation to the height of the banks. Of course, the presence of sediment deposits can raise the water level, but sediment transport may also change the interactions between the flow and the bed, thus modifying the water level. One example is the appearance of dunes in sandy rivers, which develop due to increasing sediment loads. In any case, whatever the size of the sediments concerned, the assessment of flood risk can be altered strongly and the hazard increase can lead to unexpected damages.

However, an intense erosion that can reduce the flood hazard can lead to the destruction of the structures (bridges, weirs, etc) that cross the river.
Environmental impacts are also often linked with the transport of fine sediments that are likely to carry pollutants (heavy metals, pesticides, etc). Moreover, by itself, the deposition of fine sediments in areas with gravel bed leads to a decrease of the ecological potentialities.

3. Basic requirements of a 1-D sediment transport model

Most part of the sediment transport occurs during high flows. The flood events should be modelled in a detailed way to assess the main morphological changes. This fact implies that uneven flow modelling should be possible. This unevenness may be connected with the characteristics of the flow linked with the river basin, but also with the evolution of the bed during the flood itself. Coupling of sediment transport modelling and flow modelling are thus necessary, although for engineering studies, the approximation of steady flow can be often used if the flood events last a long time and the bottom evolution is very slow. This point is also due to the difficulties of calibrating a sediment transport model that generally relies on

measurements taken before and after the flood event only. Development of technical devices such as the ones that allow bathymetry measurements during the flood event could be a relevant means to increase accuracy of calibration for very transient processes.
The processes within the river itself could then be followed with both small space and time steps. However, except for solving local questions (for instance around a structure), the main questions remain at the scale of the whole reach of a river (corresponding to the scale of the river basin) for which the river flow can be described by a 1-D model. It implies that, in most cases, a 1-D sediment transport model is the most suitable; it takes into account a smaller set of parameters, which also means simpler calibration.
The parameters specific to sediment transport models should describe both the way of transportation, and the exchange fluxes between the bottom (including the banks) and the flow. The basic distinctions are between bed material load and suspended material load, although in most cases, the models will consider the two separately. The main factor of the bed material load is the sediment transport capacity that will define the maximum sediment discharge that can be transported by the flow in uniform conditions. The methods of assessment of this capacity come from empirical relations that take into account the flow parameters (water depth, velocity, etc) and the sediment parameters (diameters of the various groups, interactions between these groups, etc). However, the main parameters are certainly the bottom shear stress (determined from the flow parameters), the critical shear stress under which no transport will occur (it is assessed from both features of individual sediments), and the organisation of sediments in the bed of the river. The last parameter (specific to 1-D models) is the active width, which is a multiplying factor of the unit sediment discharge, and it corresponds to the width of the cross section on which the transport of sediments is effective.
For the wash load, the interactions with the bottom are very weak and the main parameter is the fall velocity that determines if, relative to the flow behaviour (particularly turbulence), the sediment particle will be deposited.

4. Description of RubarBE software

RubarBE is a one-dimensional sediment transport model that tends to represent the uneven flow and the bed evolution in the case of a bed material load. The set of relations used in the model is as follows:

De Saint Venant equations for water:

(1) $$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q$$

(2) $$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\,\frac{Q^2}{A}\right)+gA\,\frac{\partial z}{\partial x}=-g\,\frac{Q^2}{K^2\,A\,R^{4/3}}+kq\,\frac{Q}{A}$$

in which t is time (s), x streamwise coordinate (m), A is the cross-sectional flow area (m^2), Q is the water discharge (m^3/s), q is the lateral water flow per unit of length (m^2/s), R is the hydraulic radius (m), z is the water surface elevation (m), g is acceleration due to gravity (m/s^2), K is the Manning-Strickler coefficient ($m^{1/3}$/s), β is the coefficient of quantity of movement and k is the ratio between the velocity of the main flow and the axis velocity of the lateral flow.

Equation for conservation of sediment mass (or Exner equation):

(3) $$(1-p)\frac{\partial A_s}{\partial t}+\frac{\partial Q_s}{\partial x}=q_s$$

in which A_s is the bed-material area (m^2), Q_s is sediment discharge (m^3/s), q_s is the lateral sediment flow per unit of length (m^2/s) and p is porosity.

Sediment transport capacity relationship :

First, RubarBE software used the classical relationship that (Meyer-Peter and Müller, 1948) proposed for bed load transport:

(4) $$C_S=\frac{8La\sqrt{g}}{(\rho_s-\rho)\sqrt{\rho}}\left(\rho JR-0.047D_{50}(\rho_s-\rho)\right)^{3/2}$$

in which C_s is the sediment transport capacity (m^3/s), D_{50} is the median diameter of sediment (m), J is the slope friction, La is the active width (m), ρ_s is the density of sediment (kg/m^3) and ρ is the density of water (kg/m^3).

For practical use, this relationship can be modified considering a change in the value of the parameters, particularly the non-dimensional ones: critical shear stress that is set at 0.047 in equation (4) and the multiplying factor of capacity that is set at 8 in equation (4). Other relationships have been also introduced to take into account the cases in which suspended load should also considered: the one proposed by (Bagnold, 1966) and the one proposed by (Engelund and Hansen, 1967).

Spatial lag equation :

(5) $$\frac{\partial Q_s}{\partial x}=\frac{C_s-Q_s}{D_{char}}$$

in which D_{char} is the distance that characterizes the ability of sediment transport to reach the value of the sediment transport capacity. For bed load transport in rivers, this value is generally very short (a few meters), which means that it is shorter than the space step and thus can be neglected.
The method for solving the set of equations is based on several steps. First, de Saint Venant equations are solved by a Godunov type second order finite difference scheme that makes possible the calculation of flow variables even if critical flow appears (Paquier, 1995). Then, the sediment transport capacity is calculated. Solving the spatial lag equation inside a cell is carried out according the

scheme shown on figure 1, which calculates the sediment discharge downstream Qs^{ds} from the upstream sediment discharge Qs^{us}, while distinguishing the sediments that are only transferred (Qs^{tra}) to the ones that are interfering with the sediments previously present in the cell (deposited Qs^{dep} and eroded Qs^{ero}) .

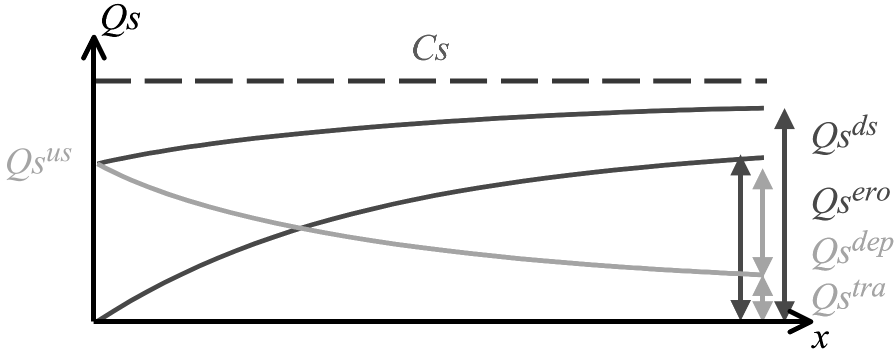

Figure 1. Scheme for spatial lag calculation (Balayn, 2001)

Then the sediment continuity (equation (3)) is applied to every cell on the basis of figure 2. This leads to a change of *As* that should be translated as a change of the shape of the cross section. This change will then change the water level as the hypothesis of no change in the water depth and velocity is applied.
In figure 2, the active layer that corresponds to the sediment that is moving during the time step has its thickness fixed from the sediment transport capacity, the velocity of the flow and the space step. The deposits and erosions occurs when this active layer is respectively too thick or not thick enough.
Thus, inside one cell, a sedimentary compartment corresponds to a set of sediments that have a coherent behaviour and three compartments are defined:
- A compartment M^M of movable sediments: the contents of the water column where particles are moving at one time. We distinguish a compartment M_{am} of input sediments and a compartment M_{av} of output sediments.
- A compartment A of the active layer: a layer near the bed where sediment particles slide or roll at one point during the time step.
- A compartment B of one or several substrate layers: it reflects historical deposition of sediments on the riverbed or undisturbed subsurface. Some of the layers can be created or can disappear.

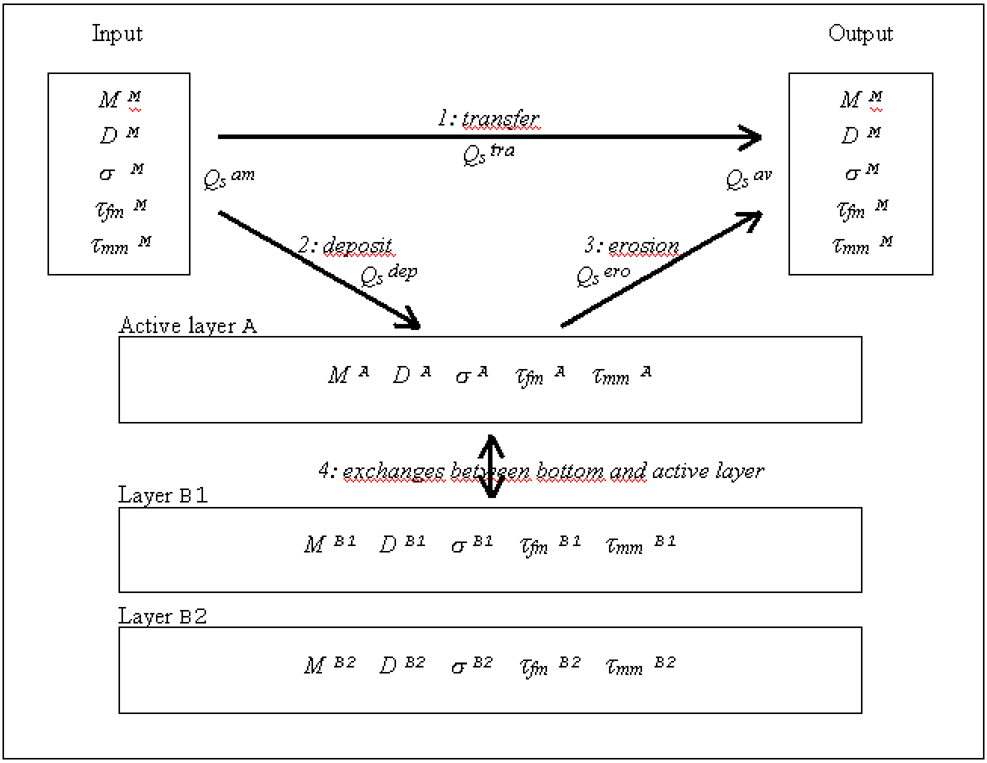

Figure 2 Scheme of distribution of sediments inside one cell (Balayn, 2001)

The simplest one-dimensional models represent sediments only by a mean diameter D_{50}. This simplification clearly does not fully describe the processes that occur in many channels (armouring, presence of mixed sediments of various sizes, etc). Therefore, a complementary parameter was added: the standard deviation σ (defined by the square root of the ratio between D_{84} and D_{16}), which appears convenient to describe grain size distribution in a river for which sediments are homogeneous (Shih and Komar, 1990). Extra parameters of one compartment are the shear stress τ_{mm} at beginning of the movement and τ_{fm} shear stress at the end of the movement. Generally, these two last parameters are set equal and determined from D_{50}. During the phases 1 to 4 of figure 2, sediments are mixed or shared into two fractions of different characteristics. The relations used are specific averages (equations (6), (7) and (8) for respectively the mass, the diameter and the standard deviation).

(6) $$M = M_1 + M_2$$

(7) $$D = D_1^{(M_1/M_1+M_2)} * D_2^{(M_2/M_1+M_2)}$$

(8) $$\sigma = \sigma_1^{(M_1/M_1+M_2)} * \sigma_2^{(M_2/M_1+M_2)}$$

in which indexes 1 and 2 refer to the quantities of sediments that are added to the mixture (no index), *M* is the mass, *D* is the mean diameter and σ is the standard deviation. These relations are the only ones for which addition of once a double mass and addition of twice a unit mass are strictly equivalent.

For sharing, the diameter D_2 of the coarser sediment can be calculated from a relation as (9) introducing an additional parameter *C*, the expression of which is still to be determined. Although various relations were tested (Palussière, 2002) it was concluded that stable and realistic results for *C* were less than 0.1. The standard deviation σ_2 can be calculated from (10) in order to keep D_{84}.

(9) $$D_2 = D^*\left(1 + C(\sigma - 1)\right)$$

(10) $$\sigma_2 = \sigma \frac{D}{D_2}$$

For the change of the shape of the cross section, various alternatives were tested:
- in the case of erosion, the entire movable bed under water lowers uniformly, sometimes also in areas not suffering erosion;
- in the case of deposition, either, the volume of deposited sediment is spread across the channel width, starting from the bottom, or the deposits are identical for all the points below the water.
- more complicated types of evolution have been also developed by using a calculation of local shear stress called the Merged Perpendicular method (Khodashenas and Paquier, 1999); some of these methods make possible erosion and deposition at the same time in one cross section. Applied to the River Rhône, preliminary calculations show the necessity to integrate also the curvature of the river and the local critical shear stresses that explain a large part of the variability inside the cross section (Paquier and Khodashenas, 2002).

5. The example of lower Isère river

The case concerns a 3 kilometres long stretch of the River Isère immediately upstream of the junction between the Isère and the canalised reach of the River Rhône (Fig. 3). The downstream boundary is the water level upstream from the regulation dam. This water level is lowered only during floods. Because of such conditions, a huge volume of sediments (about 650 000 m3) has deposited in the downstream part of the river. The question was: will these deposits be flushed during a high flood? If not, the calculation of water levels shows that the banks and may be the roads could be overflowed.

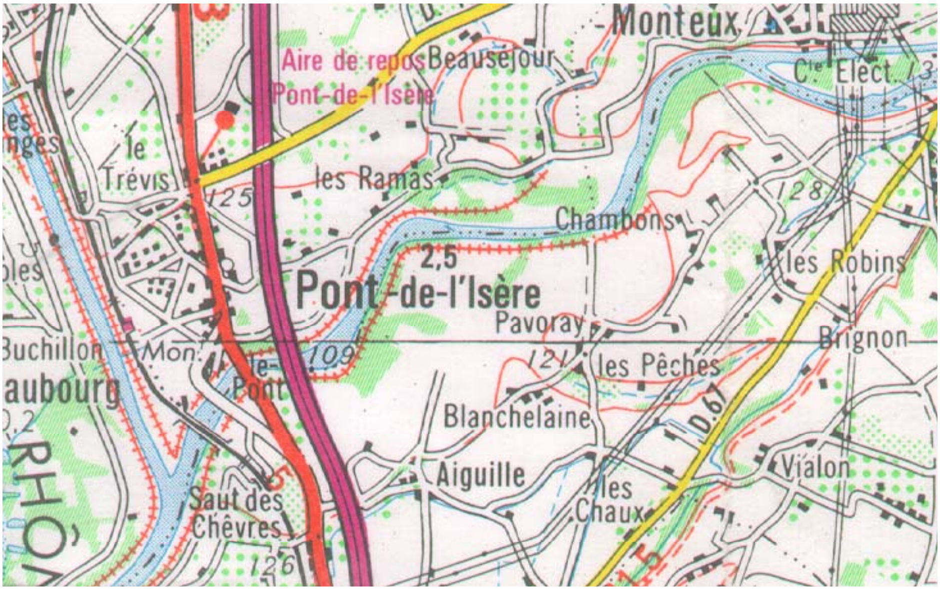

Figure 3 Situation map of lower Isère River. The modelled reach was between Chambons and the junction.

To obtain information about what might happen, a laboratory model was built by the CNR (National Company of Rhône) at scale of 1:100 with the sediments represented by maize powder of density equal to 1.04 and diameter of 0.4 mm. The volume of flushed sediments was measured in eight short sections of the river in the downstream area. From these laboratory tests, it appears (CNR, 1999) that for both the 100 year and the 1000 year floods, the sediments are strongly removed during the beginning of the water increase, so that the water levels will remain relatively low.

To confirm this conclusion, RubarBE software was used, but at the field scale (Balayn, 2001), not at the scale of the laboratory. This was because an adaptation of the numerical model should have been necessary and would not have proved the validity of the results at the field scale. Thus, actual diameter of the sediments of 0.32 mm and density equal to 2.6 were used. From the cross sections measured in 1995 (not far from present topography), a topographical model of the river bed was built. Initial cross sections, and some other ones interpolated to reach a space step of about 50 metres (maximum: 100 m), were used for the 1-D calculations.

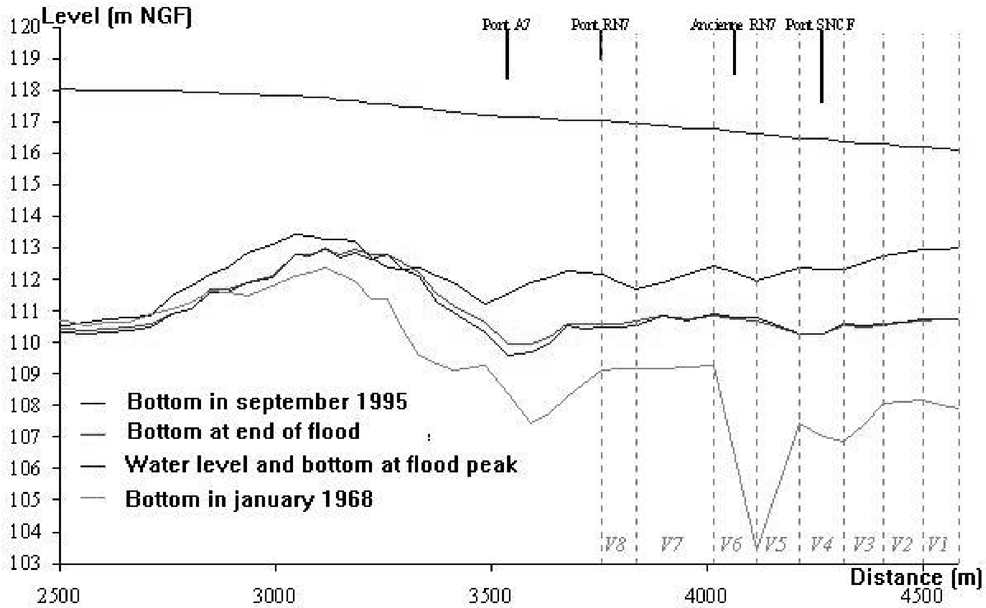

Figure 4 Calibration of the model on the 1000 year flood (Balayn, 2001)

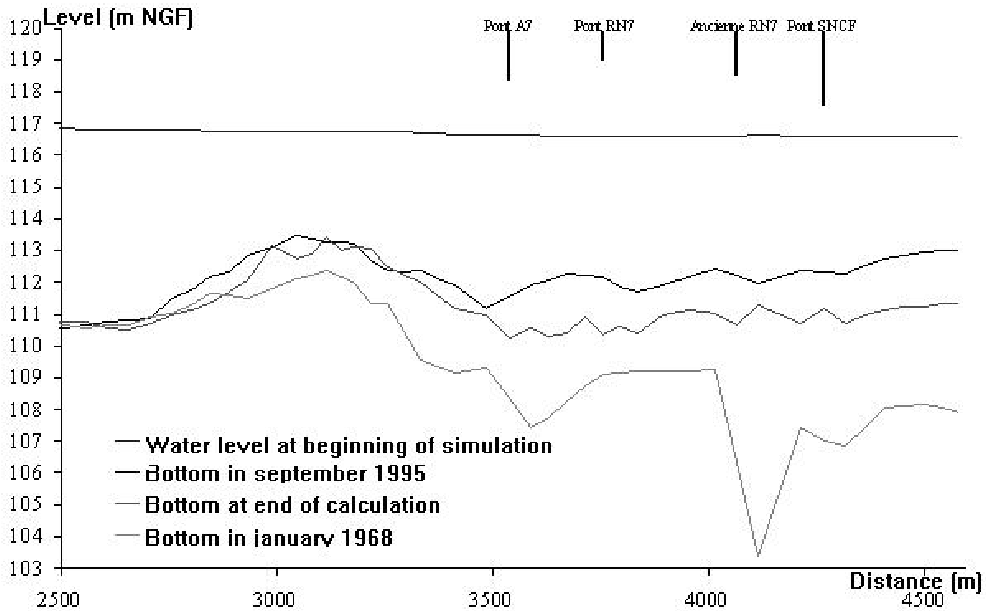

Figure 5 Comparison of the deposition process during the period 1968-1995 (Balayn, 2001)