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USING LIDAR DATA FOR DEBRIS FLOW MODELLING

Jošt Sodnik[1], Tomaž Podobnikar[2] and **Matjaž Mikoš**[3]

ABSTRACT

Mathematical modelling is a common approach when assessing debris flow hazard. In this study we applied the widely used Flo-2D model. The high accuracy of the input parameters is essential for obtaining acceptable results. The numerical grid in the area of the debris flow movement is generated from topographic data. In Slovenia, DEM5 and DEM12.5 are publicly available data. Yet, morphological accuracy of those datasets is questionable because of their development methods and their low morphologic resolution. A better solution is LiDAR derived data with higher resolution and a lot of options for further improvements with different methods and algorithms. Results with LiDAR data are more accurate and more useful for debris flow hazard mapping. The modelled depths and velocities are more accurate and follow better field conditions. Downside of the high resolution data is much longer computational time. Since torrential fans are often densely populated, modelling of built structures' influences is also important. With adequate modelling of such structures the obtained results are more accurate with better expressed local flow conditions.

Keywords: Debris-flow, numerical modelling, LiDAR data, DEM, hazard assessment

INTRODUCTION

The determination of hazard areas due to different mountain hazards, among others are also debris flows, has gained wide acceptance in the alpine countries. Due to their relatively rare and sporadic occurrence in many areas, their numerical modelling is an important part of the debris flow hazard assessment. The reliability of such a modelling is a function of several input parameters, but to a different extent for each one of them. Our past sensitivity analyses of the widely used numerical model Flo2D showed that the most influential parameters were event magnitudes and topographic data of an investigated area (Sodnik et al., 2009; 2010). For natural conditions prevailing in Slovenia, we have already checked different methods for estimation of debris flow magnitudes (Sodnik and Mikoš, 2006). Now we have tried to evaluate the usefulness of LiDAR data for numerical debris flow modelling in comparison with other DEMs.

TESTBED DESCRIPTION

The Koroška Bela torrential fan in NW Slovenia covers 1.02km^2 with numerous houses and 2200 residents (high damage potential). The torrential watershed area is 6.4km^2 with average slope of 52% and the height difference of 0.57km. In the headwaters there is an active landslide that might under unfavourable conditions turn into a debris flow. In 1789, a large debris flow on the fan ruined 40 houses and several mills (Jež et al., 2008).

DEBRIS FLOW MODEL DESCRIPTION

We used for debris flow modelling the commercially available model Flo-2D that has been applied successfully several times in Slovenia for these purposes, i.e. in the village of Log pod Mangartom (Četina et al., 2006), in the village of Koseč above Kobarid (Mikoš et al., 2006), for the official

[1] Jošt Sodnik, MSc in Civ. Eng., Water Management Company, Kranj & Faculty of Civil and Geodetic Engineering, University of Ljubljana, Slovenia
[2] Tomaž Podobnikar, PhD, Scientific Research Center of the Slovenian Academy of Art and Sciences & Faculty of Civil and Geodetic Engineering, University of Ljubljana, Slovenia
[3] Prof. Dr. Matjaž Mikoš, MSc in Civ. Eng., Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova c. 2, 1000 Ljubljana, Slovenia (e-mail: matjaz.mikos@fgg.uni-lj.si)

determination of the risk area due to potential debris flows in the village of Log pod Mangartom (Mikoš et al., 2007), and for a potential debris flow in the Hrenovec torrential watershed (Sodnik and Mikoš, 2010).

Flo2d (O'Brien, 2011) is software for two-dimensional mathematical modelling of water movement and fast flowing slope processes including debris flows. This model is in the USA recommended software tool by the Environmental Protection Agency (EPA) for analysis of natural hazards that found wide usage in many countries. Modelling is based on physical laws of the flow and is useful under different geographical conditions – the specialties of each single treated problem are taken into account by selecting different model coefficients and, of course, by the input of topographic data. For the description of the area geometry the model uses the numeric grid made out of quadratic cells of selected size. Computational grid cell size is user defined. After definition of grid cell size, model uses interpolation methods to define height of each cell, basing on applied DEM. Water flow respectively debris flow modelling depends on the form of the computing model as well as on the roughness of each computing cell. A very important role when modelling movement of debris flows is also given to rheological parameters of a water-debris mixture that are into more detail described in continuation of this paper. The basic model equations in all directions (shown here are only equations for the x-direction) are the continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial h V_x}{\partial x} = i \tag{1}$$

and the dynamic equation:

$$S_{fx} = S_{0x} - \frac{\partial h}{\partial x} - \frac{V_x}{\partial x}\frac{\partial V_x}{\partial x} - \frac{V_x}{g}\frac{\partial V_x}{\partial x} - \frac{1}{g}\frac{\partial V_x}{\partial t} \tag{2}$$

where h is flow depth [m], V_x is depth-averaged flow-velocity component in the x-direction [m/s], S_{fx} is slope of energy line or simply the total friction slope [-], and S_{ox} is the channel (relief) slope [-]. Part of the equations are also pressure gradient i [-] and local flow accelerations.

The dynamic equation is used in such a way that we compute the depth-averaged flow velocity in each computing cell separately for the eight directions (similarly as the directions in the sky are defined; a similar procedure named the D8 algorithm is used for modelling rock falls on slopes; Petje et al. 2005). The velocity in each direction is computed as one-dimensional quantity not-dependent on the other velocities. The stability of the computing numerical scheme is assured by selecting correspondingly short computing step as a function of the selected computing cell size.

Debris flows are non-homogenous (anisotropic) and non-Newtonian fluids (Mikoš, 2000/2001). Their movement is dependent on the rheological properties of the mixture, relief, surface slope and surface roughness. The debris flow mixture is composed of water and debris of different sizes; the debris flow movement is thus actually a multi-phase flow that might also have wooden additions (bushes, trees, stumps, branches). The quantity of material respectively material concentration determines the specific gravity, shear strength and mixture viscosity. The material concentration in the mixture is expressed by the volumetric concentration C_v that is itself expressed by a ratio of the debris volume to the total volume of the water-debris mixture. This concentration is of importance for further treatment of debris flow movement, since this data helps to determine the debris flow magnitude. Also the way of movement is dependent on the concentration of the water-debris mixture. That is why apart from the volumetric concentration also the following data are needed for modelling a debris flow:

- the resistance parameter for laminar flow
- specific weight
- yield stress
- viscosity

The resistance parameter for laminar flow [-] expresses the surface roughness, over which the debris flow moves. This parameter is of importance for phases when the flow is laminar or in a transient regime. For strict turbulent flows is this parameter of less importance. The value of the resistance parameter K goes from 24 for smooth prismatic channels all the way up to 50,000 for rough and geometrically more complicated cases. For modelling of debris flows its calibrated value is 2285 (O'Brien, 2006). For turbulent flow resistance is presented with n_d being the turbulent dispersive n of Manning roughness coefficient which is user defined for each computational grid cell. The depth-integrated dissipative friction slope (S_f) is shown in following equation

$$S_f = \frac{\tau_c}{\gamma_m h} + \frac{K\mu_N u}{8\gamma_m h^2} + \frac{n_d^2 u_2}{h^{4/3}} \tag{3}$$

where γ_m is specific debris flow weight, h the flow depth, u the mean flow velocity, K the resistance parameter for laminar flow and n_d the turbulent dispersive n of Manning (Cesca & D'Agostino, 2008).
Debris specific weight γ_m [N/m^3] is an important data for determining the mixture specific weight that depends on the debris specific weight and the volumetric concentration C_v of the debris in the mixture. The mixture's flow characteristics on the slope strongly depend on the specific weight of the mixture. When modelling the debris flow on the Koroška Bela fan, we used the specific weight of 27kN/m^3.
Yield stress depends on the volumetric concentration C_v of the debris in the mixture. We should determine two coefficients, namely α and β, because the yield stress is determined from the equation of the following form:

$$\tau_y = \alpha e^{\beta C_v} \quad [\text{dyn/cm}^2 = 10^{-5}\ \text{N/cm}^2] \tag{4}$$

Viscosity of the mixture depends on the volumetric concentration C_v of the debris in the mixture. Also here we should determine two coefficients, namely α and β, because the viscosity is determined from the equation of the following form:

$$\eta = \alpha e^{\beta C_v} \quad [\text{P} = \text{g cm}^{-1}\ \text{s}^{-1} = 10^{-1}\ \text{Pa.s}] \tag{5}$$

TOPOGRAPHIC DATA IN SLOVENIA

The digital elevation models are basically recorded as raster layers in 2.5D, with one attribute of elevation. The 3D DEM production requires much more complex structure and modelling, especially when using very detailed laser scanning-based (LiDAR) data. In our case the solution of the problem requires only 2.5D DEMs that are realised as raster data sets where each square cell contains an elevation value.
Quality of the DEMs has been considerably increased during the last years and consequently more advanced applications based on DEM-analysis are used, e.g., for enhances morphometric analysis of floods or debris flows (Podobnikar, 2009). The quality of any spatial analyses that is based on a DEM depends greatly on its geometrical and, especially, on morphological accuracy. However, due to its complexity, the primary challenge is to produce a high quality DEM according to well defined nominal ground (data model), ideally without errors and in an appropriate resolution. Many acquisition methods – especially contemporary ones through LiDAR or radar interferometry are relatively fast and can offer quality data sources.

Tab. 1 Characteristics of the DEMs used in this study

Name (produced)	Accuracy (RMSE*)	Production method
DEM12.5 (2001-2005)	3.8 m	fusion of existing geodetic datasets of different type/quality
DEM5 (2006-2007)	3.5 m	resampling of DEM12.5 + stereo photogrammetry and local adjusting with CAD-tools
DEM0.5 (2009-2010)	5-10 cm (in channels gross errors > 1m)	datasets of 12 blocks (leaves & snow); different approaches to filtering and interpolation
DEM5 from DEM0.5 (2010)	5-10 cm (in channels gross errors > 1 m)	resampling of DEM0.5

* RMSE (Root Means Square Error)

Four DEMs were applied in our study: DEM12.5, DEM5, DEM0.5, and DEM5 derived from DEM0.5 (Tab. 1). The first two are property of Surveying and Mapping Authority of the Republic of Slovenia (public available data) and the second two of the Flycom Company.
The DEM12.5 was produced according to appropriately fused various existing data sources, which were of different quality, where their best properties were exposed (Podobnikar, 2005; 2010). The final DEM is overall of better quality than any used data source. The method of weighted sum of sources with morphologic enhancement includes iterative repeated processes where the experiences and evaluations of the procedures and results acquired from previous steps provide better starting-point for each of the subsequent steps. Such iterative process takes more time, however it was rationally finished within two loops. The principal steps for such DEM production are:

- mosaicking selected data sources to produce a principal DEM,
- weighted sum of secondary data sources,
- (geo)morphologic enhancement, and
- reference point consideration in the modelling.

Different aspects of quality were continuously monitored trough the process. The final product was an optimised DEM that considered different properties of landform, geometrical and morphological accuracy, and wide range of users and applications. The DEM is somewhat universal for many different users' requirements.
The DEM5 was produced by simply resampling of the DEM12.5, and with further improving of geometrical accuracy on the areas where the previously RMSE was considerably significant (Podobnikar 2008). Aerial photographs and principles of stereo photogrammetry were applied. The areas with significant RMSE were locally adjusted CAD-tools. The final DEM 5 is geometrically higher quality than the DEM12.5, but quite inhomogeneous with low morphological accuracy. This DEM is unfortunately not much useful for any geomorphometric spatial analysis, i.e. for debris flow modelling.
The DEM0.5 was captured as a fullwave point cloud in two different periods, where some snow in the high mountains and leaves on most trees in the lower elevations occurred. Point density was inhomogeneous, from 1 to 10points/m^2. The vertical angle of scanning was 0º to ±30º with laser scanner Litemapper LM 5600 (alias Riegl LMS –Q560). Orthophotos with the resolution of 0.5 m were acquired together with scanning. The final DEM of 0.5m resolution was produced with Terrasolid software. The result is not perfect. The problem was reconstruction of a surface of the bare ground on the areas of leaf canopies, buildings and especially on the areas of streams. The main problems for our debris flow simulation are the areas of steams and their surroundings. At those areas occurs at some places combination of trees and bushes and the buildings are located just along the streams. Less important, but obvious errors occur due to rough mountain landscape. The produced DEM0.5 needs further improvement, where more advanced filtering and possible combination and fusion of the other data sources will be implemented. Additional model for the debris flow simulation will be produced – a digital surface model (DSM), as a combination of the DEM and buildings, where the required level of detail (LOD) according CityGML standard is 0.
All DEMs were resampled to resolution of 5m and 12.5m using two interpolation approaches. In case of interpolation to lower resolution a bilinear interpolation was applied and in case of interpolation to higher resolution a spline interpolation with filtering was applied.

STRUCTURES AND DEBRIS FLOW MODELLING

Torrential fans are often densely populated, a fact that makes structures an important part of the debris flow modelling. Structures and people living on the fan are also one of the main reasons for debris flow hazard assessment and delineating hazard zones. The Koroška Bela testbed is densely populated which makes proper structure influence modelling very important.
We used two approaches for presentation of structures on the fan. First we used increased Manning roughness values to represent areas with buildings. Second we used blocked cells to present buildings. Using aeral photos we recognized objects on the fan and defined blocked cells for the buildings using function "area reduction factor" of the Flo-2D model.

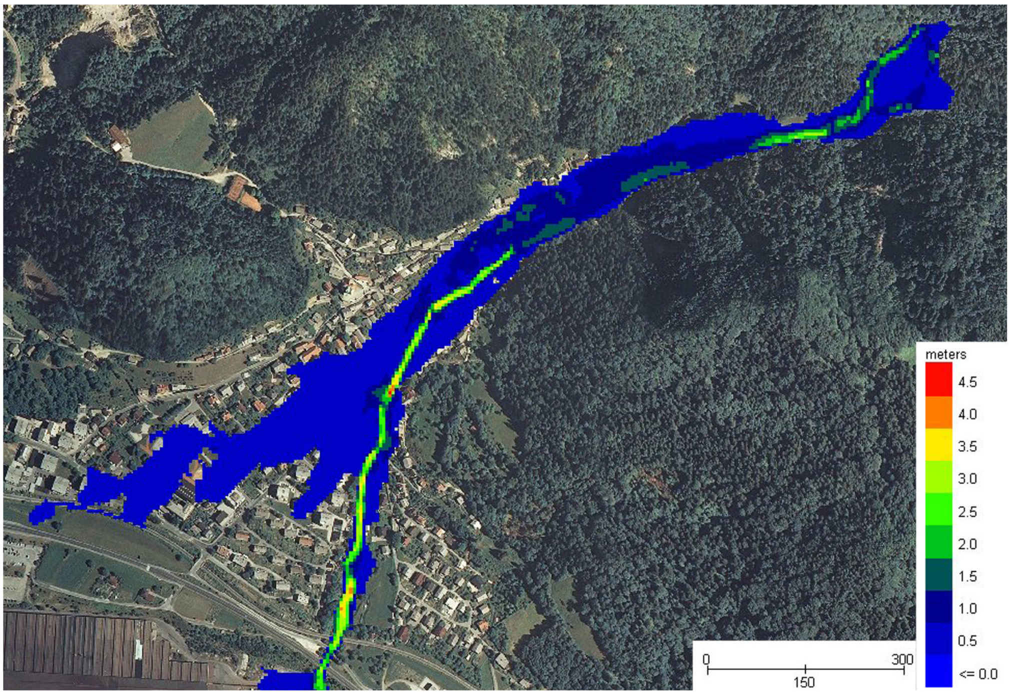

Fig. 1 Maximum depths using higher Manning coefficient for representing structures.

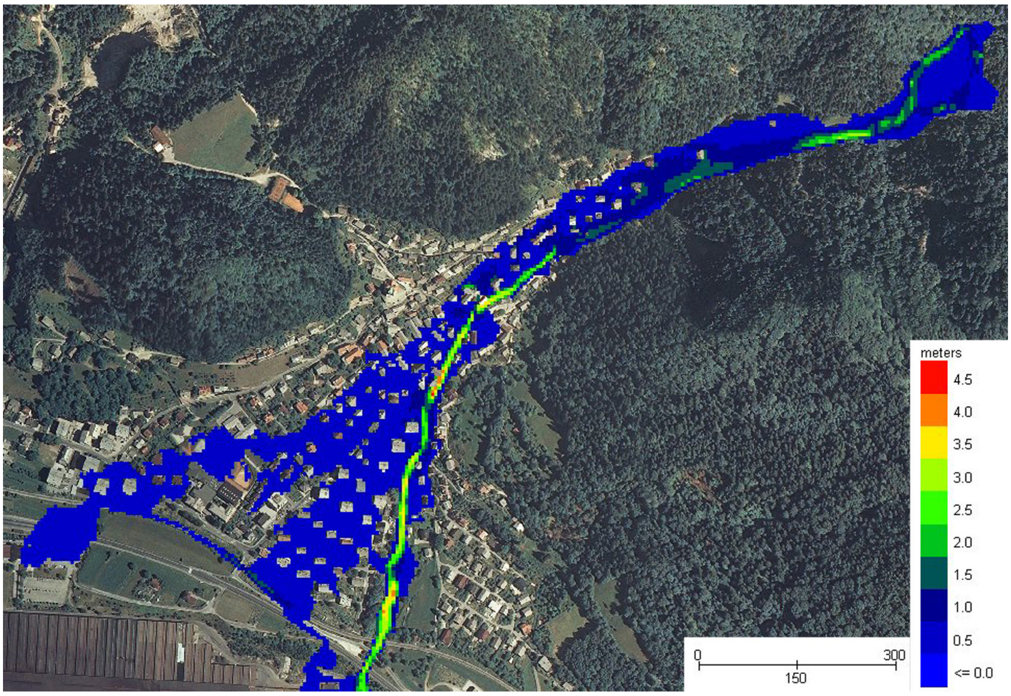

Fig. 2 Maximum depths using blocked ("dry") cells for representing structures.

In both cases we used exact same debris flow event scenario and parameters. We used 19h inflow hydrograph modelled with HEC-HMS using 100-year precipitation. The peak discharge was $50m^3/s$ + debris = $87.5m^3/s$. Since we have no historical data of past events in testbed, we used parameter values gathered when calibrating Flo-2D model for other recent debris flow cases in Slovenia. The volume concentration and rheological characteristics were calibrated with the Flo-2D model for debris flow in Log pod Mangartom (Četina et al, 2006). The volumetric concentration was 0.42, the critical shear stress 20Pa and the Bingham viscosity 10Pa.s. The defined control parameters of the model were: the surface detention 0.03, the percent change in flow depth 0.2 and the dynamic wave stability coefficient 5. The following Manning roughness coefficients were used: n_g(forest) = $0.16sm^{-1/3}$, n_g(meadow) = $0.033sm^{-1/3}$, n_g(channel) = $0.13sm^{-1/3}$, n_g(building area) = $0.035sm^{-1/3}$ and n_g(buildings) = $0.2sm^{-1/3}$ for

two topographical situations: buildings are represented by higher roughness values (n_g(buildings) = 0.2sm$^{-1/3}$) and buildings are represented by blocked (dry) grid cells (for the area around dry cells we used n_g(building area) = 0.035sm$^{-1/3}$).
Figs. 1 and 2 show that blocked cells (houses) cause debris flow to concentrate in the channel, because dry cells are more realistic obstacles in the flow on the fan. In the model with higher roughness coefficients flooded area in the upper part of the fan is wider, less flow in the channel area. In the lower part of the fan we can see the difference in the reach of debris flow. The flooded area in the case with blocked cells is larger because the flow can travel between the objects (n_g = 0.035ms$^{-1/3}$). In the case with the higher roughness coefficient, the flow stops due to higher flow resistance.

Fig. 3 Maximum velocities (vectors) using blocked ("dry") cells for representing structures (the upper part of the fan).

The influence of blocked cells modelling is even better expressed with local conditions. Fig. 3 shows the increased local velocities of the flow between the buildings. The approach with blocked cells is more precise plus it is more useful for estimating impact forces on the structures in flooded areas.

Tab. 2 Comparison of results (modelling structures)

Model description		Maximum inundated area [m^2]	Average flow depth [m]	Average flow velocity [m/s]
Structures represented as higher Manning coefficient		148,800	0.47	1.05
Structures modelled as blocked cells	Included all blocked cells	158,600	0.41	1.20
	Without 40% of blocked cells	139,290	0.47	1.36

Table 2 shows comparison of maximum inundated area, average maximum flow depth and average maximum flow velocity. The area of all blocked cells is 48,000m^2. If we consider 40% of all blocked cells to be in the inundated area, we can see that the largest influence of blocked cells is on maximum velocities of the flow. Higher average value is consequence of higher local velocities between the objects, shown also in Fig. 3. Average maximum flow depth is similar in both cases. With blocked cells approach, because of the building the "effective" flow area is smaller which results in higher average maximum flow velocities values.

Increased roughness coefficient does not represent local phenomena among the buildings. Option with higher roughness coefficients is useful for preliminary estimations and rough estimations of debris flow hazard. It has to be mentioned that using blocked cells increases computational times for 20 – 25%. House by house defining blocked cells in cases with dense population can also be quite time-consuming work. A question of structures collapsing under impact of debris flow stays open. With blocked cells we presume that all structures will stand the load of debris flow impact.

TOPOGRAPHIC DATA AND DEBRIS FLOW MODELLING

In past researches we have established that topographic data of the fan is one of the most important input data of the debris flow model. DEM topographic data is a basis to prepare numerical square grid for 2D modelling of possible debris flow on torrential fan. In present research we used publicly available DEM5, DEM12.5 and LiDAR derived DEM0.5 and DEM5 (re-sampled DEM0.5) (LiDAR).
The event scenario is defined with inflow hydrograph on the peak of the fan. We used 15min potential event scenario with 250m^3/s peak discharge + debris = 431m^3/s. The total magnitude of the event was 155,500m^3 (water + debris). The volumetric concentration was 0.42, the critical shear stress 20Pa and the Bingham viscosity 10Pa.s. The defined control parameters of the model were: the surface detention 0.03, the percent change in flow depth 0.2 and the dynamic wave stability coefficient 5. The following Manning roughness coefficients were used: n_g(forest) = 0.16sm$^{-1/3}$, n_g(meadow) = 0.033sm$^{-1/3}$, n_g(channel) = 0.13sm$^{-1/3}$ and n_g(buildings) = 0.2sm$^{-1/3}$. Buildings are represented by higher n_g roughness values, since the objective of the research was to research the influence of topographic data on modelling results.
Fig. 4 shows the lack of morphologic accuracy of DEM5. Even with lower resolution of data the model with DEM12.5 (Fig. 5) is more correct. In the upper part of the fan Fig. 4 debris flow overbanks and depths are practically the same all over the fan (no concentration of the flow in the channel). The width of the channel in that part is 5 to 7m. In Fig. 5 the channel is made wider than in nature due to the DEM resolution 12.5m but morphologically more correct, since the torrential channel is better expressed. Comparison between Figs. 4 and 5 shows that despite of poor resolution the DEM12.5 is more useful for preliminary hazard assessment, because the flow is more concentrated in the channel. DEM5 underestimates the channel which leads to increase of assessed hazard outside the channel. The answer for better quality of DEM12.5 lies in a different creation processes of DEM12.5 and classic DEM5.

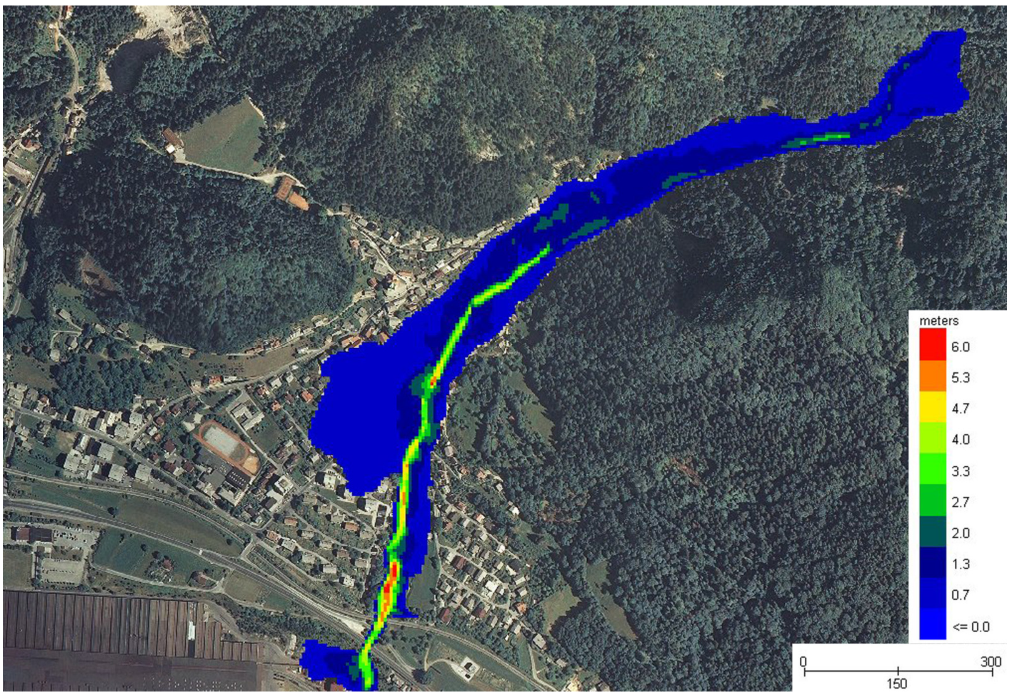

Fig. 4 Maximum flow depths using classical DEM5

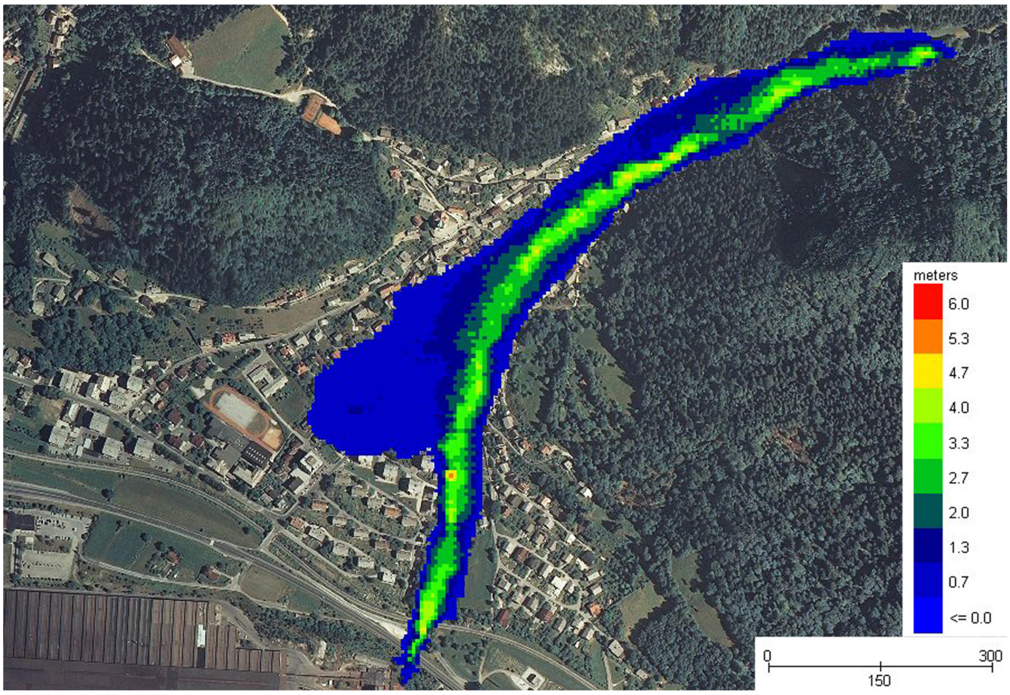

Fig. 5 Maximum flow depths using classical DEM12.5

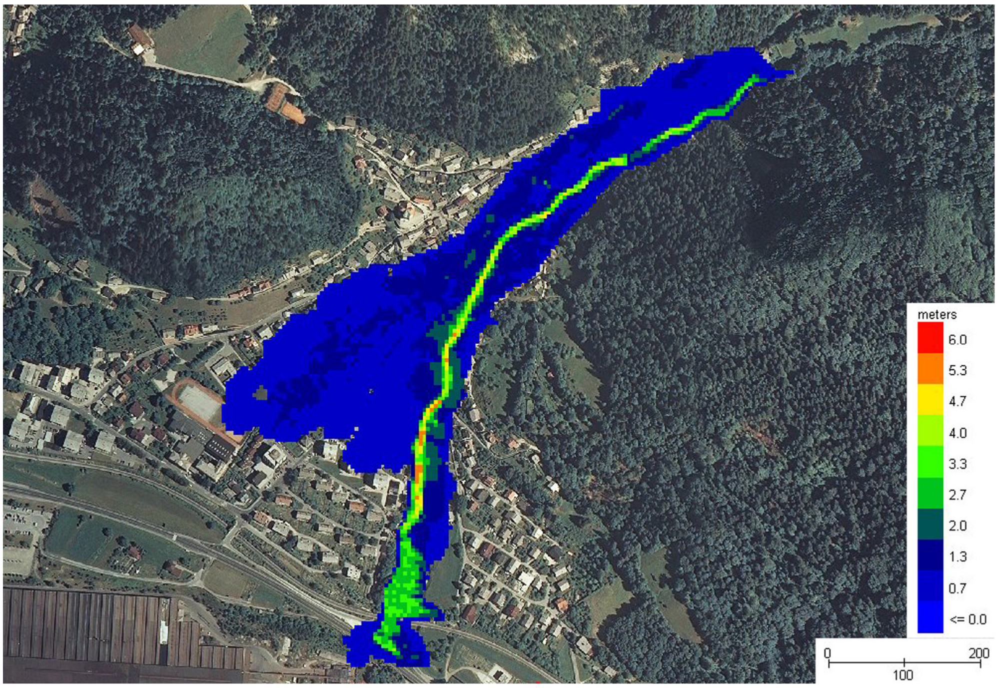

Fig. 6 Maximum flow depths using DEM0.5 (original LiDAR data)

LiDAR derived DEM's (Figs. 6 and 7) enable much more accurate topographic data of the fan. Both models (DEM5 and DEM0.5) are morphologically more correct than other two models (public DEM5 and DEM12.5). The main difference is in the topography of the torrential channel. With LiDAR derived data the channel is better expressed and larger part of debris flow travels in the channel. Flow depths on the fan are more heterogeneous because the surface is more agitated due to more precise data. Variations in the flow depths lead to more accurate hazard mapping.
Inter-comparison between the models with LiDAR derived DEMs (Figs. 6 & 7) shows that the main difference is the modelled flow depths in the inundation areas outside of the channel. The model with DEM0.5 (grid cell height interpolation integrated in a Flo-2D) derives bigger differences in flow depths in the inundation area when compared to LiDAR derived DEM5 (bilinear interpolation) which leads to more precise hazard mapping. With higher resolution DEM data, local conditions of the flow

are better represented. Higher resolution data leads to similar improvements than correct structures modelling (Fig. 3).

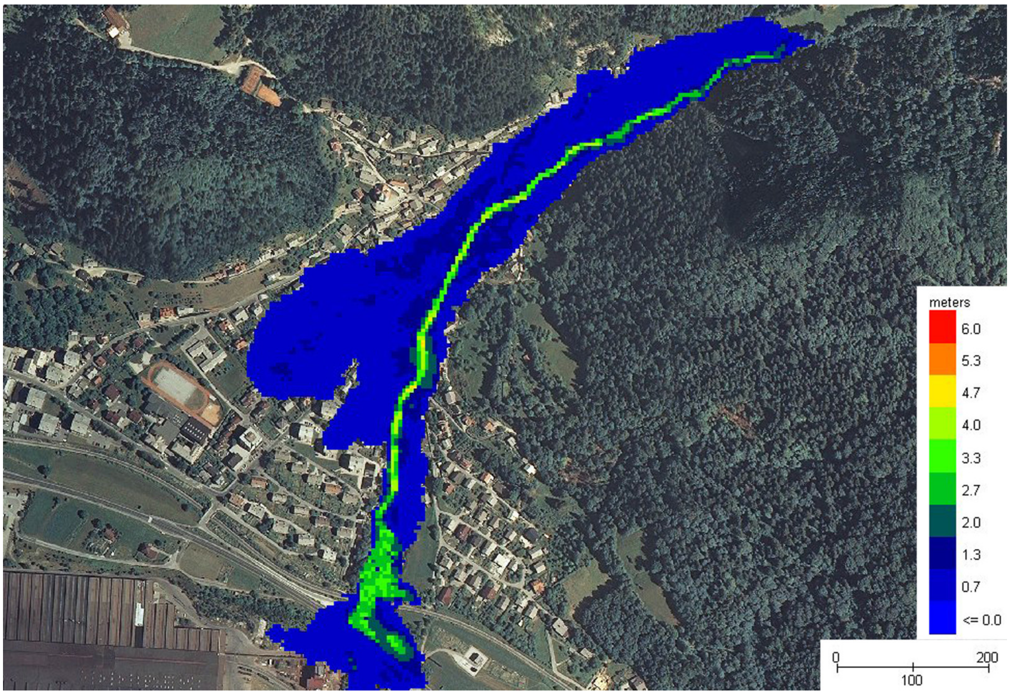

Fig. 7 Maximum flow depths using DEM5 (re-sampled LiDAR data)

Tab. 5 Comparison of results (topographic data)

Model description	Maximum inundated area [m^2]	Average flow depth [m]	Average flow velocity [m/s]	Computational time [h]
Public DEM5	145,325	0.78	2.38	1.9
Public DEM12.5	118,675	1.18	2.37	2.8
LiDAR DEM0.5	131,200	0.80	1.84	32
LiDAR DEM5	131,325	0.71	2.40	26

Table 5 shows comparison of maximum inundated area, average maximum flow depth and average maximum flow velocity with using different input DEM data. Computational times of all models are also presented. Table 5 shows that modelled values and computational times vary with use of different DEM data.

With using public DEM5, poor expression of the torrential channel in the upper part leads to largest maximum inundation area. Average flow depths and average flow velocities with public DEM5 are comparable with using LiDAR data. Considering the differences shown in Figs. 5 - 8 that fact is most likely a coincidence. The maximum inundated area with DEM12.5 is lower due to a fact that torrential channel is overestimated which leads to underestimation of flow depths and inundation area outside the channel. The same reason stands behind the highest value of the average flow depth using DEM12.5.

The maximum inundation areas with LiDAR derived DEMs are practically the same. The difference is shown in the flow depths and flow velocities.

The influence of DEM0.5 is shown in higher flow depths and lower average velocities. Those two results are consequence of a better presentation of the local conditions on the fan (Fig. 6 shows more heterogeneous image of flow depths). A more agitated surface leads to lower velocities and higher flow depths. With higher data resolution the local surface conditions are much better presented. The difference between LiDAR derived DEM5 and DEM0.5 also shows the difference between the height interpolation integrated in Flo-2D and the bilinear method used for re-sampling LiDAR data for creating the LiDAR derived DEM5.

A large increase of computational time is also shown in Table 5. For 15min event computational time varies from 1.9 to 32h.

CONCLUSIONS

Debris flow hazard assessment is very important on torrential fans exposed to that phenomenon. Torrential fans are often occupied with settlements and different infrastructure (Mizuno and Terada, 2004). Numerical (mathematical) modelling is surely the answer, but input data and type of model is a question still open. With LiDAR technology it is possible to get very accurate and quite reliable topographic data of the surface, and there is a lot of possibilities of re-sampling and improving the data (Seijmonsbergen, 2008). With high quality data it is also possible to develop algorithms for torrential fans remote detection. In Slovenia we have debris flow susceptibility map in scale 1:250,000, where grid cells (25x25m) with high potential for debris flow initiation are detected. With better accuracy of susceptibility map (scale 1:25,000 or smaller) and areas parted over torrential basin areas and combination with LiDAR based torrential fans detection it is possible to recognize debris flow endangered torrent, where more detailed analysis with modelling is needed. This approach would help regional hazard assessment. In Slovenia we still don't have proper legislation to prescribe methodology for debris flow hazard assessment and hazard map production.

When performing debris flow modelling besides topographic data the main question remains magnitude of event and rheological characteristics of the mixture. For debris flow magnitude estimation different methods have been developed which are based on past events in different regions (Sodnik and Mikoš, 2006). These methods can be tested and modified for other regions, like Slovenian Alps. For modification and verification detailed terrain investigations should be carried out. Rheological characteristics of potential debris flow are very hard to estimate without any terrain investigations (Coussot et.al., 1998). For every region, debris material samples from basins should be gathered and rheological characteristics should be measured. Different mechanisms and devices are available for measurements. With measurements of samples we could define boundary values of rheological characteristics and use them when defining event scenario for hazard assessment.

Recently a lot of simulation models have been developed with different mathematical backgrounds. Besides Flo-2D used in this study there are different models available: TopRunDF, TopFlow, PCFlow2D, RAMMS and others. Some of them are based on empirical equations and are more useful for quick hazard assessment. The PARAmount project partners are developing a new operative tool for debris flow hazard assessment which includes triggering model, which is a step forward.

When it comes to question of type of model for hazard assessment it has to be clear that every model has its own theoretical background and sensitivity for input parameters. The Flo-2D model used in this study requires many input parameters and has many setup options when defining debris flow model. The most dependable way is to calibrate model to past event. In Slovenia there is no historical data about past debris flow events. There are records about extreme torrential events, but there is no data about inundation areas, magnitudes or flow depths. There is not even a clear line between "classic torrential outbursts" and debris flows.

We performed extensive sensitivity analysis with the Flo-2D model. The most important parameters turned out to be magnitude of the event (input hydrograph, peak discharge) and topographic data (Sodnik et al., 2009).This paper shows the influence of different types of modelling structures and different sets of topographic data. Other studies (D'Agostino and Tecca, 2006) showed that also rheological parameters in combination with resistance parameter for laminar flow K can be significant when calibrating model to past event. Large number of parameters and coefficients in Flo-2D model lead to a conclusion that we can achieve the same result (inundation area) with different combinations of parameters. That means it is very important to use only reliable data and parameters. It becomes even more complicated when assessing debris flow hazard for potential event where no parameters of the debris flow are known. In that case the knowledge of influence of each parameter and coefficient is crucial. That knowledge influences the final decision about the model for hazard assessment

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