ON HOW TERRAIN TOPOGRAPHY AND RHEOLOGICAL PROPERTIES INFLUENCE MODELING OF DEBRIS-FLOW RUN-OUT DISTANCES –CASE STUDY OF THE SAVA DOLINKA VALLEY, NW SLOVENIA

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ABSTRACT

Debris flow hazard assessment is based on assumptions on source areas and magnitudes of potential debris flows, their rheological characteristics, and their run-out predictions. We performed two-dimensional modeling of potential debris flows on selected torrential fans in the Alpine glacial Sava Dolinka River valley (NW Slovenia). The sensitivity analysis of a commercially available model (Flo-2D) was performed with regard to terrain topography and rheological parameters. We used numerical square grids, generated from freely available DEM 5 and DEM 12.5. With regard to terrain topography, we showed that buildings that are part of DEMs should be modeled, because they have large influence on the nearby flow field. The approach to introduce buildings into the numerical grid model by simply defining them as blocked (dry) cells proved to be better solution than raising the roughness (Manning) coefficient in these cells to account for flow obstruction by buildings. With regard to rheological properties, we showed that the main model rheological parameters (yield stress, dynamic viscosity) are relevant parameters but with a limited influence on final modeling results (debris-flow run-out, also flow depths and velocities). More important parameters when modeling potential debris-flows are precise data on terrain topography (at least DEM 5) and the potential debris-flow magnitude.

Key Words: Debris flows, Digital Elevation Model, Mathematical modeling, Sensitivity analysis

INTRODUCTION

Recently, as a part of the developing a methodology for assessment of debris-flow hazard in Slovenia, an analysis of the whole territory of the Republic of Slovenia with regard to slope debris flows susceptibility has been performed using DEM 25 and selected initiation factors (48-hour rainfall rates, slope inclination, slope potential energy, lithology) as well as transport factors (energy of close-by hydrologic network, distance to river network, relief concavity). Several forecasting models have been tested using relatively scarce database on registered historical debris flows. The analysis yielded a debris-flow susceptibility map of Slovenia

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(Komac *et al.*, 2010). This can be seen as the first step towards an establishment of debris-flow hazard maps. In a targeted area where debris-flow susceptibility is estimated to be high but no historic records are available, debris-flow hazard assessment is based on hydro-geological and hydro-meteorological assumptions on origins and magnitudes of potential debris flows and on estimations on their rheological characteristics as well as on their run-out predictions.

In order to be able to apply planning tools in debris-flow hazard areas, we should be able to assess magnitudes (Sodnik and Mikoš, 2006) and predict run-out of future (potential) debris flows (Mikoš *et al.*, 2007). Many different run-out prediction methods can be applied to estimate the mobility of future debris flows during hazard assessment, such as empirical, analytical, simple flow routing and different numerical techniques (Hürlimann *et al.*, 2008). According to these, only the use of numerical models provides »final hazard maps«, because they can incorporate different event magnitudes and supply output-values for intensity calculation. In contrast, empirical relationships and flow routing algorithms, or a combination of both, could be applied to create »preliminary hazard maps«. The precision of such hazard maps is to a large extent a function of several parameters, such as the magnitude of a potential debris flow, rheological characteristics of the water-sediment mixture, surface roughness characteristics, and surface inclination.

Topographic surfaces can be generated in many ways, among them e.g. from an airborne laser altimetry (LiDAR) survey, a ground-based differential GPS (DGPS) survey, or from digital elevation data (Rayburg *et al.*, 2009). A Swiss study that used three generically different digital elevation models (DEMs) with grid spacing of 25, 4 and 1 m showed that DEM 25 can give an approximate estimation of the potential hazard zone, and the other higher-resolution DEMs confine the simulated debris flow to existing channels and were in accordance with observations of recent debris-flow events (Stolz and Huggel, 2008).

Infrastructure of different types (roads, bridges, houses) also has an important influence on numerical modeling of such flow phenomena, as was shown in the case of a hypothetical dam breach of the Rhine River close to Widnau in Switzerland (VAW, 2003). Knowing that topography is one of the major factors in landslide hazard analysis (van Westen *et al.*, 2008), it is important to assess the impact of different topography representations on numerical modeling of debris flows.

This paper deals with the possibility of using public domain (existing) digital elevation data in Slovenia for debris-flow risk assessment, but does not discuss any other available techniques to obtain topographic surfaces. In the framework of the targeted research project entitled Assessment of debris-flow hazard in Slovenia, the Alpine glacial valley of the Sava Dolinka River was chosen as a test region. Within this region, four torrential watersheds were selected: Trebiža, Suhelj, Presušnik, and Koroška Bela. Some results for two of the torrential fans (Koroška Bela, Trebiža) are reported in this paper.

An important part of numerical modeling was the way how rheological properties were taken into account. Because we were examining potential debris flows, we had no direct field data on soil rheological properties in potential source areas. Hence, we intentionally used our experiences gained when modeling real debris-flow cases in Slovenia in the recent past: a large debris flow in Log pod Mangartom in 2000 (Četina *et al.*, 2006), and numerous small debris flows in Koseč above Kobarid in 2002 (Mikoš *et al.*, 2006).

TOPOGRAPHIC DATA

For two-dimensional modeling of debris flows we need topographic data in the form of numerical grids, easily generated from digital elevation models (DEM). After the InSAR DEM 25, the DEM 12.5 was produced in 2005 as a composite model of all existing data. Such composite digital elevation model proved to be of high geomorphologic quality but has not found wide usage. Since 2006, in Slovenia DEM 5 is available by the Geodetic Survey of the Republic of Slovenia. Therefore, this topographic representation was selected to be used for debris flow modeling on the selected torrential fans in the Sava Dolinka valley as the state-of-the-art DEM freely provided by the state.

We are aware that "traditional" DEMs created by interpolations between contour lines digitized from topographic maps produced from aerial photographs are lacking higher accuracy needed for studies not only limited to contributing drainage area or channel gradient (Snyder, 2009). Nevertheless, at this stage and for the purpose of testing they are the best available topographic representation available for the whole of Slovenia, although this means neglecting promising and already existing possibilities of higher precision, such as obtained by airborne light detection and ranging (LIDAR) for direct and detailed measurement of the digital elevation model (DEM). This new technique has already been successfully tested for many purposes, such as e.g. analysis of a large debris flow event (Breien *et al.*, 2008), landslide recognition (Sato *et al.*, 2007), general hydraulic modeling of water courses, or specifically two-dimensional modeling of flood waves.

The main reason was also very practical, i.e. that the existing computational capabilities using personal computers allow us to reach ratio between the duration of a natural event and the computer time to simulate it close to 1 : 1. Nevertheless, it is worth mentioning that on one hand automatically derived DEM 5 in Slovenia should have been cleaned of any infrastructure such as roads, bridges or buildings, and on the other it is not able to fully represent fluvial channels. The quality of DEM 5 in Slovenia for modeling natural phenomena such as debris flows will be shown in this paper.

The 15 x 15 m numerical grid on the Koroška Bela torrential fan was generated within the Flo-2D program using its capabilities to interpolate the grid element elevations (FLO, 2007). The 15 x 15 m numerical grid cell elevation was computed using interpolation of all DEM 5 points in the 15 m radius of interpolation. Furthermore, user can define high or low elevation filtering scheme, where the program offers the following options: no filtering, maximum elevation difference and standard deviation difference. We used the no-filtering option. Using extreme rainfall and widely used hydrologic model HEC-HMS, a computational hydrograph for each torrential fan was determined (see details in Table 1).

Table 1 Main geometric and hydrologic parameters (magnitudes were computed assuming volumetric sediment concentration C_v of a design dry debris flow to be 0.5 and of a design wet debris flow to be 0.42) of selected torrential fans in the Sava Dolinka valley, NW Slovenia

Torrential fan	Clear water event: peak discharge & duration	Dry debris flow event: magnitude	Wet debris flow event: magnitude	no. of cells for 5 x 5 m grid	no. of cells for 15 x 15 m grid
Trebiža	39.0 m^3/s & 20 hours	407,150 m^3	294,776 m^3	31,953	3,717
Koroška Bela	50.7 m^3/s & 20 hours	479,390 m^3	236,024 m^3	21,708	2,385
Suhelj	21.9 m^3/s & 20 hours	182,050 m^3	131,804 m^3	25,050	8,687
Presušnik	38.7 m^3/s & 20 hours	387,770 m^3	347,078 m^3	11,264	998

TERRAIN TOPOGRAPHY AND DEBRIS-FLOW MODELING RESULTS

As a debris-flow mathematical model we selected the commercially available two-dimensional model FLO-2D (FLO, 2007) that has been successfully applied in Slovenia for post-event analysis in Log pod Mangartom (Četina *et al.*, 2006), and for debris-flow hazard assessment in Koseč above Kobarid (Mikoš *et al.*, 2006).

We used the Flo-2D model to compute clear water and debris flow events (a debris flow is a mixture of water and sediments in different proportions). The sensitivity analysis of the computer model on the numerical grid cell size 5 x 5 m and 15 x 15 m and the roughness (Manning) coefficient (expressing energy losses) on flow depths, flow velocities, and on inundated area was performed using clear water case. When applying the computer model for a debris flow event, two rheological model parameters are to be determined: yield stress that determines the maximum slope at which a debris flow can come to a stop (as opposed to clear water that flows at any slope), and dynamic viscosity that should be used because debris flow is viscous fluid (for clear water normally viscosity is neglected). Since for a potential debris flow event in the test region we do not have precise material rheological data from past (recent) debris-flow events, we used parameter values gathered when calibrating Flo-2D model for other recent debris flow cases in Slovenia (Stože; Koseč). Therefore, we used: yield stress $\tau = 20$ Pa, dynamic viscosity $\eta = 10$ Pa.s for $C_v = 0.42$ (wet debris flow), yield stress $\tau = 2000$ Pa, and dynamic viscosity $\eta = 156$ Pa.s for $C_v = 0.50$ (dry debris flow). More detailed description of the Flo-2D model is given elsewhere (FLO, 2007).

The computational time using a desktop personal computer (Intel Core2Duo processor 3.0 GHz, 4 Gb RAM) was very dependent on the computational grid size. Because no LIDAR high resolution topography was available in the selected areas, we decided to use the official DEM 5 as the basis for the 5 x 5 m numerical grid, and were also able to downscale it to the 15 x 15 m grid in order to speed up the modeling process. For the simulated hydrograph of 20 hours, the computational time for the 15 x 15 m numerical grid was around 5 minutes (ratio around 240:1), and with the 5 x 5 m numerical grid it was between 40 and 60 hours (ratio between 1: 2 and 1:3). Therefore, the sensitivity computer test for surface roughness was mainly done for the 15 x 15 m grid to speed up the computational process.

If there are no field data available on recent debris flows, the selection of appropriate Manning roughness coefficients for a specific field study can be done only on the basis of literature review and/or own experiences with debris flow modeling. The roughness coefficients used in our numerical modeling were firstly selected from existing technical literature to be typical for these field conditions (Chow, 1988; Julien, 2002) as well as from Flo-2D manual (FLO, 2007). They were tested for clear-water cases on the Presušnik fan and for debris-flow cases on the Koroška Bela fan. Lastly, they were compared to the values obtained when the Flo-2D model of the Stože debris flow was calibrated using field data (Četina *et al.*, 2006) and when modeling the debris flows in the village of Koseč (Mikoš *et al.*, 2006).

The Koroška Bela fan is densely populated, which is why we used the following Manning roughness coefficients: n_g(forest) = 0.16 $sm^{-1/3}$, n_g(meadow) = 0.033 $sm^{-1/3}$, n_g(channel) = 0.13 $sm^{-1/3}$, n_g(building area) = 0.035 $sm^{-1/3}$ and n_g(buildings) = 0.2 $sm^{-1/3}$ for two topographical situations: buildings are represented by higher roughness values (n_g(buildings) = 0.2 $sm^{-1/3}$) and buildings are represented by blocked (dry) grid cells (for the area around dry cells we used n_g(building area) = 0.035 $sm^{-1/3}$). In the 15 x 15 m grid model, 206 grid cells (out of

2,385 cells or 8.64% resp. 46,350 m^2) and in the 5 x 5 m grid model, 1931 grid cells (out of 21,798 cells or 8.86% resp. 48,275 m^2) were blocked by buildings. The results of this sensitivity analysis (i.e. total inundated area (ha), average flow depths (m), and average flow velocities (m/s)) are for the Koroška Bela fan shown in Table 2. Using the 15 x 15 m numerical grid instead of the 5 x 5 m numerical grid yields lower values of flow depths and average flow velocities when representing buildings by higher Manning roughness values, and higher values when representing buildings by blocked (dry) grid cells, respectively (Table 2).

Table 2 The main modeling results for the Koroška Bela torrential fan using the 5 x 5 m and the 15 x 15 m grid (the first row shows the results for the case where buildings were modeled by higher roughness coefficients, and the second row for the case where buildings were modeled by blocked (dry) cells)

	5 x 5 m / 15 x 15 m		
case	**Total inundated area (area covered by blocked cells) (ha)**	**Average flow depth (m)**	**Average flow velocity (m/s)**
Clear water	9.455 / 13.300	0.45 / 0.32	1.10 / 0.90
	10.200 / 12.950 (2.250)	0.35 / 0.41	1.07 / 1.43
Wet debris flow	11.115 / 16.200	0.47 / 0.37	1.10 / 1.00
	11.460 / 15.750 (2.800)	0.41 / 0.43	1.26 / 1.50
Dry debris flow	12.780 / 19.150	0.48 / 0.46	0.96 / 0.95
	11.945 / 15.800 (3.250)	0.48 / 0.58	1.19 / 1.60

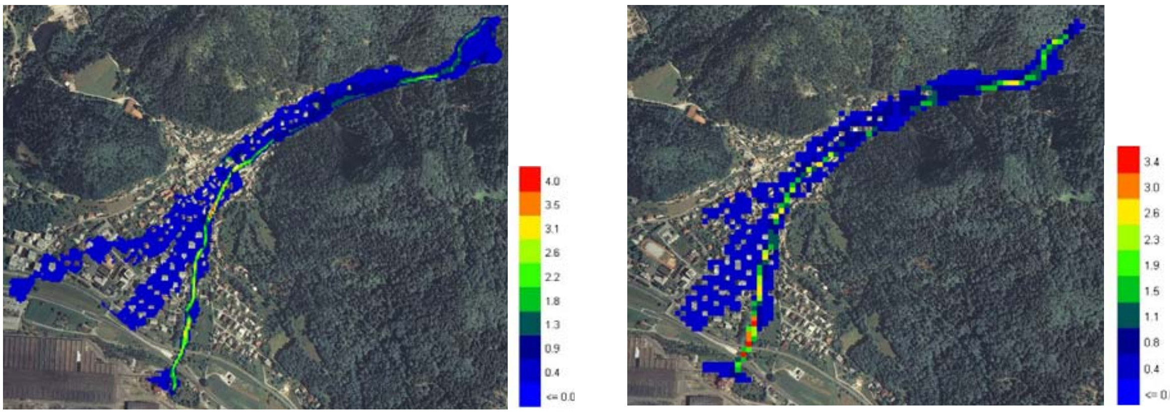

Fig. 1 Flo-2D model results for clear water on the Koroška Bela fan using two different numerical grids: 5 x 5 m (left) and 15 x 15 m (right) - building effects are covered by blocked (dry) grid cells where buildings were recognized on the ortophoto - colors refer to maximum flow depth in meters.

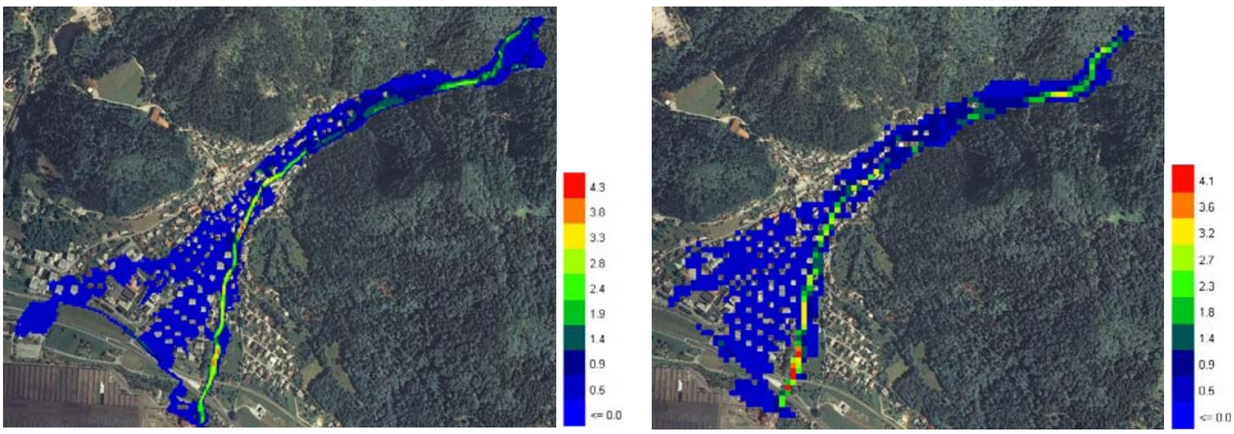

Fig. 2 Flo-2D model results for wet debris flow (C_v = 0.42) on the Koroška Bela fan using two different numerical grids: 5 x 5 m (left) and 15 x 15 m (right) - building effects are covered by blocked (dry) grid cells where buildings were recognized on the ortophoto - colors refer to maximum flow depth in meters.

The difference between using the 15 x 15 m numerical grid and the 5 x 5 m numerical grid is especially pronounced for the clear water case (pure torrential event, Figure 1) and using blocked cells. Using the 15 x 15 numerical m grid, the debris-flow modeling showed that out of 206 blocked cells for the case of clear water 100 cells (48.54%), in the case of the wet debris flow 146 cells (70.87%), and in the case of the dry debris flow 125 cells (60.68%) would be overtopped. These results show how many existing buildings on the Koroška Bela torrential fan are threatened by a torrential or a debris-flow event.

When modeling debris-flow events, using the 5 x 5 m numerical grid instead of the 15 x 15 m numerical grid yields more detailed hazard map with smaller inundated area and clear debris-flow path in the main torrential channel (Figure 2). This example clearly shows the potential advantage of using DEM 5 over DEM 15 when constructing a numerical grid for simulation of natural processes in mountainous areas in order to assess their hazard.

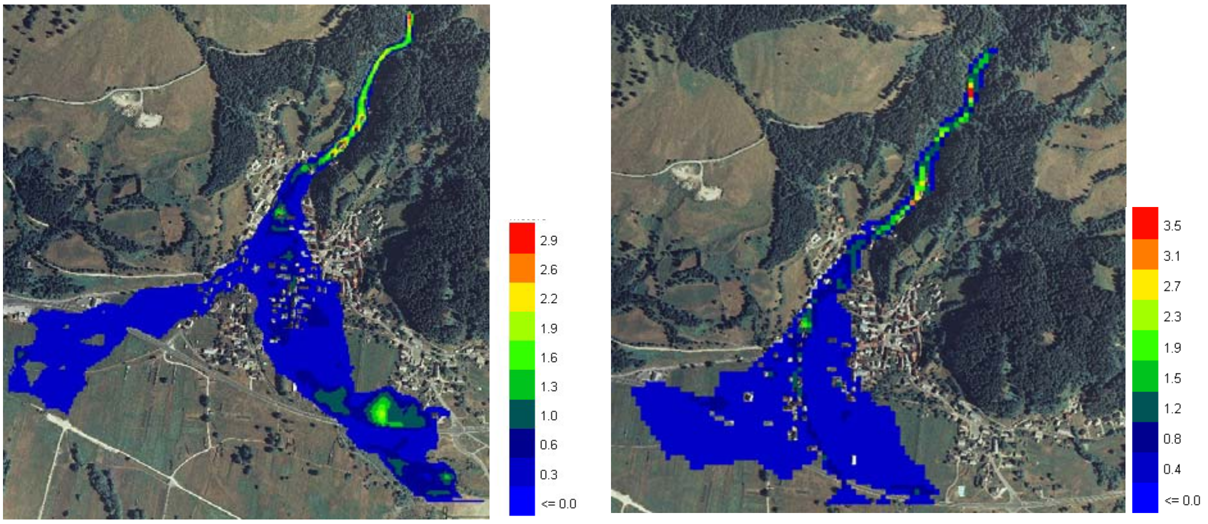

Fig. 3 Flo-2D model results for clear water on the Trebiža fan using two different numerical grids: 5 x 5 m (left) and 12.5 x 12.5 m (right) - building effects are covered by dry grid cells where buildings were recognized on the ortophoto - colors refer to maximum flow depth in meters

Furthermore, we also applied the 5 x 5 m numerical grid on the Trebiža torrential fan. For the Trebiža fan the same Manning roughness coefficients were used as for the Koroška Bela fan: n_g(forest) = 0.16 $sm^{-1/3}$, n_g(meadow) = 0.033 $sm^{-1/3}$, n_g(channel) = 0.13 $sm^{-1/3}$, n_g(building area) = 0.035 $sm^{-1/3}$ and n_g(buildings) = 0.2 $sm^{-1/3}$ for two topographical situations: buildings are represented by higher roughness values (n_g(buildings) = 0.2 $sm^{-1/3}$) and buildings are represented by blocked (dry) grid cells (for the area around dry cells we used n_g(building area) = 0.035 $sm^{-1/3}$). Even using the 5 x 5 m numerical grid for the clear water case, the water flow “jumps” out of the channel close to the torrential apex (presumably due to a road bridge that was automatically interpreted in DEM 5 as terrain) and runs down the inclined fan through the inhabited area that is lower than the Trebiža torrential channel (Figure 3).

The problem with the 5 x 5 m numerical grid generated from DEM 5 in the case of the Trebiža torrential fan is a clear example how problematic DEM 5 may be due to its limited capability to reproduce channel features in the case of steep torrential channels on fans. Because the torrential channel in the upper part of its course on the fan is poorly reproduced, the clear water flow as well as debris flow reach out of the channel and start inundating the fan. We checked this assumption by applying coarser 12.5 x 12.5 m numerical grid generated from DEM 12.5. We used the same model parameters as with the 5 x 5 m numerical grid. The results are given in Figure 3.

With regard to building representation, similar results to ours were achieved for the case of a hypothetical dam breach of the Rhine River close to the town of Widnau in Switzerland (VAW, 2003). In this case, a comparison between DEM 25 without buildings and digital ortophoto incorporating buildings of this urbanized area yielded higher water depths for the case where buildings were taken into account.

Similar approach was also used for the case of the Log pod Mangartom debris flow, where buildings were introduced into the 2 x 2 m and 4 x 4 m grid models by defining buildings as blocked (dry) grid cells (Fazarinc *et al.*, 2006). This approach also proved to be successful for debris-flow modeling described in this paper. The main advantage to replace existing buildings with blocked (dry) cells instead of increasing roughness coefficient is a more detailed description of the flow field around buildings (dry cells): flow velocities around dry cells increase and, as a consequence, flow depths behind the dry cells increase as well (physically correct). This better representation of the flow field is computed faster only for clear-water cases (10–15%). In the debris-flow case the computational time is longer by 20-25% due to sharper differences in the flow field around and behind dry cells due to rheology when compared to clear-water cases.

RHEOLOGY AND DEBRIS-FLOW MODELING RESULTS

When assessing future debris-flow hazard areas using mathematical models, the most difficult parameters to be determined according to our experiences are the rheological properties of a potential debris flow: the yield stress τ and dynamic viscosity η for a given volumetric concentration C_v. The other relevant model parameters it is possible to determine rather straigthforward. One possibility to evaluate rheological properties of a potential debris flow is to perform a laboratory analysis on field samples taken in potential debris flow source areas.

Table 3 Limit values of rheological parameters for given volumetric concentrations C_v (FLO, 2007)

Volumetric concentration	**Yield stress τ (N/m^2)**		**dynamic viscosity η (Pa.s)**	
	τ_{min}	τ_{max}	η_{min}	η_{max}
$C_v = 0.40$	2.6	170	0.63	27
$C_v = 0.45$	6.7	275	1.9	70
$C_v = 0.50$	18.0	800	5.4	185

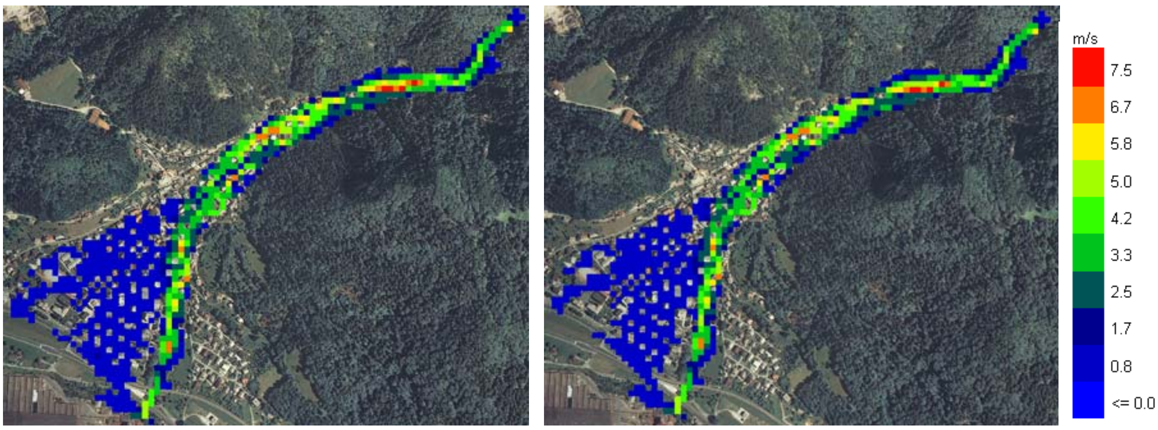

Fig. 4 Maximum debris-flow velocities on the Koroška Bela fan using the numerical grid 15 x 15 m, the Q_{100}: hydrograph and the volumetric concentration C_v=0,5: (left) model Bela21 (τ = 18 N/m^2; η = 5.4 Pa.s); (right) model Bela22 (τ = 800 N/m^2; η = 185 Pa.s).

For three selected volumetric concentration C_v (0.40; 0.45 and 0.50), we define from literature (FLO, 2007) the lower and upper theoretical limits for the two rheological parameters in the quadratic law applied in Flo-2D, namely τ and η, as determined for numerous debris flows. Then we applied these extreme values (12 combinations, see Table 3) to assess the sensitivity of the numerical model with the grid 15 x 15 m with regard to flow depths and velocities as well as run-out on the Koroška Bela fan. The position of the input hydrograph and the other model parameters were kept unchanged: resistance parameter for laminar flow K was taken to be 2285 (as suggested in FLO, 2007), and sediment specific gravity of 27 kN/m^3, the existing buildings on the fan were represented by blocked (dry) cells, and the Manning roughness coefficients for the typical land uses were selected as follows: forest 0.16 sm$^{-1/3}$; grassland 0.033 sm$^{-1/3}$; torrent channel 0.13 sm$^{-1/3}$; built areas between buildings 0.035 sm$^{-1/3}$.

Using the numerical grid 15 x 15 m, the results for very different rheological parameter values but for the same volumetric concentration C_v were practically the same (Figure 4), also in cross sections. The difference was noticeable only when comparing the modeling results for different volumetric concentrations. This in a way stresses the importance of assessing potential debris-flow magnitudes and determining the corresponding volumetric concentrations C_v.

Table 4 Further numerical models on the Koroška Bela fan

Model	Hydrograph	Yield stress τ (N/m^2)	Dynamic viscosity η (Pa.s)
Bela22	$Q_{100,}$(19 h) $C_v = 0.5$	800	185
Bela22a	$Q_{100,}$(19 h) $C_v = 0.5$	18000	185
Bela22b	$Q_{100,}$(19 h) $C_v = 0.5$	800	3000
Bela22c	$Q_{100,}$(19 h) $C_v = 0.5$	18000	3000

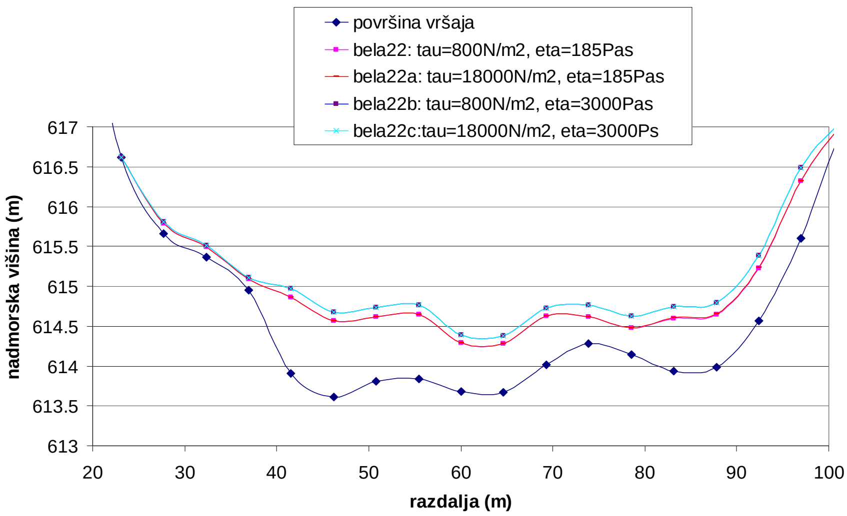

Fig. 5 A cross section in the upper part of the Koroška Bela fan – a comparison of computed debris-flow surfaces using different values for rheological parameters

Due to discussed insensitivity of the numerical models on the rheological parameters, further sensitivity analysis using wider spectrum of rheological parameter values in the order of more than one magnitude has been undertaken (Table 4). All other model parameters were kept unchanged. In the selected cross section in the upper part of the Koroška Bela fan, shown on Figure 5, we can see only slight differences between debris-flow surfaces on the Koroška Bela fan for several numerical models. The applied rheological parameter values might seem unrealistic but even now the influence yield stress τ was neglecting and of the dynamic viscosity η was rather moderate. Comparing the model Bela22a with the model Bela22, both with the same dynamic viscosity η, the flow depths and velocities stayed practically the same. When introducing changed dynamic viscosity η into the model Bela 22b, only moderate changes when compared to the model Bela22 were observed: maximum flow depth increased from 4.3 m to 4.4 m, and maximum flow velocities decreased from 7 m/s to 5.8 m/s.

There are practically no differences between the Models Bela22b and Bela22c (Figure 5). The yield stress τ is much less important than dynamic viscosity η and the surfaces for two numerical models with the same dynamic viscosity η in different yield stress τ are practically the same.

CONCLUSIONS

A 2D modeling of potential debris flows on selected torrential fans in the Sava Dolinka valley in NW Slovenia, using commercial software Flo-2D, yielded some interesting conclusions. If the 5 x 5 m grid was used, computational times using a state-of-the-art desktop personal computer (Intel Core2Duo processor 3.0 GHz, 4 Gb RAM) were of the same order as the duration of the design extreme debris-flow event (ratio between 1:2 and 1:3), but the 15 x 15 m grid accelerated the computations by a factor of more than two magnitudes (between 480 and 720 times faster), thus making it possible to perform an effective model sensitivity analysis in an acceptable time frame.

Nevertheless, for preparing proper debris-flow hazard maps, as precise as available DEMs should be used. Due to its automatic production, DEM 5 causes the flow to “jump” out of the channel on the Trebiža Fan. On the other hand, DEM 12.5 yields much more physically realistic results, since it was produced by combining different existing data using an innovative approach and applying high quality assurance standards. With regard to these uncertainties of DEM 5, more refined topographic representation is needed in some field cases when modeling torrential flows or debris flows. The next step in modeling natural hazards such as debris flows will eventually be the application of even more precise DEM, such as e.g. DEM 1 from laser scanning – a direction that we could only strongly support.

Furthermore, we showed that buildings that are not shown on DEMs should be modeled, because they have large influence on the nearby flow field. The approach to introduce buildings into the numerical grid model by simply defining them as blocked (dry) cells proved to be a better solution than raising the Manning roughness coefficient in these cells to account for flow obstruction by buildings.

The sensitivity analysis has also shown that main model rheological parameters (yield stress, dynamic viscosity) are relevant parameters but with a limited influence on final modeling results (debris-flow run-out, also flow depths and velocities). More important parameters when modeling potential debris-flows are definitely precise data on terrain topography (at least DEM 5; roughness coefficients) and the potential debris-flow magnitude.

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