TERRAIN TOPOGRAPHY AND DEBRIS-FLOW MODELLING

TOPOGRAFIJA POVRŠJA IN MODELIRANJE GIBANJA DROBIRSKIH TOKOV

Jošt Sodnik, Urška Petje, Matjaž Mikoš

UDK:519.61/.64:528.93:556.535

Klasifikacija prispevka po COBISS-u: 1.01

ABSTRACT

Debris flow hazard and risk assessment is not only based on assumptions on source areas and magnitudes of possible debris flows and their rheological characteristics, but also on their runout predictions. With regard to topographic presentation of slope surface over which a slope debris flow runs or presentation of a torrential channel along which a debris flow runs, this paper reports on the results of two-dimensional modelling of possible debris flows on selected torrential fans in the Sava Dolinka valley as a function of the numerical square grid (5 x 5 m, and 15 x 15 m), generated from freely available digital elevation model DEM 5. From the aspect of debris-flow numerical modelling we showed that buildings that are not shown on DEMs should be modelled, because they have large influence on the flow field close to them. 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 coefficient in these cells to account for flow obstruction by buildings. We also checked the applicability of the digital elevation model DEM 12.5 and generated from it a numerical grid 12.5 x 12.5 m. In the case of the Trebiža torrential fan it can be concluded that DEM 12.5 can be more geomorphologically representative than DEM 5. The next step in modelling natural hazards such as debris flows will eventually be the application of even more precise numerical grid, generated from LIDAR surveys of relief.

KEY WORDS

topography, digital elevation model, precision, modelling, numerical grid, debris flows, physical planning

POVZETEK

Presojanje nevarnosti in ogroženosti zaradi delovanja drobirskih tokov ne temelji samo na domnevah o izvornih območjih in magnitudah možnih drobirskih tokov ter njihovih reoloških lastnostih, temveč tudi na napovedi njihovega dosega. Glede na zajem topografije površine pobočja, po katerem teče pobočni drobirski tok, ali zajem oblike hudourniške struge, po kateri se premika drobirski tok, predstavljamo rezultate dvodimenzijskega matematičnega modeliranja možnih drobirskih tokov na izbranih hudourniških vršajih v dolini Save Dolinke v odvisnosti od velikosti računske mreže (5 x 5 m in 15 x 15 m), generirane iz digitalnega modela višin 5 m (DMV 5). Z vidika numeričnega modeliranja drobirskih tokov smo pokazali, da je treba modelirati tudi zgradbe, ki jih DMV 5 ne obsega, saj imajo velik vpliv na tokovno polje v bližini. Pristop, pri katerem so se zgradbe v numerični računski mreži upoštevale z vpeljavo blokiranih (suhih) celic, se je pokazal kot boljša rešitev od večanja koeficienta hrapavosti v teh celicah, da bi upoštevali motnje v toku, ki jih povzročajo zgradbe. Preverili smo tudi uporabnost digitalnega modela reliefa DMV 12,5 in iz njega generirali numerično mrežo 12,5 x 12,5 m. Na primeru hudourniškega vršaja Trebiže smo ugotovili, da je DMV 12,5 lahko bolj geomorfološko reprezentativen kot DMV 5. Naslednji korak pri modeliranju naravnih nevarnosti, kot so drobirski tokovi, bo uporaba bolj natančne računske mreže (recimo 1 x 1 m), generirane iz lidarskih posnetkov površja.

KLJUČNE BESEDE

topografija, digitalni model višin, natančnost, modeliranje, numerična mreža, drobirski tokovi, prostorsko načrtovanje

1 INTRODUCTION

In the field of physical planning in the European Alps, natural hazards play an important role. When using physical planning tools as prevention tools against natural hazards, it is important to take into account different types of Alpine natural hazards, such as flash torrential floods, landslides or debris flows (Mikoš, 1997). It is nowadays a legislative obligation in the majority of our Alpine neighbouring countries that all new construction permits for new infrastructure or buildings are issued only if adequate risk maps allow that (Đurović and Mikoš, 2004). For preparing risk maps, firstly, hazard maps should be prepared and in predefined areas at high hazard any new elements at risk (damage potential) should be avoided (Zakon, 2002). This modern approach in the field of risk management has been steadily reported and stimulated in literature, also in Slovenia (see Đurović and Mikoš, 2006 for terminology; see Mikoš et al., 2007 for the first Slovenian debris-flow risk map in Log pod Mangartom, incorporated into a special governmental decree (Uredba, 2004)). Soon we may expect further progress into this direction in the field of flood hazard and risk maps (Mikoš, 2007).

Debris flows as fast moving mixtures of earthen material (debris), water and in some cases woody debris (e.g. in Log pod Mangartom) are non-Newtonian fluids physically described by a set of non-linear equations for two-phase flows (FLO, 2006a). They can be initiated on slopes or in steep torrential channels during heavy (but rather short-duration) rainfalls or triggered by strong earthquakes (Mikoš, 2000/2001), and can be classified into the group of slope movements (Skaberne, 2001). Their advancement along a slope or a torrential channel and ultimately over a fan towards a valley floor is therefore rather complex and not very easy to predict. In order to be able to apply planning tools, we should be able to assess magnitudes (Sodnik and Mikoš, 2006) and predict run-out of future (possible) debris flows. 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 possible debris flow, rheological characteristics of the water-sediment mixture, surface roughness characteristics, and surface inclination (Sodnik and Mikoš, submitted for publication).

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 modelling 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 modelling 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 (CRP, 2009), the Alpine 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 modelling was the way how rheological properties (soil mechanical properties of sediment-water mixtures called debris flow) were taken into account. Doing that, we intentionally used our experiences gained when modelling real debris-flow cases in Slovenia in the recent past (large debris flow in Log pod Mangartom in 2000, and numerous small debris flows in Koseč above Kobarid in 2002).

2 TOPOGRAPHIC DATA

For two-dimensional modelling of debris flows we need topographic data in the form of numerical grids, easily generated from digital elevation models (DEM). The early development of digital elevation models in Slovenia down to DEM 25 is shown in Oštir et al. (2000) and Podobnikar (2003) from what is called Interferometric Synthetic Aperture Radar, or InSAR DEM 25. DEM 12.5, produced in 2005 as a composite model of all existing data, is shown in Podobnikar and Mlinar (2006). Such composite digital elevation model proved to be of high geomorphologic quality, but unfortunately could not be directly applied to two-dimensional modelling of stone falls and rock falls (Petje et al., 2005a). Therefore, in the case of the Berebica and Osojnik rockfalls in the Trenta valley, a field measured 2D computational profile was used instead (Petje et al., 2005b). The latest development of digital elevation models in Slovenia is summarised in Podobnikar (2008).

Guzzetti et al. (2004) successfully applied a 5 m grid cell for topographic representation along a transportation corridor in the Umbria Region of central Italy to study rock-fall hazard and risk assessment. 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 modelling 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 digitised 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 modelling of water courses (Rak et al., 2006), or specifically two-dimensional modelling of flood waves (Četina and Krzyk, 2007a; 2007b).

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 modelling natural phenomena such as debris flows will be shown in this paper.

The differences between the two computational numerical grids generated from DEM 5 for the Koroška Bela torrential fans can be seen from Figure 1. The 15 x 15 m grid was generated within the Flo-2D program using its capabilities to interpolate the grid element elevations (FLO, 2006b). The 15 x 15 m 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 hydrologic model HEC-HMS (HEC, 2000), a computational hydrograph for each torrential fan was determined (see details in Table 1).

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

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.

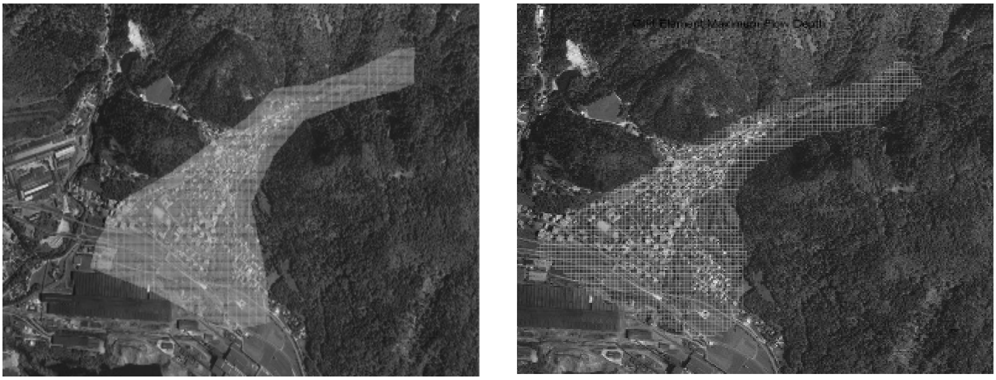

Figure 1: *Computational numerical grid 5 x 5 m (left) and 15 x 15 m (right) of the Koroška Bela fan.*

3 DEBRIS-FLOW MODELLING RESULTS AND DISCUSSION

As a debris-flow mathematical model we selected the commercially available two-dimensional model FLO-2D (O'Brien, 2006) that has been successfully applied in Slovenia, such as for post-event analysis in Log pod Mangartom (Četina et al., 2006), for debris-flow hazard assessment in Koseč above Kobarid (Mikoš et al., 2006), or for hazard assessment due to possible debris flows in the torrential watershed Hrenovec above Kropa (Sodnik and Mikoš, under review).

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: critical shear 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 Bingham 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 above Log pod Mangartom and Koseč above Kobarid). Therefore, we used: critical shear stress 20 Pa, Bingham viscosity 10 Pa.s for $C_v = 0.42$ (wet debris flow), critical shear stress 2000 Pa, and Bingham viscosity 156 Pa.s for $C_v = 0.50$ (dry debris flow). More detailed description of the Flo-2D model is given elsewhere (Fazarinc et al., 2006; Flo, 2006; Sodnik and Mikoš, submitted for publication).

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 modelling process. For the simulated hydrograph of 20 hours, the computational time for the 15 x 15 m grid was around 5 minutes (ratio around 240:1), and with the 5 x 5 m 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.

	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

Table 2. The main modelling 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 modelled by higher roughness coefficients, and the second row for the case where buildings were modelled by blocked (dry) cells).

If there are no field data available on recent debris flows, the selection of appropriate roughness (Manning) coefficients for a specific field study can be done only on the basis of literature review and/or own experiences with debris flow modelling. The roughness coefficients used in our numerical modelling were firstly selected from existing technical literature to be typical for these field conditions (Chow, 1959; Julien, 2002) as well as from Flo-2D manual (FLO, 2006a). 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 (Hojnik et al., 2001) and when modelling the debris flows in the village of Koseč (Hojnik, 2004; Rajar et al., 2004).

The Koroška Bela fan is densely populated, which is why we used the following roughness (Manning) 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 model, 206 grid cells (out of 2,385 cells or 8.64% resp. 46,350 m^2) and in the 5 x 5 m 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 grid instead of the 5 x 5 m grid yields lower values of flow depths and average flow velocities when representing buildings by higher Manning roughness values, and

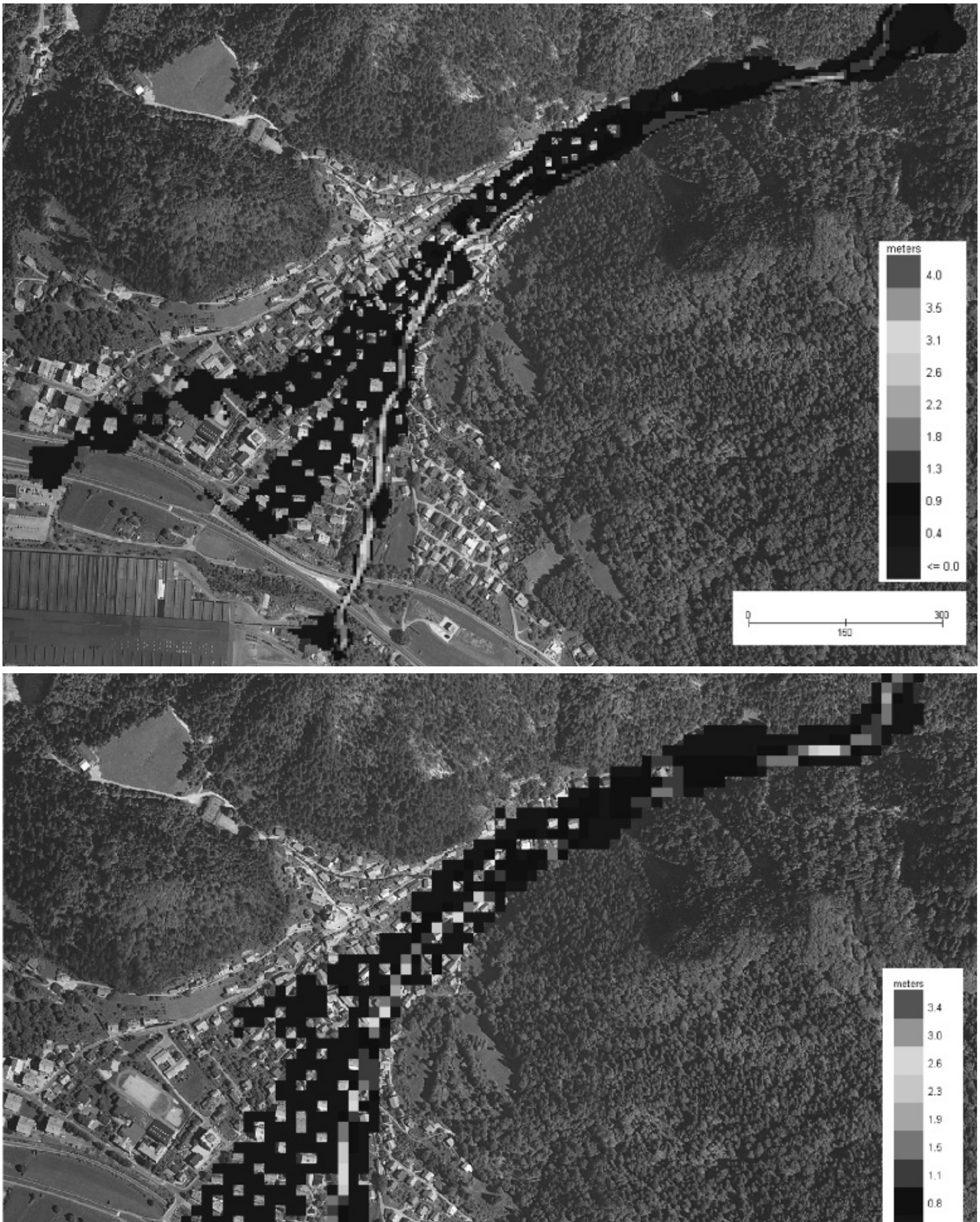

Figure 2: *Flo-2D model results for clear water on the Koroška Bela fan using two different numerical grids: 5 x 5 m (up) and 15 x 15 m (down) - building effects are covered by blocked (dry) grid cells where buildings were recognised on the ortophoto. Colours refer to maximum flow depth in metres.*

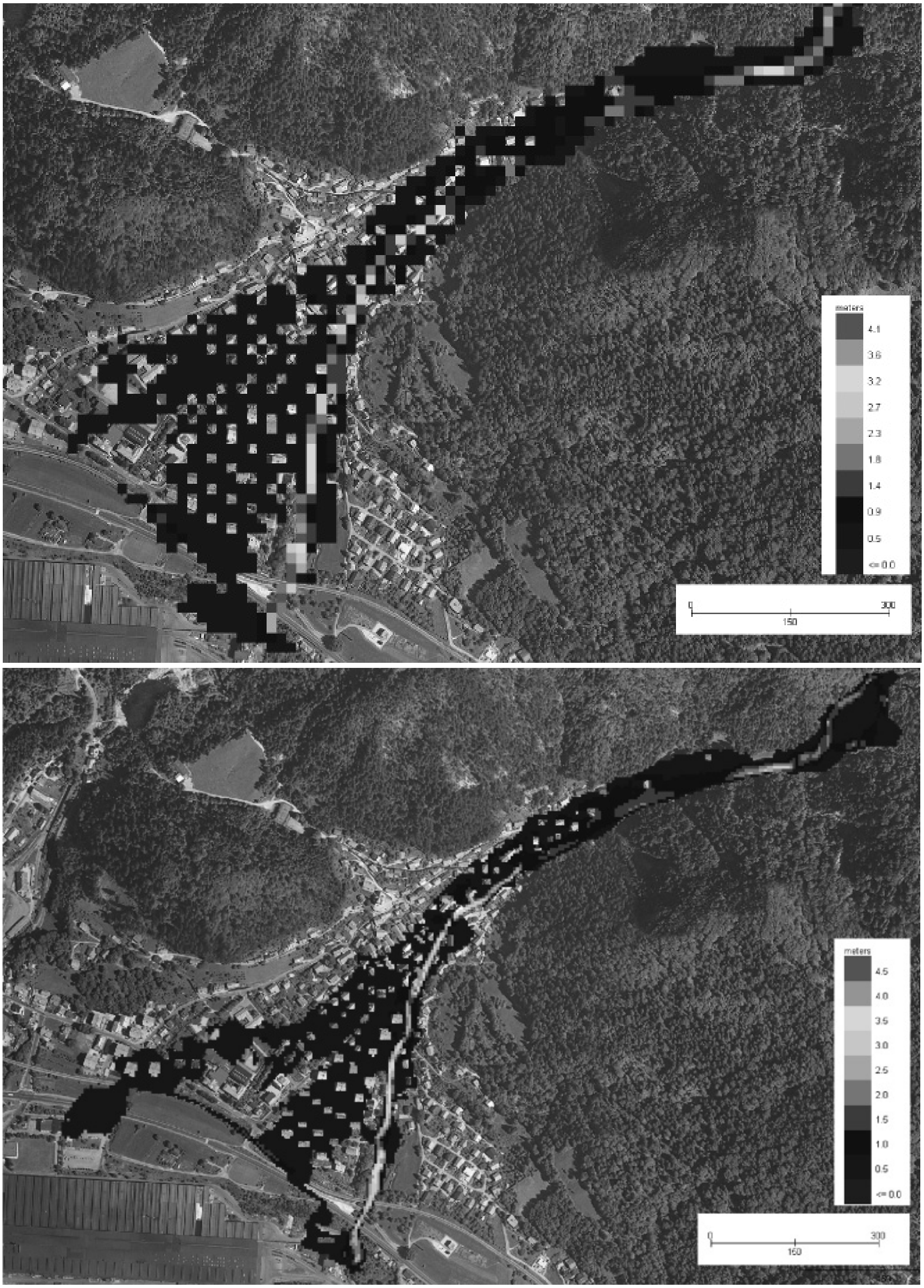

Figure 3: *Flo-2D model results for wet debris flow (C_v = 0.42) on the Koroška Bela fan using two different numerical grids: 5 x 5 m (up) and 15 x 15 m (down) - building effects are covered by blocked (dry) grid cells where buildings were recognised on the ortophoto. Colours refer to maximum flow depth in metres.*

higher values when representing buildings by blocked (dry) grid cells (Table 2). The difference between using the 15 x 15 m grid and the 5 x 5 m grid is especially pronounced for the clear water case (pure torrential event) and using blocked cells. Using the 15 x 15 m grid, the debris-flow modelling 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 modelling debris-flow events, using the 5 x 5 m grid instead of the 15 x 15 m grid yields more detailed hazard map with smaller inundated area and clear flow in the main torrential channel (Figure 3). This example clearly shows the advantage of DEM 5 over DEM 15 when assessing natural hazards in mountainous areas.

Furthermore, we also applied the 5 x 5 m grid on the Trebiža torrential fan (Figure 4). For the Trebiža fan the same roughness (Manning) 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 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 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 5). The problem with the 5 x 5 m 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

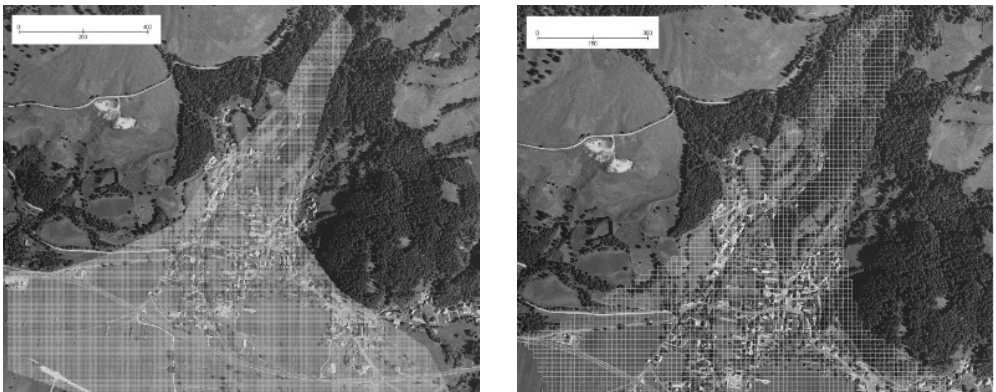

Figure 4: *Computational numerical grid of the Trebiža fan (the 5 x 5 m grid generated from DEM 5 on the left, and the 12.5 x 12.5 m grid generated from DTM 12.5 on the right).*

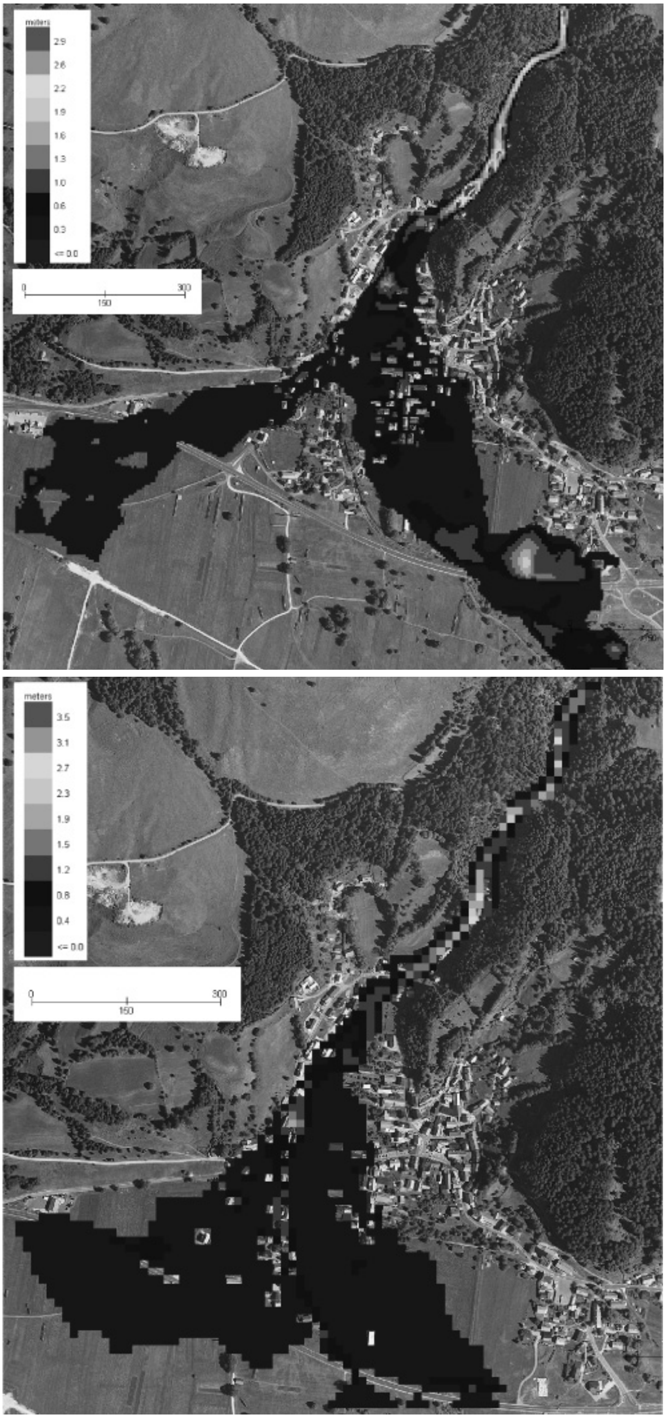

Figure 5: *Flo-2D model results for clear water on the Trebiža fan using two different numerical grids: 5 x 5 m (up) and 12.5 x 12.5 m (down) - building effects are covered by dry grid cells where buildings were recognised on the ortophoto. Colours refer to maximum flow depth in metres.*

fan. We checked this assumption by applying coarser 12.5 x 12.5 m numerical grid generated from DEM 12.5 (Figure 4). We used the same model parameters as with the 5 x 5 m grid. The results are given in Figure 5.

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 urbanised 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 modelling 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.

4 CONCLUSIONS

We performed a two-dimensional modelling of possible debris flows on selected torrential fans in the Sava Dolinka valley in NW Slovenia and we report on the results of this modelling as a function of the numerical square grid, generated from freely available DEM 5. If the 5 x 5 m grid was used, computational times using a state-of-the-art desktop personal computer 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 hazard maps only DEM 5 should be used. However, the widely used and generally available DEM 5 is still not perfect DTM for all applications. As shown on the case of the Trebiža torrential fan, due to its automatic production, DEM 5 causes the flow to "jump" out of the channel. 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 (Podobnikar, 2006). Therefore, for precise numerical modelling of e.g. debris flows over terrain it should be more thoroughly tested.

With regard to these uncertainties of DEM 5, more refined topographic representation is needed in some field cases when modelling torrential flows or debris flows. The next step in modelling natural hazards such as debris flows will eventually be the application of even more precise DTM, such as e.g. DEM 1 from laser scanning (Podobnikar, 2008) – a direction that we could only strongly support.

From the aspect of debris-flow numerical modelling, we showed that buildings that are not shown on DEMs should be modelled, because they have large influence on the flow field close to them. 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 roughness (Manning) coefficient in these cells to account for flow obstruction by buildings.

Acknowledgements

The authors would like to thank the State Research Agency and the Ministry of Defence, both of the Republic of Slovenia, for their financial support in the framework of the Targeted Research Project M2-0144 Debris-Flow Risk Assessment. The first author did the research work also as a part of his post-graduate studies at the University of Ljubljana – FGG. The data were kindly provided by the Geodetic Survey and the Environmental Agency, both of the Republic of Slovenia. The authors are grateful to the reviewers, Tomaž Podobnikar and Matjaž Četina, for their comments that significantly improved the draft of the paper.

REFERENCES

Breien, H., De Blasio, F.V., Elverhři, A., Hřeg, K. (2008). Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. Landslides 5-3, 271-280.

Chow, V.T. (1959). Open-Channel Hydraulics. Mc-Graw Hill, New York.

CRP (2009). Ocena ogroženosti zaradi delovanja drobirskih tokov. Uprava RS za zaščito in reševanje, Ministrstvo za obrambo RS, Ljubljana. Internet: http://www.sos112.si/slo/tdocs/naloga_76.pdf (6. 2. 2009)

Četina, M., Krzyk, M. (2007a). 2D modeliranje poplavnih valov na območju HE Brežice. UL FGG, 84 p. (report in Slovenian).

Četina, M., Krzyk, M. (2007b). 2D modeliranje poplavnih valov na območju HE Mokrice. UL FGG, 85 p. (report in Slovenian).

Četina, M., Rajar, R., Hojnik, T., Zakrajšek, M., Krzyk, M., Mikoš, M. (2006). Case study: Numerical simulations of debris flow below Stože, Slovenia. Journal of Hydraulic Engineering 132-2, 121-130.

Đurović, B., Mikoš, M. (2004). Preventivno obvladovanje tveganj zaradi naravnih nevarnosti – postopki v alpskih državah in v Sloveniji (Preventive management of risks due to natural hazards – procedures in the Alpine countries and in Slovenia). Acta hydrotechnica 22-36, 17-35.

Đurović, B., Mikoš, M. (2006). Ali smo ogroženi kadar tvegamo? Pojmi in izrazje teorije tveganj zaradi naravnih nesreč, geološko pogojenih nevarnosti (Are we under threat when we risk? Notions and terminology of risk theory due to geological hazards). Geologija 49-1, 151-161.

Fazarinc, R., Majes, B., Mikoš, M. (2006). Using results of mathematical modeling of debris flows for optimization of a river channel form to convey debris flows and floods. International Conference on Fluvial Hydraulics River Flow 2006, Lisboa, Portugal. Balkema.

FLO (2006a). FLO-2D, User's Manual, Version 2006.01. Flo-2d Software, Inc.

FLO (2006b). FLO-2D, GDS Manual, Version 2006.01. Flo-2d Software, Inc.

Guzzetti, F., Reichenbach, P., Ghigi, S. (2004). Rockfall Hazard and Risk Assessment Along a Transportation Corridor in the Nera Valley, Central Italy. Environmental Management 34-2, 191-208.

HEC (2000). Hydrologic Modeling System HEC-HMS - Technical Reference Manual, March 2000. US Army Corps of Engineers, Hydrologic Engineering Center. Davis, California, ZDA. Internet: http://www.hec.usace.army.mil/software/hec-hms/documentation/CPD-74B_2000Mar.pdf (6. 2. 2009)

Hojnik, T. (2004). Dvodimenzijski matematični model drobirskih tokov na območju Koseča z oceno ogroženosti naselja Koseč zaradi njihovega delovanja. 15. Mišičev vodarski dan 2004, Maribor, 247-251.

Hojnik, T., Četina, M., Krzyk, M., Rajar, R. (2001). 2D model drobirskega toka na območju Zgornjega in Spodnjega Loga. 12. Mišičev vodarski dan 2001, Maribor, 84-91.

Hürlimann, M., Rickenmann, D., Medina, V., Bateman, A. (2008). Evaluation of approaches to calculate debris-flow parameters for hazard assessment. Engineering Geology 102, 152-163.

Julien, P.Y. (2002). River Mechanics. Cambridge University Press. Cambridge.

Mikoš, M. (1997). Ocena ogroženosti alpskega sveta z naravnimi ujmami (Natural hazard assessment of alpine habitats). Gradbeni vestnik 46-1/2/3, 2-7.

Mikoš, M. (2000/2001). Značilnosti drobirskih tokov (Characteristics of debris flows). Ujma 14/15, 295-299.

Mikoš, M. (2007). Upravljanje tveganj in nova Evropska direktiva o poplavnih tveganjih (Risk management and the new European directive on flood risks). Gradbeni vestnik 56-11, 278-285.

Mikoš, M., Majes, B., Fazarinc, R., Rajar, R., Žagar, D., Krzyk, M., Hojnik, T., Četina, M. (2006). Numerical simulation of debris flows triggered from the Strug rock fall source area, W Slovenia. Natural Hazards and Earth System Sciences 6-2, 261-270.

Mikoš, M., Fazarinc, R., Majes, B. (2007). Določitev ogroženega območja v Logu pod Mangartom zaradi drobirskih tokov s plazu Stože (Delineation of risk area in Log pod Mangartom due to debris flows from the Stože landslide). Acta geographica Slovenica 47-2, 171-198.

O'Brien, J. (2006). Users Manual FLO-2D, Version 2007.06, June 2007. Nutrioso, Arizona, ZDA. Internet: http://www.flo-2d.com/v2007/Documentation/Users Manual_2007.pdf (6. 2. 2009)

Oštir, K. (2006). Daljinsko zaznavanje. Inštitut za antropološke in prostorske študije (Institute of Anthropological and Spatial Studies), ZRC SAZU (Scientific Research Centre of the Slovenian Academy of Sciences and Arts), 250 p.

Oštir, K., Podobnikar, T., Stančič, Z., Mlinar, J. (2000). Digitalni model višin Slovenije InSar25. Geodetski vestnik 44-4, 374-383.

Petje, U., Ribičič, M., Mikoš, M. (2005a). Computer simulation of stone falls and rockfalls (Računalniško simuliranje skalnih odlomov in podorov). Acta geographica Slovenica 45-2, 93-120.

Petje, U., Mikoš, M., Ribičič, M. (2005b). Ocena nevarnosti padajočega kamenja za odsek regionalne ceste v dolini Trente (Hazard assessment due to falling stones on a reach of the regional road in the Trenta valley, Slovenia). Geologija.48-2, 341-354.

Podobnikar, T. (2003). Kronologija izdelave digitalnega modela reliefa Slovenije (Chronology of Digital Terrain Model production of Slovenia). Geodetski vestnik 47-1/2, 47-54.

Podobnikar, T. (2006). Digitalni model reliefa iz različnih podatkov (Digital Terrain Model from different data). Življenje in tehnika 4, 20-27.

Podobnikar, T. (2008). Nadgradnja modela reliefa Slovenije z visokokakovostnimi podatki (High-quality data for enhancement of the terrain model of Slovenia). Geodetski vestnik 52-4, 834-853.

Podobnikar, T., Mlinar, J. (2006). Izdelava in vzdrževanje digitalnega modela reliefa Slovenije z integracijo obstoječih virov (Production and maintenance of Digital Elevation Model of Slovenia with data integration). Geodetski vestnik 50-3, 472-480.

Rajar, R., Četina, M., Mikoš, M., Fazarinc, R. (2004). Enodimenzijske simulacije drobirskega toka in vodnih valov od vasi Koseč do Ladre. 15. Mišičev vodarski dan 2004, Maribor, 233-238.

Rak, G., Gosar, L., Steinman, F. (2006). Uporaba LIDAR podatkov v povezavi GIS in hidravličnega modela. Zbornik 17.Mišičevega vodarskega dne, Maribor, 108-114.

Rayburg, S., Thoms, M., Neave, M. (2009). A comparison of digital elevation models generated from different data sources. Geomorphology xx, doi: 10.1016/j.geomorph.2008.11.007

Sato, H.P., Yagi, H., Koarai, M., Iwahashi, J., Sekiguchi, T. (2007). Airborne LIDAR Data Measurement and Landform Classification Mapping in Tomari-no-tai Landslide Area, Shirakami Mountains, Japan. In: Sassa, K., Fukuoka, H., Wanf, F., Wang, G. (eds.): Progress in Landslide Science, Chapter 17, 237-249. Springer.

Skaberne, D. (2001). Predlog slovenskega izrazoslovja pobočnih premikanj – pobočnega transporta (Proposal of the Slovene terminology on slope movements – slope transport). Geologija 44-1, 89-100.

Snyder, N.P. (2009). Studying Stream Morphology With Airborne Laser Elevation data. EOS Transactions 90-6, 45-46.

Uredba (2004). Uredba o pogojih in omejitvah gradnje na območju Loga pod Mangartom, ogroženem zaradi pojava drobirskih tokov. Uradni list RS 87.

Zakon (2002). Zakon o vodah. Uradni list RS 67.

Received for publication: 20 March 2009
Accepted: 29 May 2009

Jošt Sodnik, Univ. Grad. in CE
Vodnogospodarsko podjetje Kranj, Mirka Vadnova 5, SI-4000 Kranj
E-mail: jost.sodnik@vgp-kranj.si

Urška Petje, MSc, Univ. Grad. in CE
VGP Projekt Kranj, Mirka Vadnova 5, SI-4000 Kranj
E-mail: urska.petje@vgp-kranj.si

Prof. Dr. Matjaž Mikoš, Univ. Grad. in CE
UL FGG – Oddelek za gradbeništvo, Jamova cesta 2, SI-1000 Ljubljana
E-mail: matjaz.mikos@fgg.uni-lj.si