# DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

**DETAILED REPORT OF CONTRACTOR FOR**

SECOND ANNUAL REPORT

**University of Padova, Italy**

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# DETAILED REPORT OF CONTRACTOR
# FOR SECOND ANNUAL REPORT

CONTRACTOR: UNIVERSITY OF PADOVA, DEPARTMENT OF LAND AND AGRO-FOREST ENVIRONMENT – WATER RESOURCES DIVISION

RESPONSIBLE SCIENTIST: PROF. MARIO A. LENZI

ADDRESS: AGRIPOLIS, VIA ROMEA, 35020 LEGNARO (ITALY)

TELEPHONE: ++39-049-8272675
FAX: ++39-049-8272686
E-MAIL: marioaristide.lenzi@unipd.it



## Section 3.1: Objectives of the reporting period (01/03/2001-28/02/2002)

According to the proposed work programme for DAMOCLES project the research team of the University of Padova (Mario A. Lenzi, Vincenzo D'Agostino, Carlo Gregoretti, Diego Sonda, Alberto Guarnieri, Francesco Comiti e Luca Mao) had the following objectives included in the workpackge WP3 "Development of a small basin debris flow impact model" and WP5 "Dissemination of the project deliverables".

- Development's improvement and preliminary validation of the 1-D sub-model to the Rio Lenzi main channel.
- Development of the 2-D sub-model for debris flow propagation and sedimentation on the fan area.
- Integration of 1-D and 2-D sub-models within a GIS system (Debris Flow Impact Model)
- Interactions with CSIC-IPE , IGME team (Spain) to confirm a test site for the U Padova model on the Pyrenees.
- Interactions with U Milan-Bicocca for the organization of Damocles Training Courses for September 2002.

## Section 3.2: Methodology and Scientific Achievements Related to Work Packages

***3.2.1 WP3 "Development of a small basin debris flow impact model":***

In the previous report (first year) the general setting out of the 1-D sub-model for debris flow routing has been described. The work carried out during the reporting period 01/03/2001 – 28/02/2002 has dealt with the following topics:

**1-D sub-model (MODDS)**

A. Capability of the model to routing an arbitrary form of the debris flow wave;
B. Automatic control of the stability condition of Courant and time interval of computation;
C. Assessing the algorithm for simulating the overflow from the banks;
D. Capability to simulate the flow super-elevation due to bends;
E. Capability to insert a one span bridge in correspondence to each cross-sections;
F. Model sensitivity of both bed slope and non-dimensional Chèzy coefficient variations;
G. Comparison of MODDS and DAMBRK soubrouting for non-Newtonian fluid simulations.

**2-D sub-model (DDPM)**

H. Development of the 2-D sub-model for debris flow propagation on the fan area

**Debris Flow Impact Model (DEFLIMO)**

I. Integration of the 1-D, 2-D sub-models and fan DTM within a GIS system.

**Field visit to Benasques Valley (Spain)**

### 3.2.1 WP3 "Development of a small basin debris flow impact model":

**1-D sub-model (MODDS)**

**Arbitrary debris flow hydrograph**

The simulation of the debris flow routing by assuming a simplified triangular-shaped debris flow graph is a suitable hypothesis for testing the “hydraulic” behaviour of a channelized debris flow. Nevertheless such scenario may not be adequate in the case of debris flow waves with very steep rising stage, i.e. a debris flow triggered by a dam-break phenomenon. In addition, especially for muddy debris flow, hyperconcentrated flow and flows caused by landslides fluidification, the event may have a longer duration and present a series of surges (VanDine, 1996). The improvements carried out to MODDS allow to model these situations by using up to 50 data for describing the debris flow graph.

**Courant condition**

The first version of MODDS needed the selection of a fixed time step of computation ($\Delta t$). The $\Delta t$ adopted was usually 5 s or even less (1 s) if the results showed a marked instability. In order to avoid that end-users must check the numerical behaviour of the model, an automatic adjustment for the computation time has been implemented. Further, when channel boundaries change very abruptly, i.e. when a bridge is present, the end-user can operate the channel description by using some cross-sections with a reduced interdistance ($\Delta x$). In such a case the Courant and Friedrich (1948) condition for explicit finite difference scheme requires the wave celerity ($a$) to be less or equal to the numerical celerity of computation ($\Delta x/\Delta t$) (Chaudry, 1993). Observed front velocities ($V$) range from 0.5 to 20 m $s^{-1}$ (Costa, 1984); nevertheless the limit of $6 \div 7$ m $s^{-1}$ is rarely exceeded in the fan area. By taking $V$ =7 m $s^{-1}$, a minimal required time step is : $\Delta t \cong \Delta x/10$. For preventing superfluous time of computation, the $\Delta t$ set initially for the computation is automatically reduced only when required by Courant’s condition. The computed results are recorded and stored by MODDS only for the $\Delta t$ originally selected by the user.

**Overflow algorithms**

The model can run choosing between these two options:

I. routing simulation in a confined channel for which the overflow is not allowed (point 10 and 11 of fig. 1 are inserted);
II. routing simulation for the actual channel geometry and capability to estimate the overflow.

Some preliminary tests have been conducted for assessing an appropriate algorithm for the overflow computation from the right and/or left bank when the debris flow wave is higher than the $Z$ coordinate of point 7 (fig.1) and/or the $Z$ coordinate of point 8. The basic assumption was that the stage-discharge relationship for diverting a part of the debris flow follows the hydraulic law of a broad-crested weir. According to this hypothesis the right overbank discharge (fig.1) can be computed as follows:

$$Q_{OVER} = C_q \sqrt{2\ g}\ [(\overline{h - Z_7})^{1.5}\ L_R\ + (\overline{h - Z_8})^{1.5} L_S\,] \qquad (1)$$

where $C_q$ is the pertinent coefficient of discharge; $L_R$ and $L_S$ are the bank lengths upstream of the current cross-section ($n$) where the overflow occurs; $(\overline{h - Z_7})$ and $(\overline{h - Z_8})$ are the related debris flow heads above the bank computed by averaging the head value along $L_R$ and $L_S$ respectively.

This unique hypothesis proved to be unable to divert a physically appropriate discharge. In fact, when the water head above a bank increases and eq.1 is applied, the residue discharge ($Q_D$) flowing downstream along the main channel become too small respect to the maximum capacity of the cross-section (excessive discharge is diverted). This gap has been solved adopting a combination of controls while computing the section *n*:

1. An appropriate coefficient of discharge can be chosen ($C_q \cong 0.3 \div .0.4$ for eq.1 in metric units);
2. For each channel cross-section we estimate the maximum allowable discharge ($Q_{ALLOW}$) before overflow occurs; this value corresponds to the minimum debris flow stage between $Z_7$ and $Z_8$;
3. The stage of the flow in the current cross-section is temporarily set equal to that of the run in the confined simulation; $(\overline{h - Z_7})$, $(\overline{h - Z_8})$ and a tentative $Q_{OVER}$ are computed.
4. Downstream "confined" discharge ($Q_D$) is step by step reduced until eq.1 and the mass conservation along the reach (sections *n-1; n*) is respected.
5. $Q_{ALLOW}$ for current cross-section (*n*) and for upstream (*n-1*) section are compared: the minimum value between two is termed $Q_{MIN}$.
6. If, during step 4, it occurs that $Q_D < Q_{MIN}$, $Q_D$ is set equal to $Q_{MIN}$ , then mass conservation is applied for $Q_{OVER}$ evaluation and eq.1 for the debris flow profile upstream of the cross-section.

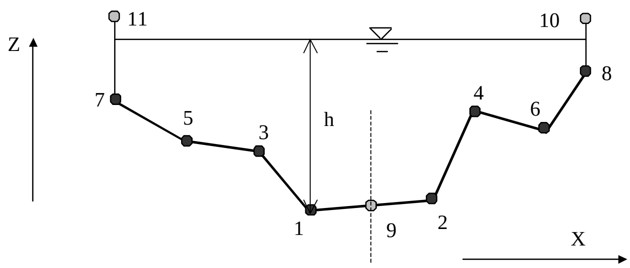



**Fig. 1 – Sketch of the cross-section implemented in MODDS model**

The adopted path of computation does not consider the possible clogging of the current cross-section imputable to coarse woody debris and big boulders stopping. The algorithm assumes that the channel uses its maximum conveyance before the overflow occurs. A scenario relative to obstructions in part of the channel can be modelled simply by modifying the original geometry of competent cross-sections.

## Bendings

An estimate of super-elevation is required to determine the height of a debris flow on the outside bend of a curve. The model predicts overelevation ($\Delta H$) using a forced vortex equation as outlined by Hungr et al. (1984), Chen (1987) and others. The used expression is:

$$\Delta H = k\ \frac{B\,V^2}{R\ g} \qquad (2)$$

$b$= surface width of flow; $V$= mean flow velocity; $R$=mean radius of curvature; $g$= acceleration due to gravity.

The constant $k$ is equal to 1 for water (Ven Te Chow, 1959) and is related to viscosity and vertical sorting that exists in debris flow; in the last case $k$ varies between 1 and 5. (VanDine, 1996). A slight cautionary hypothesis has been introduced in MODDS, by keeping the inside level in the curve equal to the straight

channel value and assigning $\Delta H$ as difference in height between the central axis of the cross-section and the outside. A positive or negative input *R* value means that curve is in direction of the hydrographic right or left respectively; zero *R* value means a straight reach (radius of curvature tends in the true to infinity).
If super-elevation causes overflow, the computation starts from super-elevation for a confined flow and find, iteratively, a congruent solution according to the algorithm adopted for the overflowing.

**Bridge**
The presence of bridges is one of the most frequent cause of diversion in the lower part of debris flow torrents. Checking and designing the stream cross-section in correspondence of road crossing is a pressing demand coming from local Authorities (torrent control and public safety). In debris flow torrents of European Alps, adoption of bridges with intermed piles is out of any reasonable use. The typical road crossing presents abutment near to the banks and an unique span (reinforced concrete slab or series of wood or steel beams). The bridge schematisation inserted in the MOODS model is presented in figure 2. For any cross-section used for describing the channel geometry the superimposition of bridge is possible. Each bridge has to be described with three data: positions of the lower point of the beam in correspondence of the right and left bank (codes of points of fig.1 are necessary: i.e. 1 or 3 or 5 or 7 for the right ), thickness *s* (fig.2) of the bridge. The assumption in MODDS is to change the stage-discharge relationship - normally used in the Muskingum-Cunge computation (uniform flow) - if the flow surface is greater or equal to $Z_c$ (*Z* coordinate of point *c* in fig.2). The adopted scheme is that of a flow under a gate with the head ($h_B$) computed as distance between the flow surface and the centroid of the liquid area ($A_B$) below the bridge. In first approximation the discharge (*Q*) is given by:

$$Q = C_{B1}\ A_B\ \sqrt{2\ g\ h_B} \qquad (3)$$

where the discharge coefficient $C_{B1}$ can be set by the user ($C_B$ = 0.4÷0.6). In addition, when the stage is higher than *Z* coordinate of point *d* (fig.2), the flow over the bridge appears and it is computed by way a broad crested weir equation: $C_{B2}$ is the related coefficient of discharge selectable by the user. If the debris flow stage during computation is over $Z_7$ and/or $Z_8$ , then overflow is also active using the algorithm previously described.

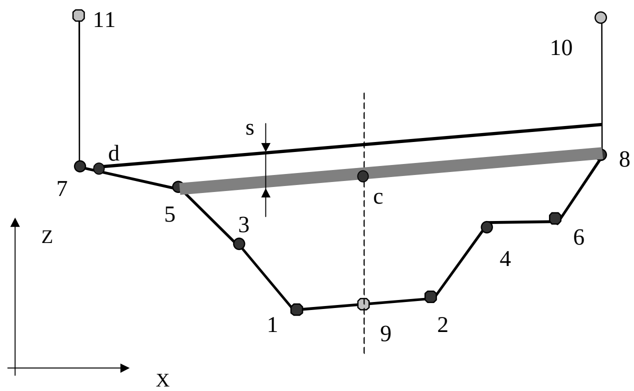



**Fig. 2 – Sketch of a cross-section with a one span bridge**

**Example of application**
A double peak entering debris-flow wave is taken into consideration: the first peak occurs after 150 s (discharge *Q*=70 $m^3\ s^{-1}$) after the beginning of the flood. Tab. 1 illustrates the pattern of the flood. The channel under simulation is rectangular, 150 m long and 6 m width; its slope is 10% and its roughness, in terms of the dimensionless Chezy coefficient, equal to 2. Cross-sections used for describing the channel are 25 m equally spaced. From cross section n.1 (progressive *x*=0 m) to section n. 3 (*x*=50 m) the banks (vertical walls) have an height of 4 m above the bottom. From section 5 to section 7 the walls are 3 m high. In section n. 4 the right of bank have a difference of 1 m in height and a bridge (*s*=1) in points 5 and 6 is superimposed (fig. 3).

| | | | |
|---|---|---|---|
| $t$=0 s | $Q$=2 $m^3$ $s^{-1}$ | $t$=750 s | $Q$=40 $m^3$ $s^{-1}$ |
| $t$=150 s | $Q$=70 $m^3$ $s^{-1}$ | $t$=900 s | $Q$=20 $m^3$ $s^{-1}$ |
| $t$=650 s | $Q$=2 $m^3$ $s^{-1}$ | $t$=1100 s | $Q$=2 $m^3$ $s^{-1}$ |

**Tab. 1 – Debris flow wave routed by the MODDS model**

The results of the simulation are summarised in figure 4 (flow rate and depths above the bottom) and can be comment on as follows:

- The highest simulated peak values of the discharge is at the limit of the conduction capacity for the section from 1 to 3: a first overflow occurs ($x$=25 m) for both right and left bank; the initial triangular shaped hydrograph assumes a flatter form;
- When the flow encounters the bridge a second larger overflow occurs mainly on the right bank ($x$=75 m); the depths in section 4 remain almost constant for the whole overflow duration and the discharge hydrograph in the last cross-section $x$=150 m is markedly reduced;
- When the second peak hydrograph passes trough the bridge the stage remain at the limit of overflowing: the stage hydrograph increases quickly for a gate controlled flow but maintains the "peak-like" form. (see $x$=75 m second wave of fig. 4).

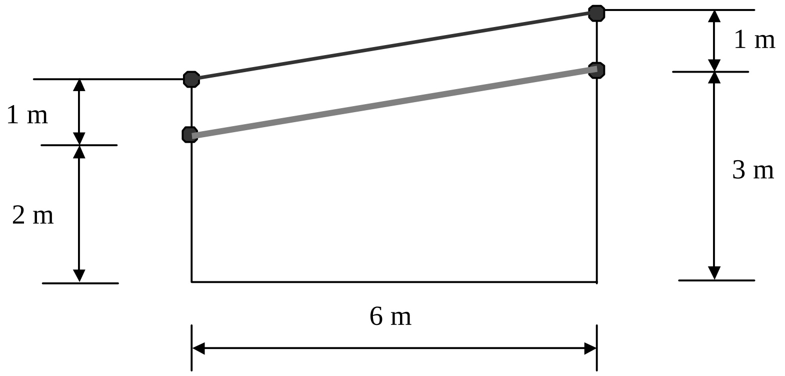



**Fig. 3 – Cross-section n. 4 in correspondence of the bridge ($x$=75 m)**

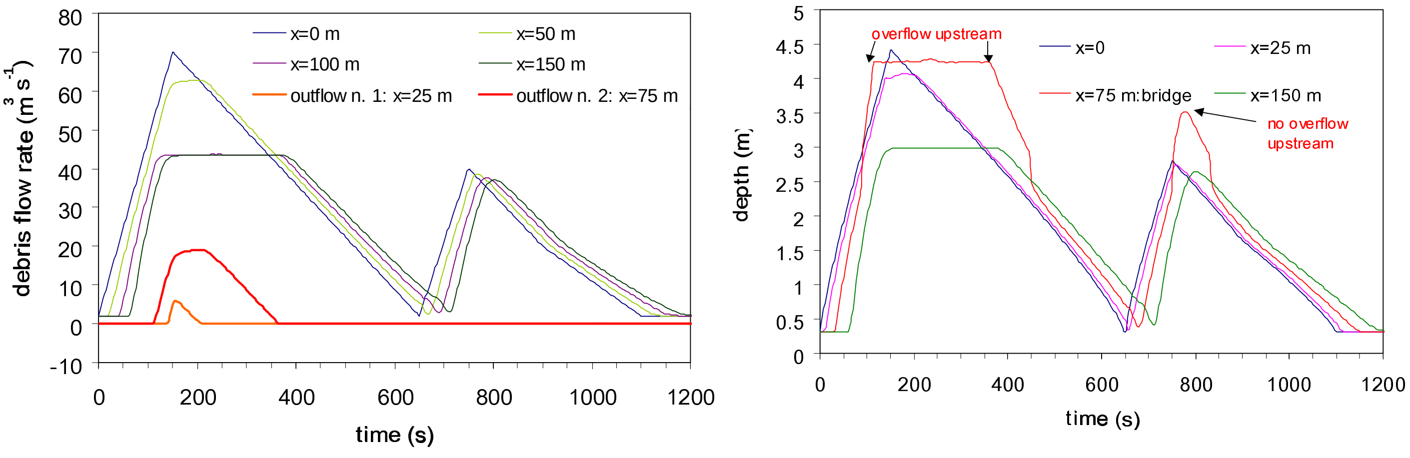



**Fig. 4 – Discharge hydrograph routing results and stage hydrograph routing results**

**MODDS sensibility test (respect to channel gradient)**

Sensibility tests have been conducted to evaluate the behavior of MODDS related to channel variations. A single peak entering debris-flow wave has been tested: debris-flow peak of 200 $m^3$/s occurs after 60 seconds the flood initiation and reaches zero after 240 seconds.

The adopted channel is 150 m long and it has a rectangular cross-section, 3 m height and 6 m width. Its roughness, in terms of the dimensionless Chezy coefficient, was hypothesized equal to 2. Seven cross sections equally spaced 25 m were used for reach representation. The test was performed by changing the bottom slope and maintaining constant the channel geometry and the inflow hydrograph.

The sensibility test have pointed out a lower limit of applicability of the model, outside which the application is discouraged. This limit could be associated to a value of bed slow of 4.5%. Below it the convective-diffusive equation, on which MODDS is based, decays. Several slope simulation was developed; two of this corresponding respectively to 3 and 7.5% are presented in Fig. 5.

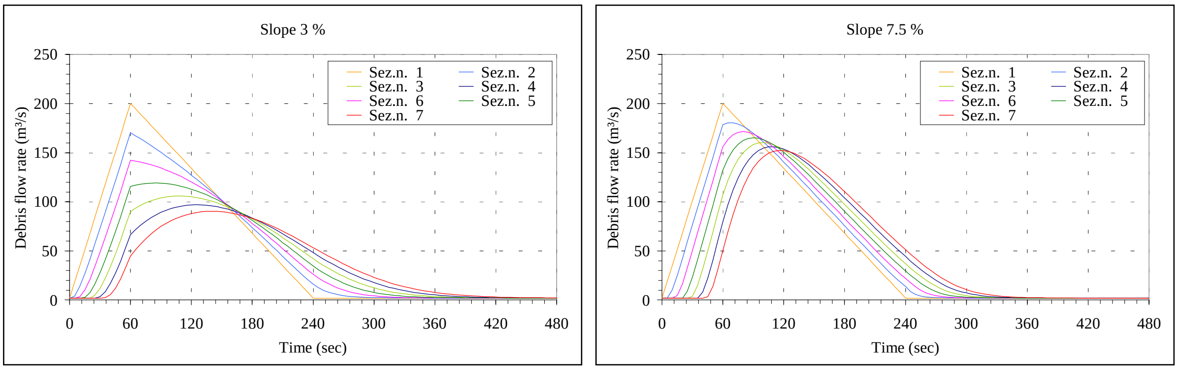



**Fig. 5 – Example of slope simulations**

High slopes inhibit the peak attenuation and maintain the sharp form of the initial hydrograph. For slopes lower than 5% the attenuation is not reliable and differs markedly from the complete 1-D dynamic solution. Considering cross-section section n. 7, located at the downstream end of the channel, fig. 6 represents the peak values associated to different slopes. Peak variation is also presented in percentages terms.

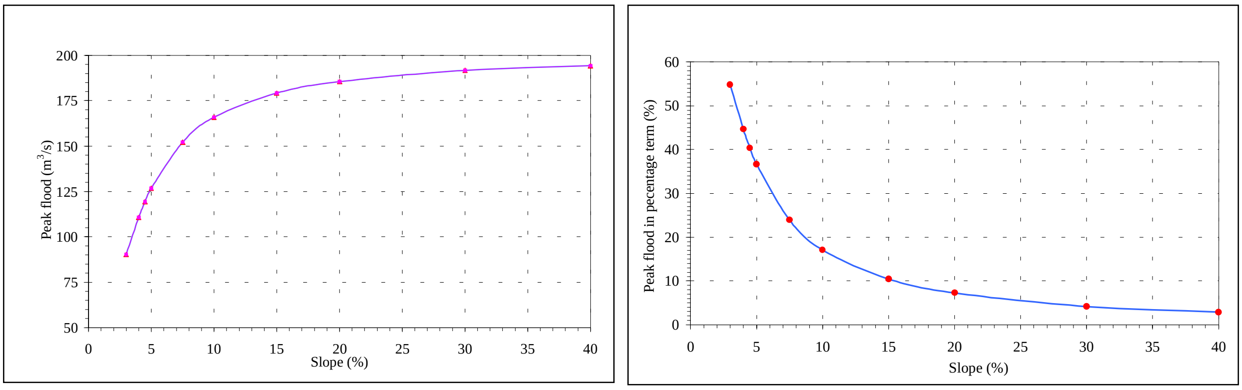



**Fig. 6 – Final cross section: peak flood debris-flood variation (in m$^3$/s and %) versus bed slope.**

Model limitation for milder slopes is also evident if we analyze the mass conservation. Fig. 7 shows a loose of total (water plus sediment) volume higher than 10% for channel slope lower than 5%.
Considering the uncertainties associated to a debris-flow routing scenario, volume losses are acceptable till 15% of the volume of the entering debris-graph.

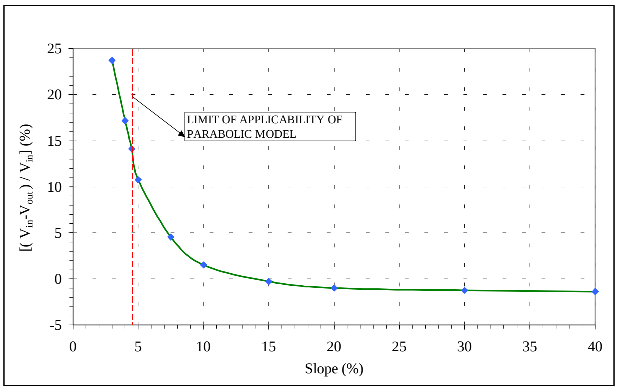



**Fig. 7 –Model limitation in relation to bed slope.**

**MODDS sensibility test (respect to dimensionless Chezy coefficient)**

A debris flow wave has been routed by assuming the peak ($Q=120\ m^3/s$) occurs 125 s after the flood initiation. Sensibility tests of MODDS Model respect to the dimensionless Chezy coefficient was carried out for the final 558 m. reach of the Lenzi stream. Tests takes into consideration a unique solid hydrograph and dimensionless Chezy roughness ranging from 2 to 9. Graphics results are summarized in fig. 8: effects of roughness variation is evident in terms of debris-hydrograph pattern and peak attenuation. In fact, smother waves correspond to lower Chezy coefficients and peak discharge for the cross-section n. 40 increases about 12% (from 106 to 119 $m^3/s$) when roughness increases from 2 to 9.

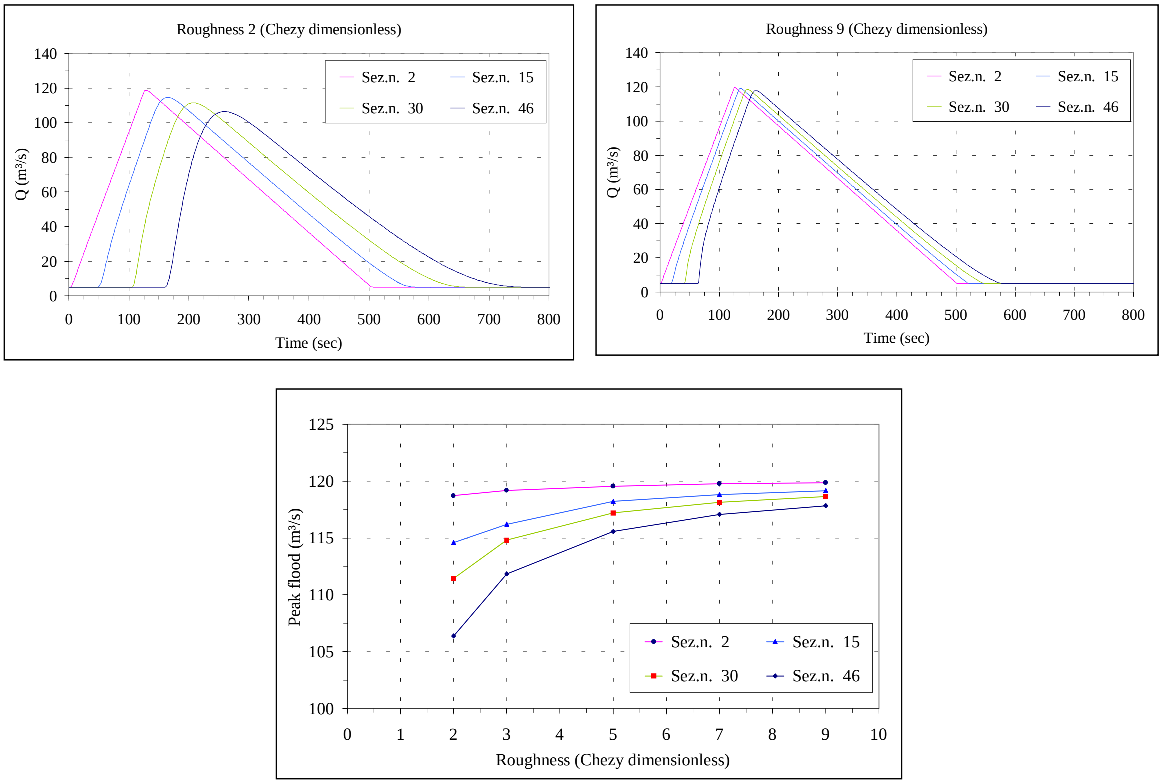



**Fig. 8 – Dimensionless Chezy coefficient simulation.**

**Comparison between MODDS and DAMBRK soubrouting for non-Newtonian fluid simulations**

Dambrk is a model for routing one-dimensional water or mud/debris flows (Fread, 1993). The model uses the St. Venant equations expressed in conservative form with additional terms for non-Newtonian flow. Derived from principles of viscous flow, the shear stress $\tau_s$ was expressed as a power function of the non-Newtonian fluid's stress rate of strain (*dv/dy*) relation:

$$\tau_s = \tau_0 + \kappa * (dv/dy)^{1/\eta} \qquad (4)$$

in which $\tau_0$ is the initial shear strength, $\kappa$ is the dynamic viscosity and $\eta$ is an exponent of the power-law component of the shear stress (when $\eta$=1 the equation represents a Bingham fluid). Debris-flows surges have been simulated in order to compare DAMBRK with MODDS. The followings DAMBRK parameters have been adopted: $\eta=1$; $\tau_0=50\ N/m^2$; unit weight $\gamma=18000\ N/m^3$. In relation to the dynamic viscosity two test have been carried out for $\kappa=100\ N\ s/m^3$ and $\kappa=1000\ Ns/m^3$ respectively. Runs were implemented for the 558 meters reach of the Rio Lenzi flowing on the fan. The main channel is described by means of 46 cross-sections. Simulated debris flow waves have the peak after 125 s the beginning of the flood (discharge $Q=120m^3/s$). Both MODDS and DAMBRK were implemented with a constant Manning roughness of 0.2 $m^{-1//3}$ s. Figure 9 shows the computed discharge hydrographs at four locations along the Rio Lenzi reach (cross section number 2, 15, 30 and 46; x=12,82 m; x=170,03 m; x=368,99 m and x=558,86 m). Main results of the comparison between two models are summarized in figure 10. In the case of a dynamic viscosity $\kappa=1000\ Ns/m^3$ the behaviour of MODDS and DAMBRK is almost superimposable in terms of routed debris-graphs. The comparative analysis also shows that times of peak arrival are in good agreement (Fig. 10).

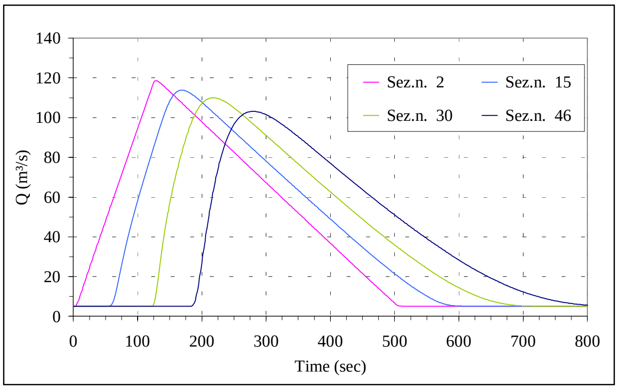



**Fig.9– Computed discharge hydrograph at four cross section along the reach of Rio Lenzi.**

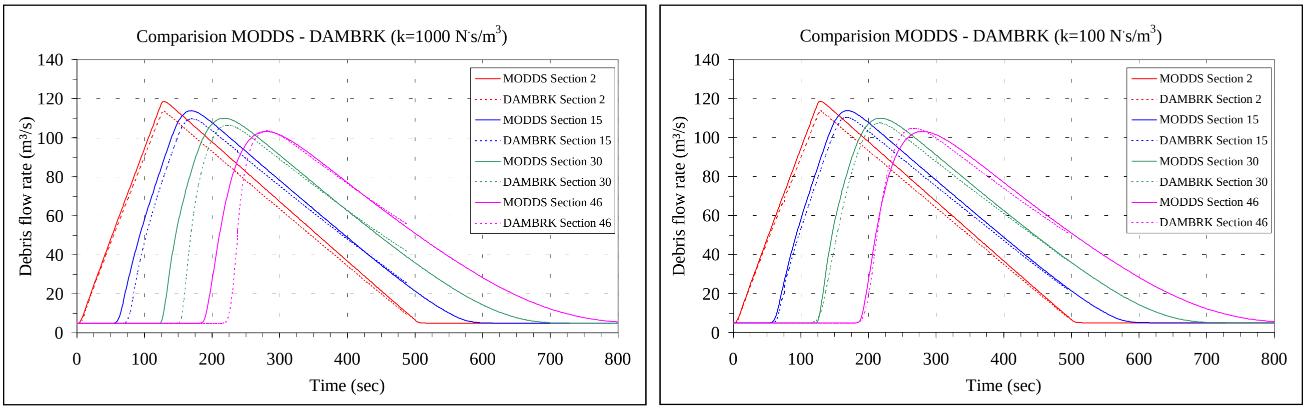



**Fig. 10 – Comparison test between Modds and Dambrk models (K=100 N's/m$^3$ and K=1000 N's/m$^3$).**

| Comparison MODDS - DAMBRK (k=1000 N's/m$^3$) | | | | | |
|---|---|---|---|---|---|
| | *MODDS* | | *DAMBRK* | | dQ |
| | *Time (s)* | *m$^3$/s* | *Time (s)* | *m$^3$/s* | % |
| *Section n.2* | 129 | 118,56 | 129 | 113,67 | 0,049 |
| *Section n.15* | 169 | 113,79 | 169 | 109,62 | 0,042 |
| *Section n.30* | 217 | 109,98 | 219 | 106,38 | 0,036 |
| *Section n.46* | 280 | 103,13 | 281 | 103,41 | 0,003 |

| Comparison MODDS - DAMBRK (k=100 N's/m$^3$) | | | | | |
|---|---|---|---|---|---|
| | *MODDS* | | *DAMBRK* | | dQ |
| | *Time (s)* | *m$^3$/s* | *Time (s)* | *m$^3$/s* | % |
| *Sectio n.2* | 129 | 118,56 | 129 | 113,94 | 0,046 |
| *Section n.15* | 169 | 113,79 | 169 | 110,43 | 0,034 |
| *Section n.30* | 217 | 109,98 | 216 | 107,46 | 0,025 |
| *Section n.46* | 279 | 103,13 | 270 | 104,76 | 0,016 |

**Tab. 2 – Results of comparison Modds – Dambrk.**

## 2-D sub-model development (DDPM)

The debris flow distributed propagation model is a DEM-based model, where the fan is discretized by square cells and each cell is assigned an altitude on the sea level; the cells of the catchment are split into two categories: source cells and stripe cells.

The source cells receive the input hydograph: the cells close to the torrent which are flooded by the debris flow overflowing the torrent embankment are source cells. The stripes cells are the cells flooded by debris flow coming from the surrounding cells. At the first time step only the source cells are flooded by debris flow coming from the torrent. At the second time step a certain number of cells are flooded by debris flow coming from the source cells. These cells constitute a stripe of cells and are assigned order two. At the third time step another group of cells are flooded by the debris flow coming from the cells whose order is two. These cells constitute another stripe and are assigned order three. The cell order of a stripe is the time step number corresponding to the transition from dry to flooded state. The mass transfer or momentum exchange between cells is governed by two different mechanisms. The mass transfer is allowed only by a positive or equal to zero flow level difference between the drained cell and the receiving cell.

The mass transfer is limited by a not negative final flow level difference between the drained cell and the receiving cells. This limitation excludes the case of possible oscillations in the mass transfer. Another

limitation is that the mass drained by a cell should be less than the available mass in that cell. This last condition provides the respect of mass conservation. The first mechanism of mass transfer is the gravity.
The mass in a cell is transferred to the neighbouring cells with lower altitude and flow level according to an uniform flow law:

$$q_j = w_j C h (g h i)^{0.5} \qquad (5)$$

being:
$q_j$ unit width flow discharge
C conductance coefficient
g gravity acceleration (9.81 m/s$^2$)
h flow depth
i $\sin\vartheta$
$\vartheta$ angle between the horizontal and the line joining the centres of two neighbouring cells
$w_j$ weight function = $\sin\vartheta_j / \sum \sin\vartheta_j$

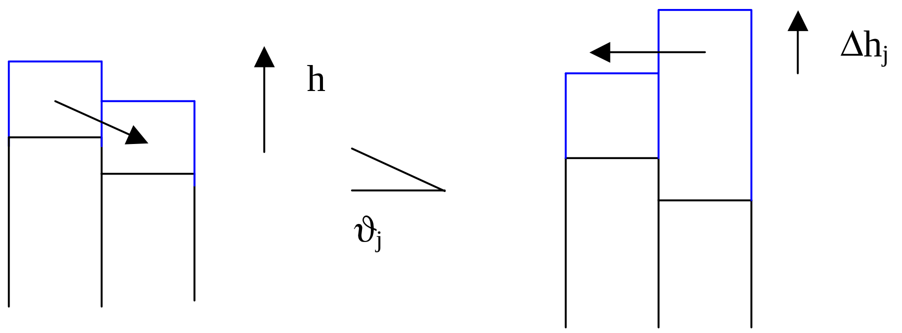



**Fig. 11 - Sketch of mass transfer mechanics between cells**

The second mechanism of mass transfer is the broad-crested weir. The mass in a cell is transferred to the neighbouring cell with higher altitude but with lower flow level according to the following discharge equation:

$$q_j = w_j\, 0.385\, (2g)^{0.5}\, \Delta h_j^{1.5} \qquad (6)$$

being:
$q_j$ unit width flow discharge
$\Delta h$ flow level difference
$w_j$ weight function = $\Delta h_j / \sum \Delta h_j$

Each cell can transfer mass up to the eight neibouring cells:

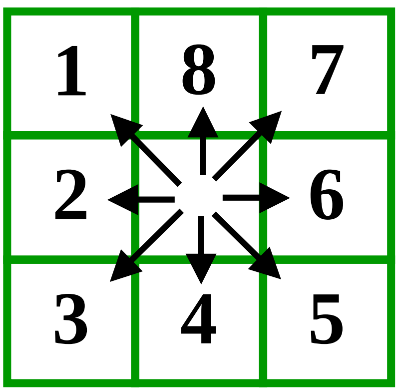



**Fig. 12 - Possible flow directions.**

The time step in not fixed but depends on the CFL condition:
$\Delta t = \Delta x / a < 1$ with $\Delta t$ time step, $\Delta x$ cell side, a wave celerity = $U + (g\ h)^{0.5}$

**Calibration of 2-D model (Debris Flow Distributed Propagation Model, DDPM) on the Rio Lazer fan**

The model can support input hydrographs in different areas. Each area is assigned an own input hydrograph. The model has three input files. The first one refers to the general characteristics of the simulation and the following data and/or parameter values are required: 1) the simulation time (seconds); 2) the time step number (integer); 3) the number of columns (integer); 4) the number of rows (integer); 5) the maximum number of cells allowed in a source area (integer); 6) the maximum number of cells allowed in a stripe (integer); 7) the number of source areas or the number of input hydrograph (integer); 8) the Courant number (less than 1); 9) grid dimension (m); 10) the flow depth under which the cell is considered dry , 11) the DEM file (binary raster file); 12) flag number: constant no dimensional Chezy coefficient (0); no dimensional Chezy coefficient binary raster file (1); 13) constant no dimensional Chezy coefficient value / binary raster file
The second input file refers to the source areas and the following data are required for each source area: 1) number of cells of the source area (integer); 2) column and row index of the cells of the source area (integer); 3) number of time steps + 1 of the corresponding input hydrograph (integer). The source areas are inserted following a chronological order: the first one is the first area which is flooded and so on.
The third input file refers to input hydrograph corresponding to the source area and the following data are required for each hydrograph: 1) time series and corresponding discharges. The input hydrographs are inserted in the same order of the source area. The origin of the time coordinate coincides with the origin of the time coordinate of the first time step of the first hydrograph.
If two source areas in different places are simultaneously flooded, the input hydrograph of the second one is shifted by the model of a time step. The same procedure is adopted by the model if the time difference between two consequent hydrograph is less than a model time step: the second one is shifted to the following time step.
Four different output files can gives by the model:

1. general binary raster files with the time in which the cell is flooded as cell value (0 if the cell is dry along all the simulation time);
2. up to 9 binary raster files time spaced or not with the flow depth as the cell value (0 if the cell is dry);
3. up to 9 binary raster files time spaced or not with the total height as the cell value
4. 1 binary raster file with the flooding time of each inner cell;
5. general control/error Ascii file: in this file are written the likely causes of errors and the times corresponding to the output files showed at points 3 and 4;

The Lazer torrent is a tributary of the Cismon River in the Brenta valley (Eastern Trento Province, Italy). Its basin drain an area of 1.57 $km^2$ and ranges in elevation from 800 m (fan apex) to 1608 m. This torrent has produced frequent and large debris-flows referenced many times over two hundred years. The largest debris flow occurred on November 4, 1966 and was triggering 300 m above the fan apex on a steep colluvial slope. The dam-break induced debris flooding engulfed a village on the fan area and a total volume of debris flow in the deposition zone of 50.000 $m^3$ was measured after the flooding event, together with the distributed pattern of depth material deposition (Fig. 13). Like many other torrents in this zone, the Lazer produces events that Coussot et al. (1998) refer to as muddy debris-flow.
Although this small catchment was not considered as test side in our original proposed project, the important field measurements carried out by the Torrent Control Agency of the Autonomous Province of Trento after the catastrophic flood of November 4, 1966, has permitted to test the Debris Flow Distributed Propagation Model (DDPM 2-D sub-model) in a better and rigorous way. On the other hand, specific local topographical conditions on the Lazer torrent channel indicated that overflow discharge and spreading on the fan area are dominant processes. This process prevailed over the flow that takes place in the channel, downstream the apex fan.
The part of the torrent crossing the apex fan can not convoy a discharge bigger than 1,5-2.0 $m^3/s$ and the flooding of the whole fan takes place. It is assumed that debris flow begins with the peak water discharge.

The peak water discharge corresponding to a rainfall with one hundred years return period was estimated equal to 10 $m^3/s$ and the corresponding debris flow peak discharge calculated as 100 $m^3/s$.

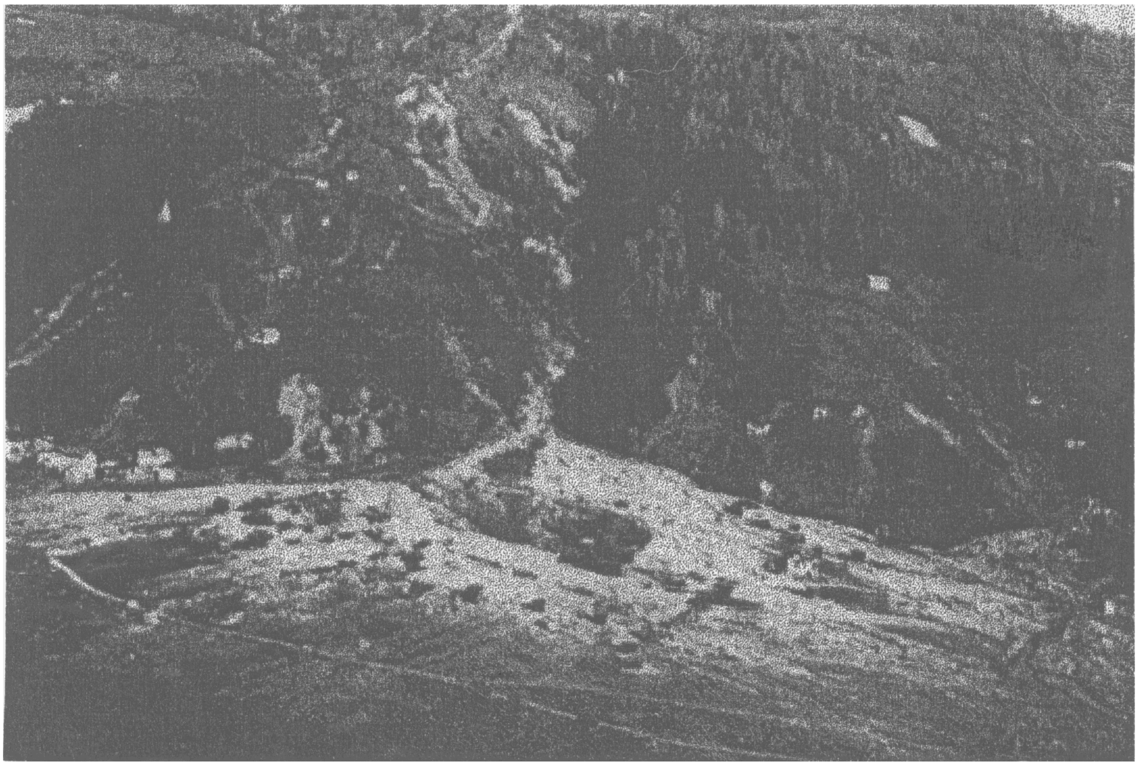


**Fig. 13 – Photograph taken after the castastrophic flood of November 4, 1966 showing the debris flow accumulation on the fan area of the Rio Lenzi**

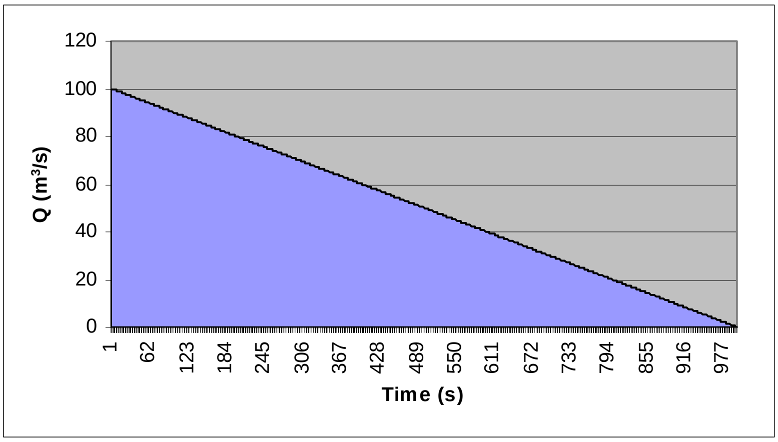
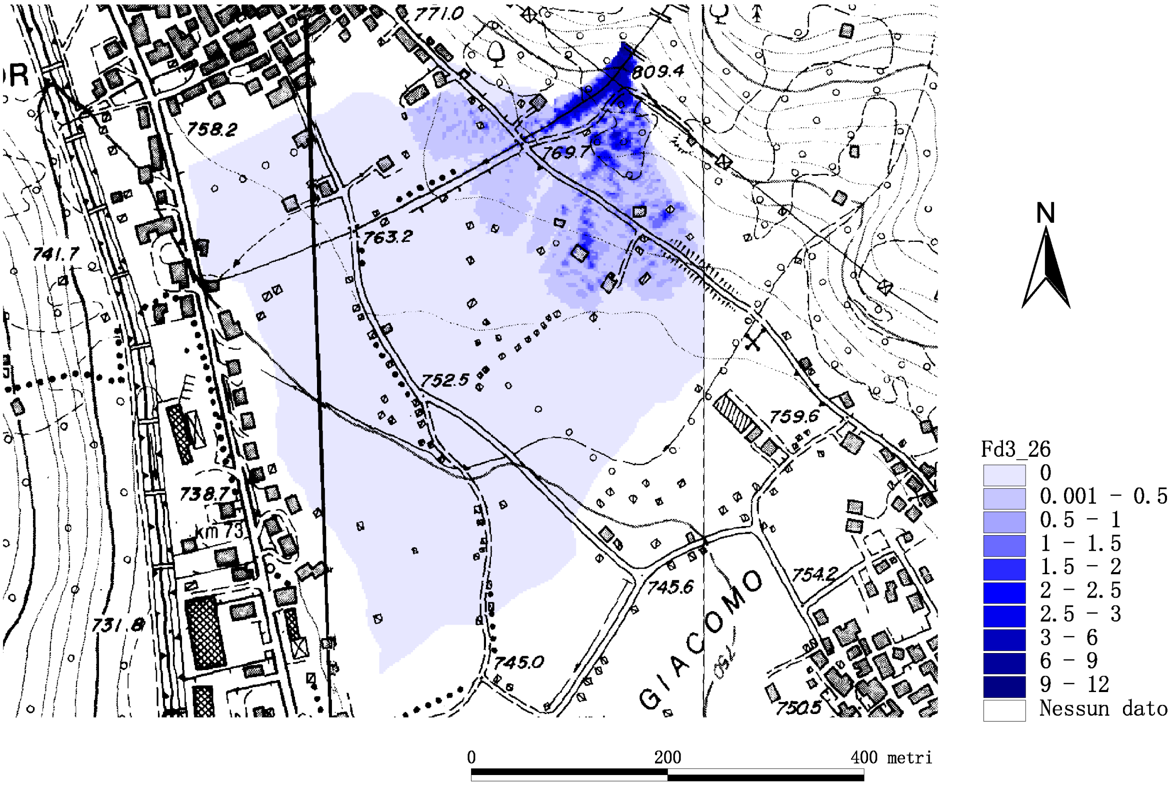



**Fig.14- Input debris-flow hydrograph considered on the simulation with the 2-D model**

Final model simulations are shown on figure 15 and 16, where the debris flow depth accumulation on the fan area are represented at the time intervals of 300 sec. and 900 sec , respectively. Figure 16 illustrates the final spatial distribution of the simulation of the 1966 debris flow spreaded on the fan area. Agreement with the pattern of the distributed debris flow accumulations measured on the field is very good , normally less than 10%. Comparison with the photograph of fig. 13 also confirm the good results of the 2-D model simulation.



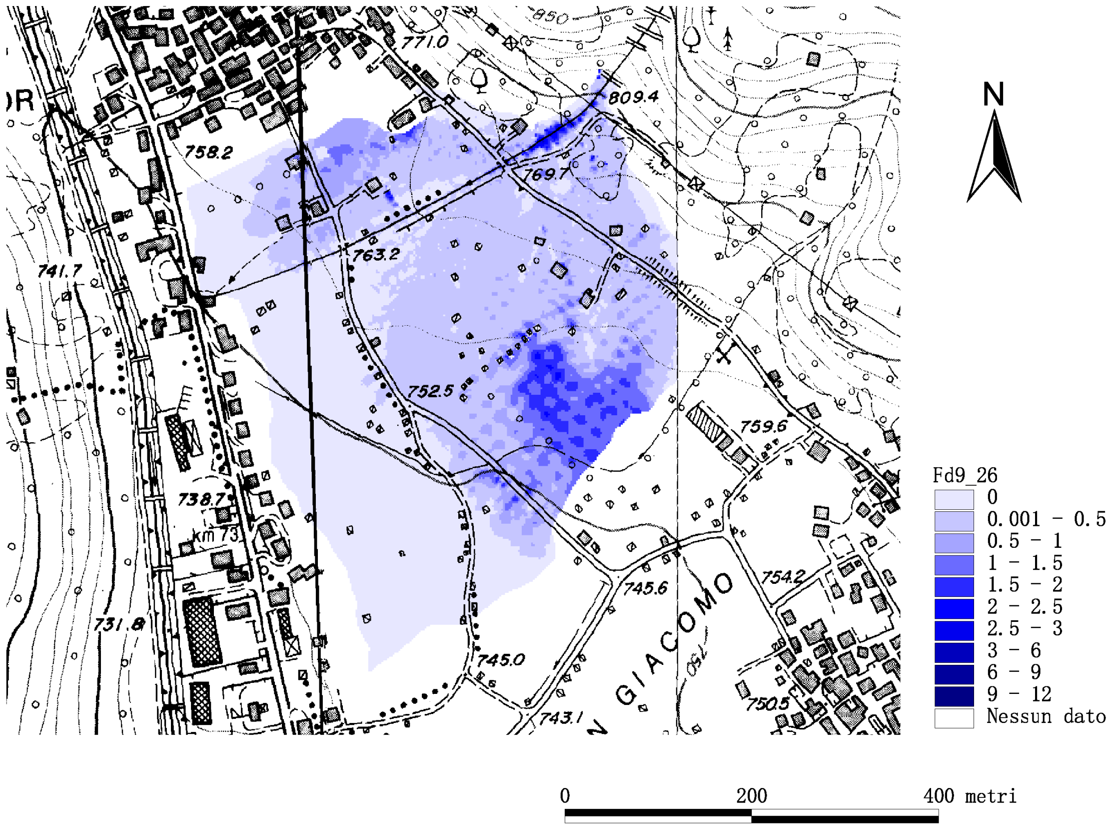




**Fig. 15 and 16 – Debris flow depth accumulation on the fan area represented at the time intervals of 300 sec. and 900 sec**

**Debris Flow Impact Model (DEFLIMO)**

**Integration of the 1-D, 2-D sub-models and fan DTM within a GIS system**

The integration of the 1-D and 2-D sub-models was carried out on the ARC-VIEW GIS framework (fig. 17). Therefore it was possible convey output results coming from the 1-D sub-model on a raster representation of the fan (cells division), as a support for visualizing also output results coming from the 2-D sub-model.

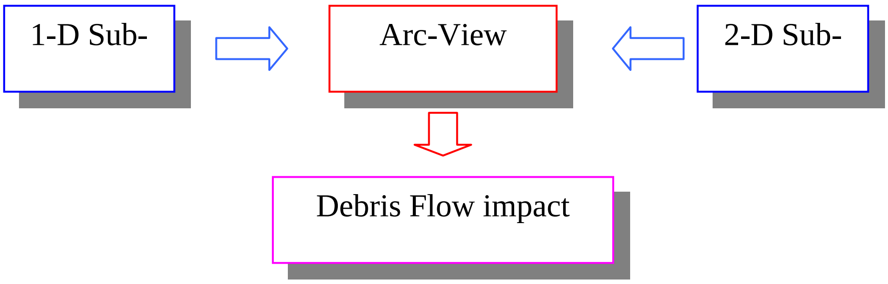



**Fig. 17 – Schematic representation of the integration within Arc-View GIS framework.**

The main improvement of the integration within Arc-View framework is the possibility to link a one-dimensional sub-model founded on vector elements (which is the propagation processes along a channel) with a bi-dimensional distributed sub-model constituted by raster cells. Furthermore it is easy and clear the visualization of debris-flow propagation along the channel and afterwards following its evolution and sedimentation on the fan.

Arc-View worked procedures could be separated in two phases. In the first one, the software works with vector data output from 1-D model. In this phase the program is able to visualize and to georeference channel cross sections, overflow stretch, identifying if overflow happens in right, left or in both sides bank simultaneously (fig. 18). Finally, software discrimination based on overflow distances (between cross section) gives number and position of the overflow cells along the channel profile (fig. 19).

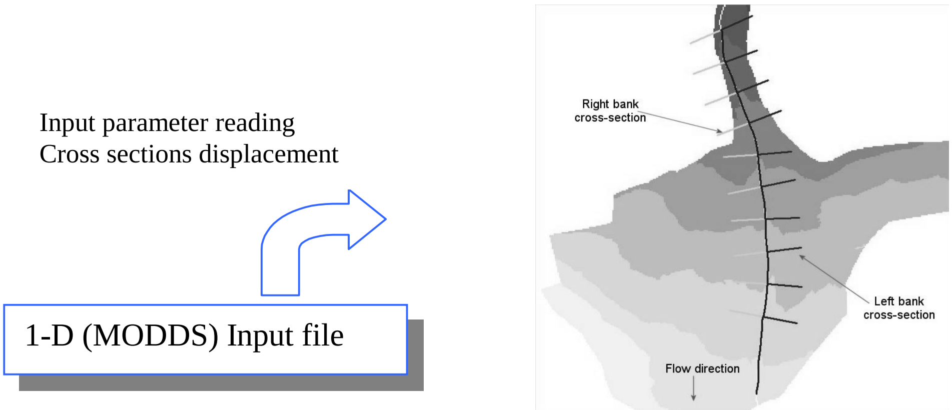



**Fig. 18 – Vector data output from 1-D sub-model.**

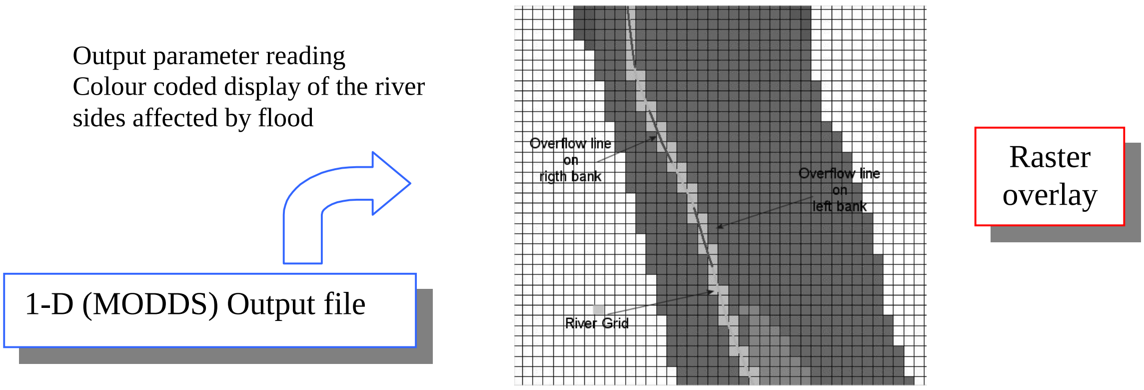



**Fig. 19 – Arc-View process with vector data output from 1-D model.**

In the second phase, the 2-D sub-model use as input data, overflow cells along the channel profile calculated from 1-D model in the previous work-step. Simulation GIS tools taking the 2-D sub-model outputs, consents to visualize on a raster map the overflow areas (fig. 20).

- ✓ Mapping and display of along-track flooded sections
- ✓ Vector-raster overlay to detect flooded cells
- ✓

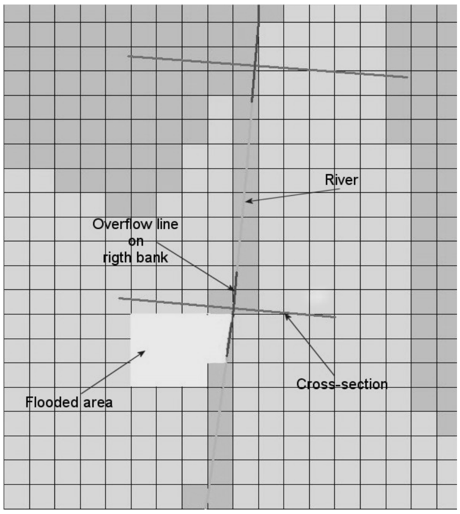



**Fig. 20 – Arc-View raster map of the overflow areas.**

Dynamic evolution of accumulation process in sedimentation cone is visualized through snapshot series with predefined times intervals ($\Delta t$).
DEFLIMO can run as an integrated model linking 1-D and 2-D sub-models with a raster representation of the alluvial fun. Nevertheless, it can also be used only the one-dimensional submodel to compute flow within the channel, as the two-dimensional model to compute the spreading and stopping on the alluvial fan.
In the first situation the unsteady flow in the channel is computed, and the model are also computed the overflow and writes a file in which values of overflowing height and discharge can be stopped for each cross section of the channel and at each time.
In the second case DEFLIMO can run only the 2-D submodel. The 2-D submodel requires input boundary condition such as the discharge resulting for overflow, and the assignation of the position of the grid cell were the overflow occurs. A delineation of the maximum extent of the flow area is produced at the and of the computation. A graphics representation of the results can be produced when model computation stopped.

**Field visit to Benasques Valley (Spain)**
Accompanied by the IGME team, the Benasque Valley was visited on September 2001 and a small basin was selected (Sahún catchment) to apply the Debris Flow Impact Model (DEFLIMO). A detailed analysis of the Sahún catchment, main collector and fan area has been carried out in relation with the required inputs. Suggestions for the topographic survey on Sahún fan in order to get cross-sections and longitudinal profile has also been provided.

### ***3.2.2 WP5 "Dissemination of project deliverables"***

The main dissemination procedures are training courses mounted by CR4 (Padova) and CR2 (Milan-Bicocca). A preliminary Training Course Programme on the models and procedures developed in WP3 and WP2 for 10 end-users was proposed at the Newcastle meeting (November 2001). The training activities planned by U Padova and U Milan-Bicocca will be held on September 9-13, 2002.

### ***3.2.3 Deviation from the proposed work schedule***

The impossibility to conclude the sub-contract with ARPAV-Avalanche Center of Arabba (scheduled for 2000-2001) and the time needed for recruitment two researchers caused 3,5-4 months delay in the Padova Project. Consequently, our time deliverable for our Debris Flow Impact Model (1-D + 2-D sub-models integrated within a GIS) scheduled for 28 Febbruary 2002 will be between June 15 and June 30, 2002.

In order to conclude the activities planned on our original project proposal, a new subcontract (in substitution of the Univ. of PD-ARPAV-Avalanche Center of Arabba) was signed December 3, 2001 with the "Associazione Italiana di Idronomia". Luca Mao and Diego Sonda were contracted as Assistant Research, (from November 15 and December 5, 2001, respectively).
In order to act on the recommendations of the expert assessors invited to the Newcastle meeting , we up-date our DAMBRK and ARC-VIEW software. A comparison of our 1-D MODDS model and DAMBRK soubrouting for non-Newtonian fluid simulations was carried out.

## Section 3.3: Socio-economic Relevance and Policy Implication

In order to clarify with an actual example the socio-economic relevance of the project advances, consider that the annual budget of the Autunomous Province of Trento for torrent control works and debris flow management is around 20 millions euros, whereas damages caused by debris flow events can reach tens of millions euros, with hundreds of deaths, since many towns are present on the alluvial fans. Another concern are the road closures, for example recently the important motorway connecting Verona with Innsbruck has remained blocked for two days because of a debris flow.
At this moment the end-users (i.e. the Protection Agencies) are using the Aulitzky methodology both to evaluate whether debris flows can occur along a stream and to produce maps with three different levels of hazards on the alluvial fan. This qualitative approach does not allow to assess how critical structures along the channel (i.e. bridges, check-dams, ripraps) affect the debris flow route along the channel, particularly where flooding is likely to occur and the volume of the overflowed material. The developed 1-D submodel permits to simulate such dynamics and the 2-D fan propagation submodel produce detailed hazard mapping with valuable information about deposition patterns, which can lead to an efficient land-use planning.
Current meetings with our End-Users (Torrent Control Agency of the Trento Province an ARPAV-Avalanche Center of Arabba, Veneto Region) were useful to improve algorithms of MODDS model and also in the integration of both 1-D and 2-D sub-models within the GIS system. The Director of the Torrent Control Agency (Trento Province) is very interested on both the Debris Flow Impact Model (DEFLIMO) applicability on the overall Province of Trento and the Damocles Training Course scheduled for September 2002. At the end of September 2001 he demanded a number of four place reserved for the Torrent Control Agency in planning training activities; this number increase to six after the last meeting of February 12, 2002.

## Section 3.4: Conclusions

A one-dimensional sub-model for debris flow routing along the channel (MODDS) has been developed and calibrated. MOODS was tested and validated in the Test Area C (Rio Lenzi channel).
1-D MODDS model sensitivity studies were carried out taking into account both slope variations from 1% to 100% and non-dimensional Chèzy coefficient variations from 2 to 9. The MODDS model was also compared with the DAMBRK subrouting for non-Newtonian fluid simulations.
Results have shown 1-D model first-rate accuracy in simulation of debris flow wave propagation in Rio Lenzi channel, both in the evaluation of peak magnitude and time peak arrival.
The behaviour of the 1-D routing model (MODDS) is satisfactory within the hypothesised range of hydraulics and topographic situations in torrents flowing on fan areas. The model is user-friendly and gives realistic results in view of checking channel conveyance and overflow occurrence.
A 2-D propagation sub-model (DDPM) has been developed and the integration of the 1-D, 2-D sub-models and fan DTM within a GIS system has also been carried out . The final Debris Flow Impact Model (DEFLIMO) was implemented on test area C (Rio Lenzi catchment).
The 2-D Distributed Propagation Model (DDPM) on fan surface need calibration and validation in other small catchments. An application of the integrated Debris Flow Impact Model (DEFLIMO) will be performed in the Sahùn watershed (Focus Area, Pyrenee, Spain)

## Section 3.5: Plan and Objectives for the Next Period

- **Task 1:** Improvement of user-friendly graphics and data input-output of the Debris Flow Impact Model
- **Task 2:** Final simulations of the Debris Flow Impact Model on the test area C (Rio Lenzi catchment)
- **Task 3:** Demonstration linking of WP2 and WP3 models.
- **Task 4:** Organisation of the Damocles Training Course in collaboration with Milano-Bicocca (9-13 September 2002)
- **Task 5:** Application of the Debris Flow Impact Model to the Rio Rudan catchment
- **Task 6:** Calibration, validation and application of the Debris Flow Impact Model to the Sahùn Catchment (Spain).
- **Task 7:** Preparation of papers, oral presentations, ecc., for the Milan Final Workshop
- **Task 8:** Preparation of Technical Report, Scientific and Final Report , T.I.P. and Cost Statement.

**Table 3 – Next project activities**

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## Section 3.6: References


Bathurst J.C., Burton A., Ward T.J., 1997. Debris flow run-out and landslide sediment delivery model test. Journal of Hydraulic Engineering, 410-419.

Bovis, M.J., and Jakob, M., , 1999. *The role of debris supply conditions in predicting debris flow activity,* Earth Surface Landforms and Processes, 24, 1039-1054.

Chaudry M. H., 1993. Open-Channel Flow, Prentice-Hall International, London.

Chen C., 1987. Comprehensive review of debris flow modelling concepts in Japan, Debris flow/avalanches: processes, recognition and mitigation, Reviews in Engineering Geology, J. E. Costa and G. F. Wieczoreck (eds.), Geol. Soc. Am., vol. VII, 13-30.

Cousot P., 1994.Steady, laminar, flow of concentrated mud suspensions in open channel. Journal of Hydraulic Research, 32 (4), 535-559.

Cousot P., Laigle D., Arattano M., Deganutti A., Marchi L., 1998. Direct determination of rheological characteristics of debris flow. Journal of Hydraulic Engineering, 124 (8), 865-868.

Courant R., Friedrichs K. O., 1948. Supersonic Flow and Shock Waves, Interscience Publishers, New York.

Costa J. E., 1984. Physical geomorphology of debris flow, Developments and applications of geomorphology, J. E. Costa and P. J. Fleisher (eds.), Springer-Verlag, Berlin Chap.9, 268-317.

Cunge J.A., 1969. On the subject of a flood propagation computation method (Muskingum method), J. Hydraulic Res., 7(2), 205-230.

Eyheramendy D., Frenette R., Zimmerman Th., 1997. Numerical modelling of Dam-Break type problems for Navier-Stokes and granular flows. Proc. Of the Int. Conf. On Debris Flow Hazard Mitigation, San Francisco, USA, PP. 586-595.

Fread D.L., 1993. Chpt 10: Flow Routing. In: Handbook of Hydrology, Edited by Maidment D.R.; McGraw Hill, New York, 10.1-10.36.

Gregoretti C., 2000. *Estimation of the maximum velocity of a surge of debris flow propagating along an open channel",* Proceedings of the Internationales Symposion INTERPRAEVENT 2000 – Villach, Band 3, 99-108.

Henderson F.M., 1984. *Open channel flow*, chap.9: Flood routing, macmillian, New York, 1966.Hungr, O., Morgan, G.C., and Kellerhals, R., *Quantitative analysis of debris torrent hazard for design of remedial measures*, Canadian Geotechnical Journal, 21(4), 663-677.

Hungr O., G. C. Morgan, Kellerhals R., 1984. Quantitative analysis of debris torrent hazards for design of remedial mesures, Canadian Getechnical Journal, 21, 663-677.

Hungr O., 2000. Analysis of debris flow surges using the theory of uniformly progressive flow. Earth Surface Processses and Landforms, 25, 483-495.

Jin M., Fread D.L., 1999. 1-D modeling of mud/debris unsteady flows. Journal of Hydraulic Engineering , ASCE, 125 (8), 827-834.

Laigle D., 1997.*A numerical model for the study of debris-flow spreading on the torrent debris fan.*, Proceedings of Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Cheng-Lung-Chen (ed)., New York, ASCE, 123-132..

Laigle D., Marchi L., 2000. *Example of mud/debris-flow hazard assessment, using numerical model*, Proceedings of Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Wieczorek & Naeser eds., Balkema, Rotterdam, 417-424.

O'Brien, J.S. and Julien P.Y., 1984. *Phisical Propeerties and Mechanics of Hyperconcetrated Sediment Flows"*, Delineation of Landslide, Flash flood, and Debris flood Hazards in Utah, Utah State University, Utah Water Research Lab., Logan, Utah, 260-279.

Rickenmann D., Koch Th., 1997. Comparison of debris flow modelling approaches. Proc. Of the Int. Conf. On Debris Flow Hazard Mitigation, San Francisco, USA, 577-585.

Rickenmann, D., Weber, D. , 2000. *Flow resistance of natural and experimental debris-flows in torrent channels*", Proceedings of Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Wieczorek & Naeser eds., Balkema, Rotterdam, 245-254.

Scheuringer, E., 1988. *Ermittung der massgeblichen Geschiebefracht aus Wildbach-Oberlauten, Wildbach und Lawinenverbau*, 52, 109, 87-95.

Spreafico, M., Lehmann, Ch., and Naef, O., 1999. *Recommandations concernant l'estimation de la charge sédimentaire dans les torrents*, Groupe de travail pour l'hydrologie opérationnelle.

Takei, A., 1984. *Interdependence of sediment budget between individual torrents and a river-system*, Int. Symp. Interpraevent 1984, Villach, Austria, vol. 2, 35-48.

VanDine D. F. , 1996. Debris Flow Control Structures for Forest Engineering, Province of British Columbia, Ministry of Forests Research Program.

Ven Te Chow , 1959. Open-Channel Hydraulics, Mc Graw-Hill Book, New York.

Weinmann, P. E. and Lauerson, E. M., 1979. *Approximate flood routing methods: A review*, J. Hydr. Div., ASCE, 105(12), 1521-1536.