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# MORPHODYNAMIC MATHEMATICAL MODEL FOR NON-UNIFORM GRAIN-SIZE SEDIMENTS: AN APPLICATION TO THE EXCEPTIONAL FLOOD EVENT OF 1987 IN THE MALLERO RIVER (ITALY)

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## ABSTRACT

This work deals with the mathematical modeling of morphological processes in rivers with non-uniform grain-size materials. In particular, the onedimensional morphodynamic model here presented is intended to be used at relatively large space scale, and for both short and long-term morphological calculations. The model is particulary appropriate for numerical simulations of sudden overaggradation and eventual inundation of mountain rivers when large amounts of sediments are fed into the river by landslides and debris flow. Water flow equations are solved together with the sediment equations in a quasi-coupled way by means of a predictor-corrector scheme. The *predictor* step was carried out with FTBS (Forward Time Backward Space) scheme while the *corrector* step was performed with a Four Points scheme. The model was successfully applied to reconstruct the exceptional flood event of 1987 in the Mallero river (Central Alps, Northern Italy) and the influence of morphological changes on flood wave propagation characteristics for this particular case was also investigated.

## INTRODUCTION

Flooding in mountain rivers, during exceptional rainfall events, are often related to extremely large inputs of sediments from landslides and debris flow, followed by sudden deposition along the hydrographic network and consequent bank overflowing.

In order to simulate correctly the overaggradation phenomena during such catastrophic events appropriate mathematical models are needed which, as for any morphological model, the governing equations should adequately describe both the water flow and the sediment dynamics, with due considerations for peculiarities of mountain streams.

In contrast to the large lowland rivers, mountain streams are generally part of a dense hydrographic network, with extremely variable, both in time and space, hydrological, morphological and sedimentological characteristics. Moreover, the sediments present in the bed and in the input material are both strongly non-uniform. On the other hand, even excluding the farthest and steepest branches of the network, mountain streams always have relatively large slopes: as a consequence, the flow in a given reach is basically controlled only by the characteristics of the reach itself (no backwater effects). In addition, although the flow pattern at small space scale is highly non-uniform, i.e., the flow locally alternates into subcritical and supercritical states, in a relatively long reach, let say of the order of magnitude of the bottom width , the average flow condition is quite well represented by a quasi uniform flow. This generally allows, from one side, to represent each reach by its averaged geometric characteristics and global roughness parameters, and on the other hand, to apply a simplified description of the fluid motion assuming uniform flow for each reach.

The present work describes a morphodynamic mathematical model for non-uniform grain-size sediments which is intended to be used for computations at relatively

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large space scale and for both short and long-term calculations. The mathematical model here presented is based on the two layers model described by Di Silvio and Peviani (1991), in which water discharge as a function of space and time was considered to be known, for the entire simulation period, before starting with the morphological calculations. In the present model the water flow equations are solved together with the sediment equations in a quasi-coupled way by means of a predictor-corrector scheme. The model is applied to simulate the exceptional flood event of 1987 in the Mallero river (Central Alps, Northern Italy) and the influence of morphological changes in flood wave propagation characteristics is also investigated.

**MATHEMATICAL MODEL**

Many mathematical models have been proposed for the simulation of onedimensional evolution of rivers with non-uniform grain-size sediments (Ribberink, 1987; Armanini & Di Silvio, 1989; Basile, 1994), all these models are based on the momentum and mass continuity for water and sediment continuity of each granulometric class. The set of equations of the present two-phase mathematical model is:

**i) Liquid phase: Kinematic Wave Model (KWM)**

Neglecting inertia and pressure differential terms in the dynamic equation for unsteady gradually varied flow in open channels and then combining it with the continuity equation we obtain:

$$\frac{\partial Q}{\partial t} + c_w \frac{\partial Q}{\partial x} = c_w q_l \qquad (1)$$

in which $Q$ is the water discharge (m$^3$/s), $q_l$ is the input lateral water discharge per unit lenght (m$^2$/s) and $c_w$ is the kinematic wave celerity (m/s) which is equal to (Cunge et al., 1980; Miller,1984):

$$c_w = \left.\frac{\partial Q}{\partial A}\right|_x \qquad (2)$$

where water discharge $Q$ is expressed by the Manning-Strickler equation:

$$Q = K_s A R^{2/3} S_f^{1/2} \qquad (3)$$

in which $A$ is the wetted area (m$^2$), $R$ is the hydraulic radius (m), $S_f$ is the friction slope and $K_s$ is the Strickler's coefficient related to grain roughness (m$^{1/3}$/s), which is calculated by means of the following expression:

$$K_s = \frac{26}{d_{90}^{1/6}} \qquad (4)$$

where $d_{90}$ is the diameter present in the bed for which 90 % of the material is finer (m). It is important to stress that $K_s$ is allowed to vary through time and space as bed material composition adjust during simulated morphology evolution of the river. The KWM is appropriated to simulate flood propagation in mountain rivers (Bellos et al., 1995).

The solution $Q(x,t)$ of eq. (1) in the domain $x_o<x<x_L$ requires one initial value $Q(x,0)$ at each point of the domain and one boundary condition $Q(x_o,t)$.

### ii) Solid phase: Two Layers Model

Mass balance for each granulometric class taking into account two layers: the *transport layer*, containing particles transported in suspension and as bed load and the *mixing layer* containing particles instantaneously at rest but susceptible to vertical movements to and from the *transport layer*. The equations for the i-th granulometric class are:

- **Sediment continuity in the transport layer** (including porosity):

$$BD_i + \frac{\partial T_i}{\partial x} = g_i \tag{5}$$

in which $B$ is the bottom width (m), $D_i$ is the deposition rate of the i-th class (m/s), $T_i$ is the total sediment transport for the i-th class ($m^3/s$) and $g_i$ is the input lateral sediment discharge per unit length for the i-th class ($m^2/s$).

- **Vertical sediment balance in the mixing layer:**

$$\frac{\partial(\delta\beta_i)}{\partial t} + \beta_i^* \left(\frac{\partial z_b}{\partial t} - \frac{\partial \delta}{\partial t}\right) = D_i \tag{6}$$

where $\delta$ is the mixing layer thickness (m), $\beta_i$ is the fraction of the i-th class in the mixing layer, $z_b$ is the bottom level (m) and $\beta_i^*$ is:

$$\beta_i^* = \begin{cases} \beta_i \Leftrightarrow \dfrac{\partial z_b}{\partial t} > 0 \;\; (deposition) \\ \beta_{u_i} \Leftrightarrow \dfrac{\partial z_b}{\partial t} < 0 \;\; (erosion) \end{cases} \tag{7}$$

where $\beta u_i$ is the fraction of the i-th class in the undisturbed material located below the mixing layer.

It is interesting to note that summing up all the grain-size classes in eq. (6) we obtain the temporal bed elevation changes which is equal to the net deposition rate:

$$\frac{\partial z_b}{\partial t} = \sum_{i=1}^{4} D_i \tag{8}$$

in the absence of bedforms, the mixing layer thickness $\delta$ may be taken equal to twice the size of the largest particles, say:

$$\delta = 2d_{90} \tag{9}$$

- **Sediment transport equation:**

The sediment transport of each class is computed as a function of the local hydrodynamic and sedimentological parameters by means of the following equation:

$$T_i = \alpha \frac{Q^m I^n}{B^p d_i^q} \beta_i \zeta_i \tag{10}$$

eq. (10) is the formula of Di Silvio (1983); adapted to the computation of sediment transport of non-uniform grain-size materials. It is done by introducing the corresponding fraction of the i-th class present in the streambed $\beta_i$, and a "hiding and exposure" coefficient that accounts for the smaller (higher) mobility of finer (coarser) particles in a mixture, compared to the mobility of the same particles in a uniform grain-size material (Parker et al., 1982). This coefficient can be expressed as follows:

$$\zeta_i = \left(\frac{d_i}{d_m}\right)^s \tag{11}$$

in which $d_m$ is the arithmetic mean diameter:

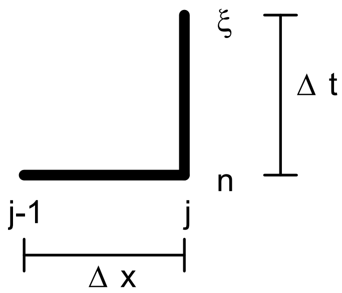
$$d_m = \sum_{i=1}^{4} \beta_i d_i \tag{12}$$

In addition, the simplified eqns. of L.Van Rijn (1984) and the formula of Engelund & Hansen (1967), were also included in the sediment transport module of the model. These formulas were also adapted to the computation of sediment transport of heterogeneous sediments by modifing the solid transport of each class in the same way as described for the equation of Di Silvio (1983).

**NUMERICAL MODEL**

The set of equations of the two-phase mathematical model was solved numerically using a finite difference approximation. A predictor-corrector method was used. The predictor step was performed with a FTBS (Forward Time Backward Space) scheme, while the corrector step was carried out with a Four-Points scheme.

- **Predictor step:**




In the predictor step the time and space derivatives of the water discharge are approximated in the following way:

$$\frac{\partial Q}{\partial t} = \frac{Q_j^{\xi} - Q_j^{n}}{\Delta t} \tag{13}$$

$$\frac{\partial Q}{\partial x} = \frac{Q_j^{n} - Q_{j-1}^{n}}{\Delta x} \tag{14}$$

while the sediment continuity equation in the transport layer is solved by means of the following difference equation:

$$D_{ij}^{\xi} = \frac{1}{B_j \Delta x}\left(T_{ij-1}^{n} - T_{ij}^{n} + G_{ij}^{n}\right) \tag{15}$$

the difference eqn. for the temporal bed level is given by:

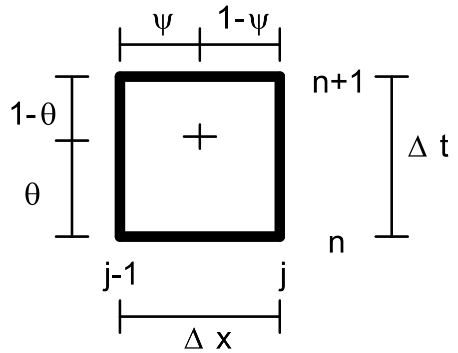
$$\frac{z_{b_j}^{\xi} - z_{b_j}^{n}}{\Delta t} = \sum_{i=1}^{4} D_{ij}^{\xi} \tag{16}$$

and the vertical sediment balance in the mixing layer is discretized in the following manner:

$$\frac{\delta_j^{n}\left(\beta_{ij}^{\xi} - \beta_{ij}^{n}\right)}{\Delta t} = D_{ij}^{\xi} - \beta_{ij}^{*}\sum_{i=1}^{4} D_{ij}^{\xi} \tag{17}$$

it is noted that in the predictor step the mixing layer thickness in equation (17) is considered constant.

- **Corrector step:**




In the corrector step the time and space derivatives of the water discharge are approximated in the following way:

$$\frac{\partial Q}{\partial t} = \frac{\psi\left(Q_j^{n+1} - Q_j^n\right) + (1-\psi)\left(Q_{j-1}^{n+1} - Q_{j-1}^n\right)}{\Delta t} \tag{18}$$

$$\frac{\partial Q}{\partial x} = \frac{\theta\left(Q_j^{n+1} - Q_{j-1}^{n+1}\right) + (1-\theta)\left(Q_j^n - Q_{j-1}^n\right)}{\Delta x} \tag{19}$$

celerity $c_W$, weighted in space and time, is expressed as follows:

$$c_{w_j}^{n+1} = \theta\left[\psi c_{w\,j}^{\ \xi} + (1-\psi) c_{w\,j-1}^{\ \xi}\right] + (1-\theta)\left[\psi c_{w\,j}^{\ n} + (1-\psi) c_{w\,j-1}^{\ n}\right] \tag{20}$$

while the sediment continuity equation in the transport layer is solved with the following difference equation:

$$D_{ij}^{n+1} = \frac{1}{B_j \Delta x}\left[(1-\theta)\left(T_{ij-1}^n - T_{ij}^n + G_{ij}^n\right) + \theta\left(T_{ij-1}^{\xi} - T_{ij}^{\xi} + G_{ij}^{n+1}\right)\right] \tag{21}$$

the difference equation for the temporal bed level changes is written as follows:

$$\frac{z_{b_j}^{n+1} - z_{b_j}^{n}}{\Delta t} = \sum_{i=1}^{4} D_{ij}^{n+1} \tag{22}$$

and the difference equation for the vertical sediment balance in the mixing layer is given by:

$$\frac{\left(\delta\beta_i\right)_j^{n+1} - \left(\delta\beta_i\right)_j^{n}}{\Delta t} = D_{ij}^{n+1} - \beta_{ij}^{*}\left[\sum_{i=1}^{4} D_{ij}^{n+1} - \frac{\left(\delta_j^{n+1} - \delta_j^{n}\right)}{\Delta t}\right] \tag{23}$$

**STABILITY CONDITION AND TIME STEP SIZE ADJUSTMENT**

In the morphodynamic model the choice of the time step size Δt is subject to Courant-Friedrichs-Lewy (CFL) stability constraint:

$$\Delta t = \sigma \frac{\Delta x}{c_{\max}} \tag{24}$$

where $0 < \sigma \leq 1$ and $c_{max}$ is the maximum celerity at a relevant time step:

$$c_{\max} = \max\left\{ c_w, c_{\beta_i}, c_{z_b} \right\} \tag{25}$$

in expression (25) $c_w$ is the celerity related to the flow which is given by the following equation:

$$c_w = \frac{5}{3} u \tag{26}$$

while $c_{\beta i}$ is the celerity associated to a disturbance in the bed material composition of the i-th class which can be expressed as follows:

$$c_{\beta_i} = \frac{T_i}{\delta B}\left(\frac{1}{\beta_i} - s\zeta_i^{1/s}\right) \tag{27}$$

and $c_{zb}$ is the celerity related to a disturbance in the bed level which is given by the following equation:

$$c_{z_b} = \sum_{i=1}^{4} c_{\beta_i}\left[\left(D_i \Big/ \sum_{i=1}^{4} D_i\right) - \beta_i\right] \tag{28}$$

In order to avoid numerical diffussion and phase error the constant σ in eq. (24) is generally set to values close to unity.

**LATERAL SEDIMENT INPUTS AND INTERNAL BOUNDARY CONDITIONS**

In the model the lateral sediment inputs from tributaries and the internal boundary conditions can be represented in different ways depending upon the kind of processes to be simulated. These can be briefly described as follows:

- Tributary conveying material as ordinary sediment transport:

  In this case the sediment transported by the water flow before the landslide event is computed (by the transport equation) with the local hydrodynamic and sedimentological characteristics of the final reach of the tributary.

- Tributary conveying material from a nearby landslide as extraordinary sediment transport:

  - In this case, to compute the sediment input as a function of the tributary water discharge it is assumed that the bed material composition of the tributary (slope less than 10-15 %), immediately after the landslide event, changes to that of the landslide material and remain that until the total volume is transported by the flow.
  - It is possible however to consider the input of a debris flow (tributary slope greater than 15-20 %) by changing the composition of the riverbed to that of the debris material and by assuming a constant debris flow velocity entering the main stream.

  In both cases the landslide material composition and volume as well as the time of occurrence and the locations of the landslide events must be known before starting with the morphological calculations.

- In mountain rivers reaches with fixed rocky bottom are usually encountered along the main streams, in this case erosion cannot progress below the rocky bottom and the sediment load coming from upstream is transferred to the downstream reaches.

**LONG-TERM MATHEMATICAL MODEL**

To run the morphodynamic model described in the previous sections boundary and initial conditions are required. While topographical and hydrologic information can be obtained through maps and rainfall records, associated with a rainfall-runoff model, it is almost impossible to have the grain size distribution of bed material previous to the exceptional event for the entire length of the river. If these data are available in the upper part of the river, the ordinary annual transport feeding the main stream and the bed material composition along the river can be calculated by using a long-term model. In fact, the application of the long-term model will reconstruct the composition of the bed material in the main stream under the ordinary flow condition, to be checked against the available data.

The mathematical model for the long-time scale processes is described by the same set of equations presented in section 2, except for the sediment transport equation which in this case is given by:

$$T_{i_{year}} = \frac{\alpha}{m} \frac{Q_o^{m-1} V_o I^n}{B^p d_i^q} \beta_i \zeta_i \tag{29}$$

where $Q_o$ and $V_o$ are the annual ordinary maximum discharge ($m^3$/s) and the annual ordinary runoff volume ($m^3$/year) respectively, computed from the available hydrologic data. Eq. (29) is obtained by integrating Eq. (10) over a period of one year or more, and by assuming an exponential duration curve for the water discharge and seasonal-compensated variations in bed material composition and bed levels during ordinary years (Di Silvio, 1983).

**OVERAGGRADATION PHENOMENA AND INUNDATION RISK IN MOUNTAIN RIVERS: THE CASE STUDY OF MALLERO RIVER**

## General description of the basin and the event of July 1987

The Mallero river is a tributary of the Adda river which is the main stream of Valtellina, in the central Alpine region of Northern Italy (see Fig. 1). The Mallero river is 24 km long, starting at the elevation of 1636 m (m.s.l.) from the confluence of the Vazzeda and the Ventina torrents, and ending at the elevation of 282 m on its confluence with the Adda river. The surface of its basin is approximately 319 $km^2$.

There are several urban settlements along the river. Sondrio near the confluence with the Adda river is the most important. The Valtellina region has always been, as has been known since the Middle Age as a place where severe storms accompanied by landslides and overaggradation have occurred.

An exceptional event produced enormous disasters in Valtellina in July 1987. Particularly, in the Mallero river basin several landslides occurred with a total volume of several millions cubic meters. This material reaching the stream and transported by the water flow was deposited in many places producing bottom overaggradation of several meters with consequent increase of water levels and flooding due to bank overflowing. A detailed study of the area was performed after the event, including the location of the landslides and an evaluation of volumes and granulometric composition of the slided material. A general survey of the Mallero river after the event, with an estimate of volumes of deposed and eroded material was also carried out.

## Application of the mathematical model

The event of July 1987 has been simulated by applying the mathematical model described previously. A schematization of the model set-up is shown in Fig. 2.

- **Reconstruction of bed material composition: long-term model**

The long-term model is used to determine bed material composition along the river under ordinary flow conditions. This result was used as the initial condition for the subsequent simulation of the exceptional flood event.

The input of water from each tributary is given by the annual ordinary maximum discharge ($Q_o$), computed for each sub-basin following the relation of the square root of the areas, and by the annual ordinary runoff volume ($V_o$), also calculated for each sub-basin following the relation of the areas. The estimated values at Sondrio are $Q_o$=162 $m^3/s$ and $V_o$=332 $*10^6$ $m^3$.

The input of sediments from each tributary is computed using the morphological characteristics (slope and width) and the ordinary bed material composition in its terminal reach, i.e before their confluence with the main stream; these quantities should be known. For the Mallero river morphological data are also introduced. As initial granulometric distribution of the bed material an arbitrary value is used. The long-term model is run until the equilibrium grain-size distribution is reached.

The values of the coefficients used in the sediment transport formula are $\alpha$=0.025, $m$=1.8, $n$=2.1, $p$=0.8, $q$=1.2 and $s$=0.8. In Figures 3, 4 and 5 the comparison between calculated and observed bed material composition at different locations is presented. After 5 years of ordinary flow events the river reaches a dynamic equilibrium and an acceptable agreement is observed between computed and measured bed material composition.

- **Numerical simulation of the exceptional flood event:**

The exceptional event of July 1987 was subsequently simulated by the numerical model. Inputs of water and sediment as a function of time during the event are the necessary boundary conditions. The hydrographs at the downstream end of each tributary were computed by applying a rainfall-runoff model of the rational method type (Di Silvio, 1989). The hydrographs corresponding to each tributary are presented in Figures 6 and 7.

The input volumes and the granulometric distribution of the landslide material as well as the position and sliding time are presented in Table 1. The full event is simulated, from Friday 17th (at 6 p.m) till Sunday 19th (at 8 p.m.).

The space step size was set equal to $\Delta$x=250 m and the values of $\theta$ and $\psi$ were equal to 0.6 and 0.5 respectively. The calibration of the model leads to the selection of the correct values of the coefficients $\alpha$ and $s$ of the sediment transport formula, these were equal to $\alpha$=0.05 and $s$=0.8.

Figure 8 shows the calculated time and space evolution of the bottom level referred to the initial one, while in Figure 9 the corresponding calculated time and space evolution of the bed material composition (class 1, $d_1$=0.316 mm) is presented.

In Figures 10 and 11 the time evolution of both bed aggradation and water level at Sondrio in two different positions are presented. It is observed the sudden overaggradation that takes place approximately 1h:15min. after the landslide event of the Torreggio torrent. In addition, is clearly observed that the time evolution of water levels at Sondrio is basically controlled by the overaggradation process of the river bed and not by the water discharge. Notably, there is a lag of 1h:20min. between the transit of the peak discharge and the maximum water level immediately downstream of Garibaldi Bridge (Sondrio, distance:+22.25 km from upstream boundary).

In Figures 12, 13, 14 and 15 the space evolution along Sondrio of bed aggradation and water level is presented for four different times. In particular, Figure 15 shows the good agreement between calculated and observed bed aggradation in some specific points.

In addition, the influence of morphological changes on flood wave propagation characteristics was investigated by comparing the hydrographs calculated without including the morphological changes (fixed bed propagation) and those obtained by including them (movable bed propagation).

The calculated hydrographs by means of both approaches are compared in Figures 16 (Distance + 10 km) and 17 (Distance +19 km). The comparison shows not significant differences between them.

**CONCLUSIONS**

The main goal of the present work was to improve and calibrate a morphodynamic mathematical model for non-uniform grain-size sediments. The model presented is appropriate for numerical simulations of sudden overaggradation and eventual inundation of mountain rivers when large amounts of sediments are fed into the river by landslides and debris flow.

The model was successfully applied to reconstruct the exceptional flood event of 1987 in the Mallero river. In particular, was clearly observed that the temporal evolution of water level at Sondrio city was basically controlled by the overaggradation process of the riverbed and not by the water discharge.

In addition, the influence of morphological changes on flood wave propagation characteristics was investigated by comparing the hydrographs calculated without including the morphological changes (fixed bed propagation) and those obtained by including them (movable bed propagation). The calculated hydrographs by means of both approaches (fixed and movable bed flow calculations) are almost identical. This shows that in this particular case the flood wave propagation characteristics are not significantly influenced by the induced morphological changes.

**ACKNOWLEDGEMENTS**

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Table 1: Characteristics of the input landslide material to the Mallero river in the model simulation.

| **Section (grid point number)** | $\beta_i$ (%)(*) 1 | 2 | 3 | 4 | **Volume ($m^3$)** | **Sliding time (s)** |
|---|---|---|---|---|---|---|
| 0 | 37 | 21 | 26 | 16 | 1000000 | 57600 |
| 39 | 39 | 27 | 24 | 10 | 270000 | 82800 |
| 58 | 22 | 17 | 37 | 24 | 600000 | 90000 |
| 59 | 26 | 24 | 41 | 9 | 230000 | 82800 |
| 77 | 16 | 21 | 27 | 36 | 210000 | 82800 |
| 78 | 18 | 23 | 31 | 28 | 50000 | 82800 |

(*) $d_i$=0.316 mm, 3.16 mm, 31.6 mm, 316 mm (i=1, 2, 3, 4)

Table 2: Comparison between calculated and measured volumes of sediment deposition (Vsd).

| Reach (km) | Nomination | Vsd ($m^3$) Calculated | Measured |
|---|---|---|---|
| 0.00 to 1.25 | Lupo | 160000 | (*) |
| 3.00 to 3.90 | Alpe Senevedo | 61000 | 47000 |
| 4.25 to 5.00 | Sabbionaccio | 120000 | 180000 |
| 10.00 to 10.70 | Cosi Battani | 110000 | (*) |
| 14.50 to 16.80 | Torre/Spriana | 500000 | 550000 |
| 19.50 to 20.25 | Arquino | 140000 | (*) |
| 21.50 to 24.00 | Ponchiera/Sondrio | 360000 | 350000 |

(*) not measured

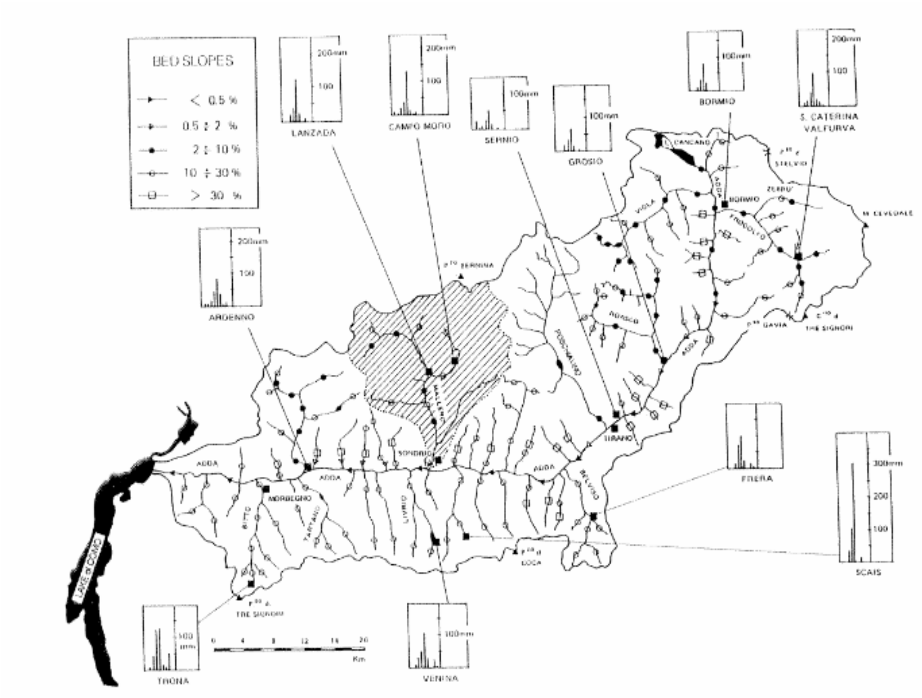


Figure 1: Location of the torrent Mallero in Valtellina (Central Alps) in Northen Italy.


Figure 2: Basin of the torrent Mallero and model schematization.

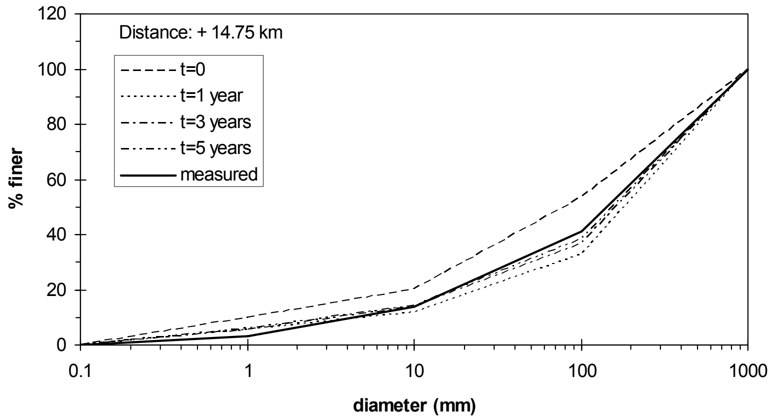


Figure 3: Comparison between calculated and measured granulometric distributions of bed material at distance14.75 km from the upstream boundary.

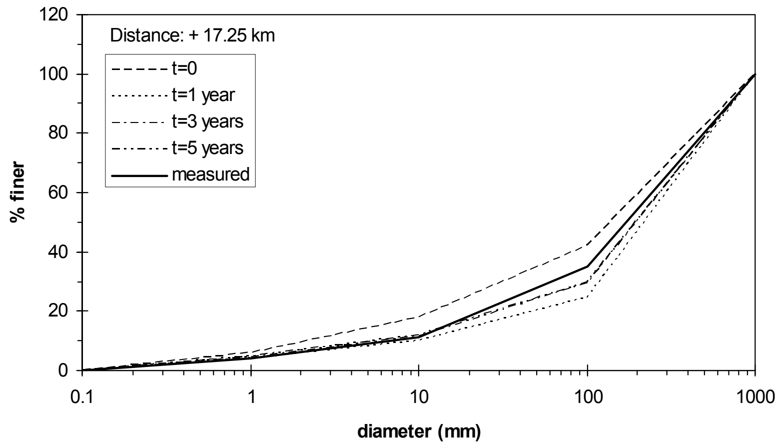


Figure 4: Comparison between calculated and measured granulometric distributions of bed material at distance 17.25 km from the upstream boundary.

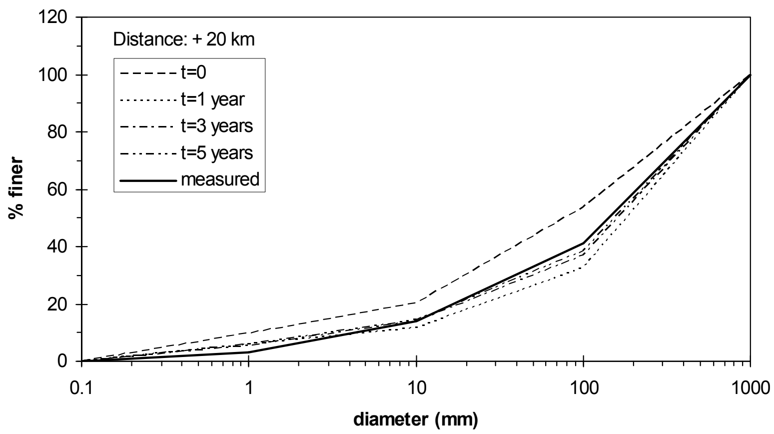


Figure 5: Comparison between calculated and measured granulometric distributions of bed material at distance 20 km from the upstream boundary.

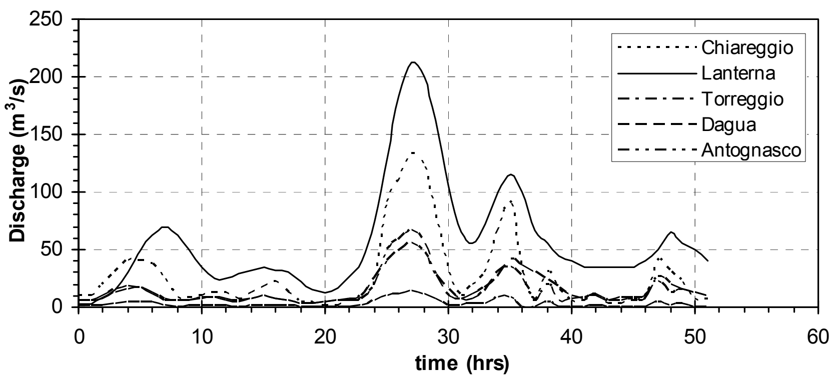


Figure 6: Hydrographs corresponding to the tributaries of the torrent Mallero from torrents Chiareggio to Antognasco.

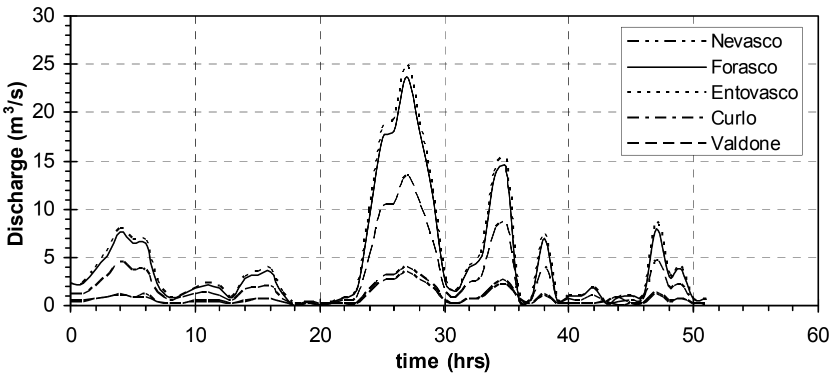


Figure 7: Hydrographs corresponding to the tributaries of the torrent Mallero from torrents Nevasco to Valdone.

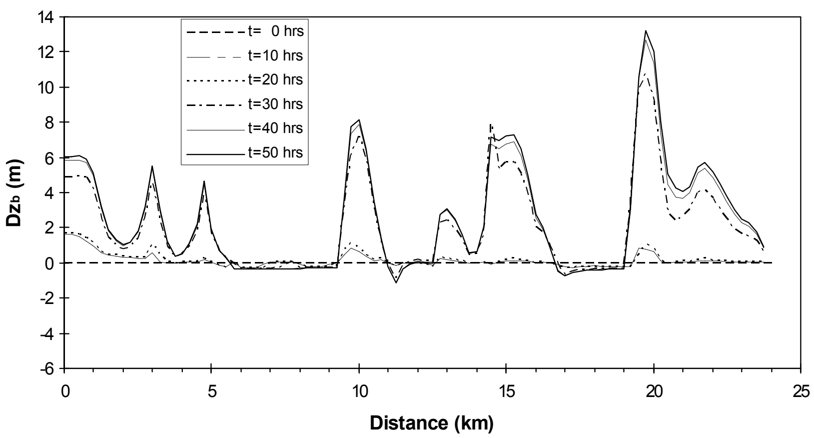


Figure 8: Time and space evolution of bottom level referred to the initial one.

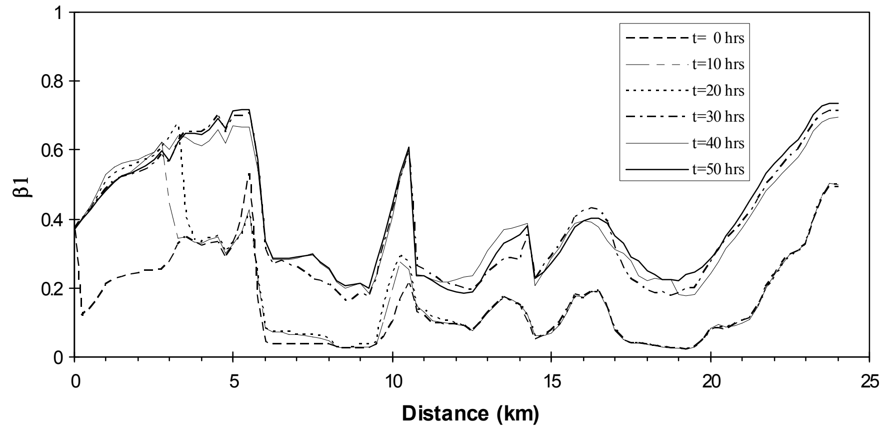


Figure 9: Time and space evolution of bed material composition (class 1, $d_1$=0.316 mm).

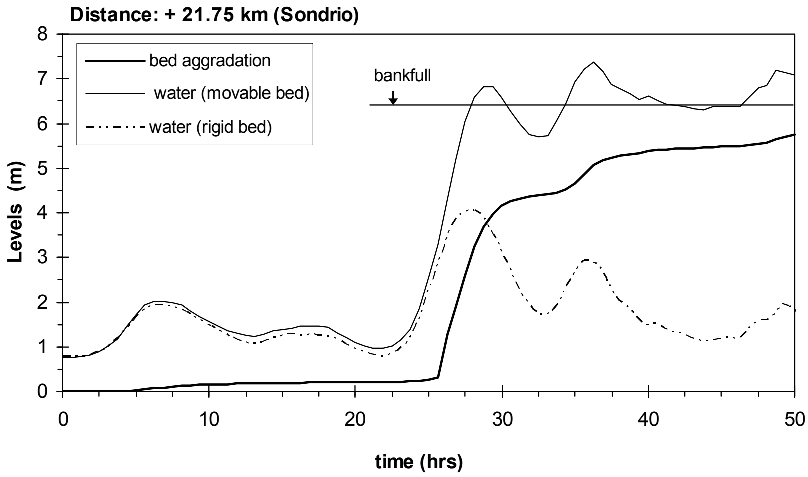


Figure 10: Time evolution of calculated bed aggradation and water level at Sondrio (walking-pass, distance 21.75 km).

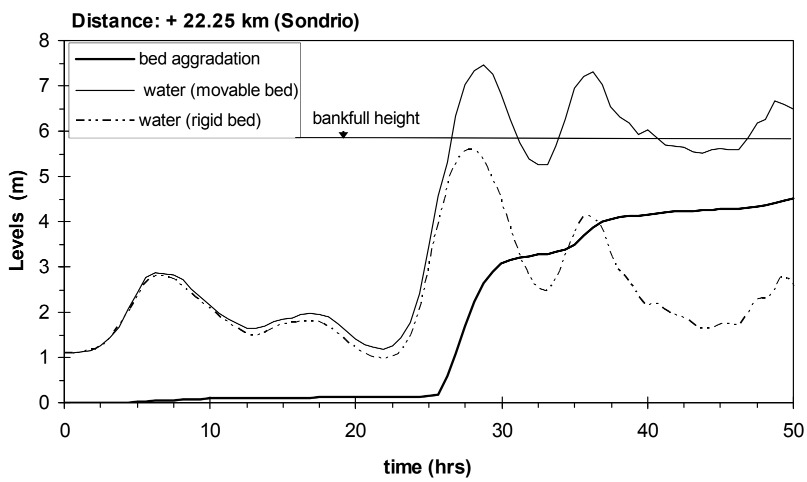


Figure 11: Time evolution of calculated bed aggradation and water level at Sondrio (downstream of Garibaldi bridge, distance 22.25 km).

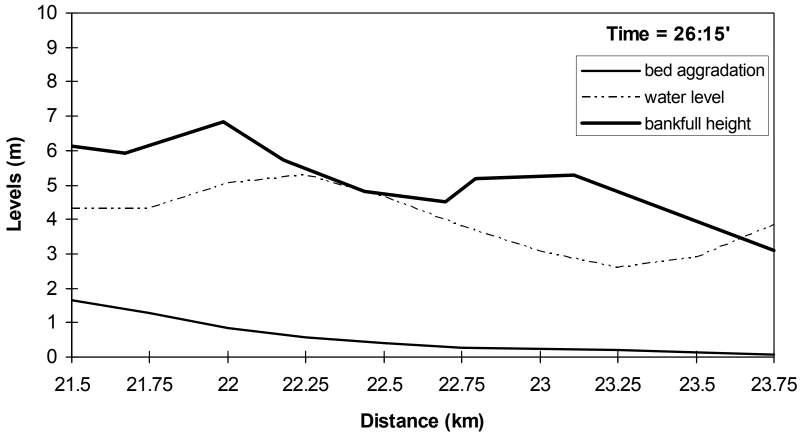


Figure 12: Space evolution of calculated bottom aggradation and water level at time 26:15' in Sondrio city.

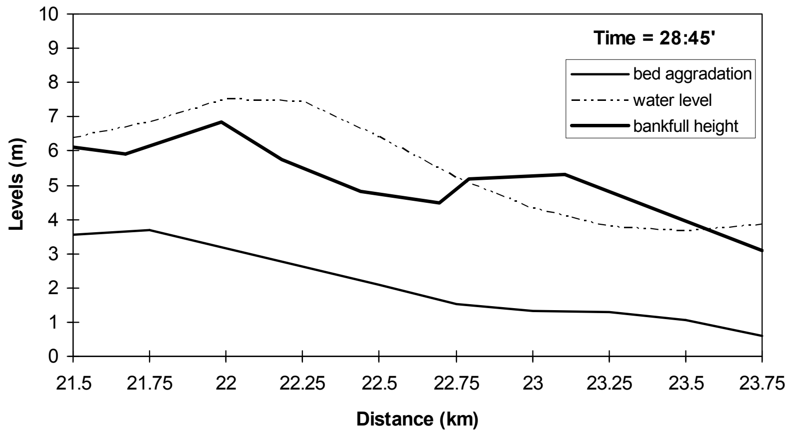


Figure 13: Space evolution of calculated bottom aggradation and water level at time 28:45' in Sondrio city.

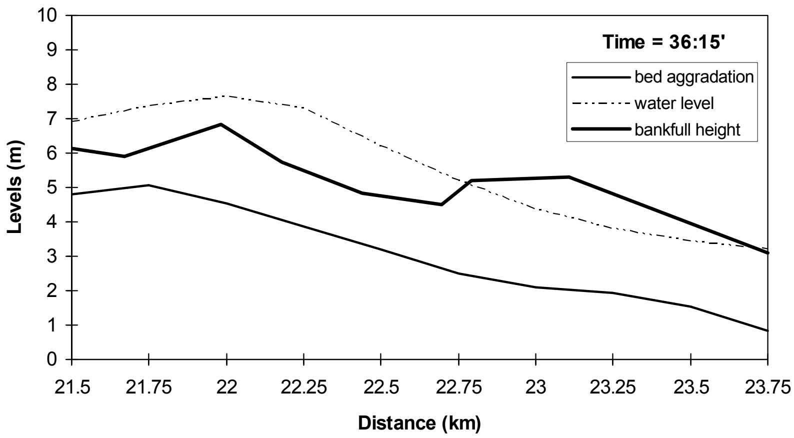


Figure 14: Space evolution of calculated bottom aggradation and water level at time 36:15' in Sondrio city.

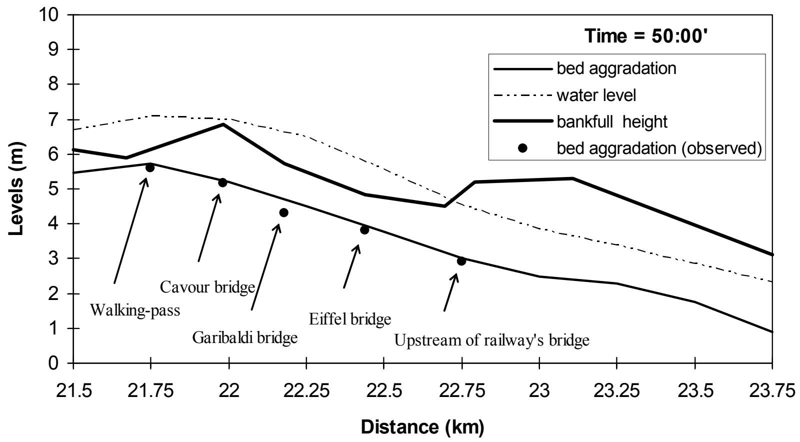


Figure 15: Space evolution of calculated bottom aggradation and water level at time 50:00' (Sondrio, Sunday 19th of July 1987, 8 p.m).

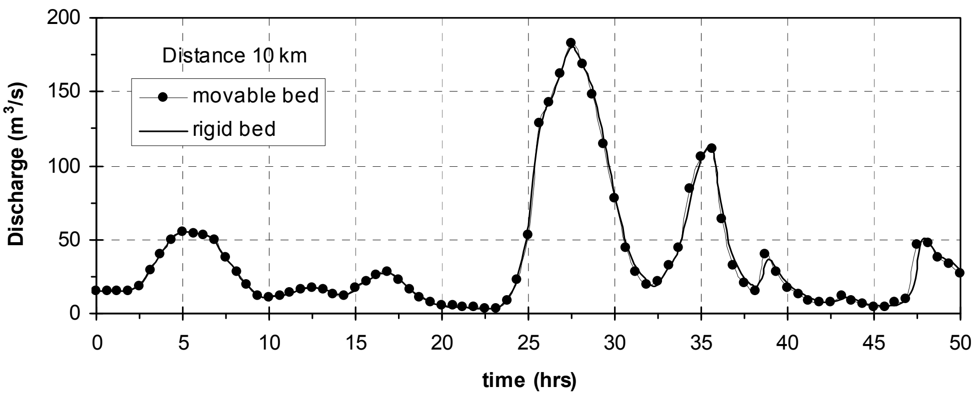


Figure 16: Comparison between calculated hydrographs by means of fixed bed propagation and movable bed propagation at distance 10 km from the upstream boundary.

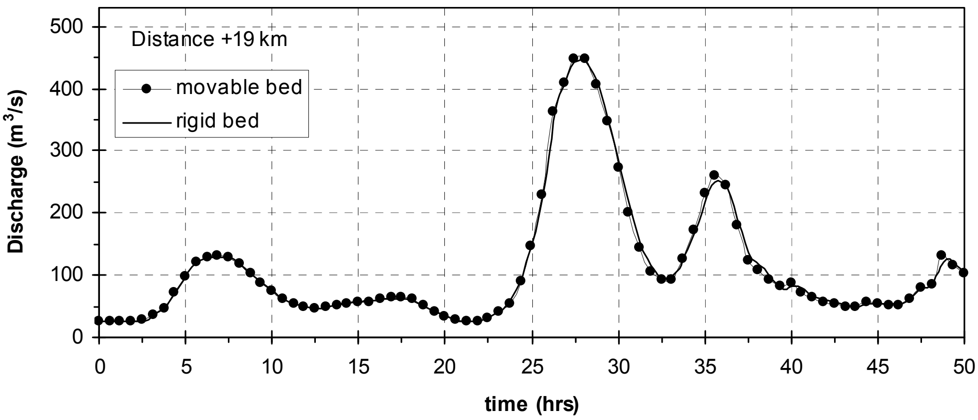


Figure 17: Comparison between calculated hydrographs by means of fixed bed propagation and movable bed propagation at distance 15 km from the upstream boundary.