Topographic Data and Numerical Debris-Flow Modeling

Jošt Sodnik, Tomaž Podobnikar, Urška Petje, and Matjaž Mikoš

Abstract

The digital elevation models (classical DEM 5 and DEM 12.5), publically available in Slovenia, have been evaluated as a basis to prepare numerical square grids 5 × 5 m for 2D modeling of possible debris flows on torrential fans, using the model Flo-2D. Also recently available LiDAR data in their original resolution have been used, as well as their decreased resolution to the one of the numerical grid (e.g. 5 × 5 m). From our numerical results it seems obvious that the use of more precise LiDAR data over classical DEMs for numerical debris-flow modeling is fully justified. Better quality of input topographic data assures higher accuracy of results and therefore also accuracy of hazard maps produced in such a way. The LiDAR data promises better representation of torrential channels on torrential fans (narrow, deep channels) and computed results (velocities, depths) are generally better estimated. Using more precise data also increases computational times compared to using classical DEMs.

Keywords

Debris flows • Hazard mapping • Numerical modeling • Roughness • Sensitivity analysis • Topography

Introduction

Debris flows are a disastrous type of landslides occurring occasionally in many places of the world, triggered mainly by earthquakes, heavy short-termed rainfalls, caused by typhoons, cyclones, and thunderstorms, and prolonged steady rainfall.

In some countries, debris-flow hazard assessment is regulated by national or local legislation. Different methods may be used, but there are some common bases for the procedures used. Debris-flow hazard assessment may be just in a written form (debris-flow scenarios, estimation of damages) or in a cartographic form (hazard maps with several hazard zones shown in different scales). In any case, source areas of future debris flows should be recognized, and a step towards that is a susceptibility map of debris flows. Such a map will help to estimate real debris flow hazard only if a realistic debris-flow scenario is assumed. Part of such a scenario is not only recognition

J. Sodnik (✉) • U. Petje
Vodnogospodarsko podjetje Kranj, Ulica Mirka Vadnova 5, Kranj 4000, Slovenia

Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia
e-mail: jost.sodnik@vgp-kranj.si

T. Podobnikar
Scientific Research Centre of the Slovenian Academy of Sciences and Arts, Ljubljana, Slovenia

Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia

M. Mikoš
Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia

C. Margottini et al. (eds.), *Landslide Science and Practice*, Vol. 1,
DOI 10.1007/978-3-642-31325-7_75,

of a source area but also estimation of a debris-flow magnitude. In many cases such magnitudes can only be empirically determined on the basis of historical data available in the region. Why do we need an estimation of a debris-flow magnitude? This is in a way needed to estimate realistic run-outs and delineate safe areas from endangered ones.

If we want to separate endangered areas into several hazard zones according to chosen debris-flow parameter values (i.e. flow depths and flow velocities), we should step away from empiric run-out determination and use mathematical modeling to determine hazard areas. If we want to do that we need furthermore specific rheological characteristics of the debris material and a very good representation of the terrain (slope surface, torrential fan, and torrential channel).

In the last years, precise topographic data, such as LiDAR data, were made broadly available. In Slovenia, a systematic gathering of LiDAR data is still under way. Therefore, one may ask a question, what the benefits of this new technology are over classical digital elevation models (DEMs) developed in the recent past and that have found wide acceptance and numerous applications.

In the field of hydromorphological alpine hazards:

- Scheidl et al. (2008) used LiDAR data to estimate magnitudes of debris-flow events in Switzerland,
- Cavalli and Marchi (2008) used LiDAR technology to characterize surface morphology of a small alpine alluvial fan in Eastern Italian Alps,
- Conway et al. (2010) used LiDAR technology in NW Iceland to study very recent debris-flow events and to derive a simple empirical model that allows future debris-flow characteristics to be predicted without the need to determine the precise fluid dynamic flow parameters (viscosity, velocity), which are required to implement more complex models, to be used,
- Lopez Saez et al. (2011) combined aerial LiDAR data and tree-ring data to reconstruct debris-flow activity in abandoned channels in French Prealps, and
- Bull et al. (2010) applied differenced LiDAR data to a debris flow event to demonstrate potential of this technique as a precise and powerful tool for hazard mapping and assessment.

The classical DEMs, as well as the ones developed from LiDAR data can be used for a debris-flow post-event analysis. A well-defined topography is also needed when establishing debris-flow hazard maps. Further topography improvement can be achieved using other techniques (i.e. radar interferometry) and by different topographic data handling and integration by so-called data fusion.

Fig. 1 The ortophoto of the Koroška Bela torrential fan, used as a test area for 2D debris-flow numerical modeling

Materials and Methods

Test Area: The Koroška Bela Torrential Fan

The Koroška Bela torrential fan in NW Slovenia (Fig. 1) covers 1.02 km^2 with numerous houses and 2,200 residents (high damage potential). The torrential watershed area is 6.4 km^2 with average slope of 52 % and height difference of 570 m. In the headwaters there is an active landslide that might under unfavorable 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 modeling a commercial model Flo-2D that has been applied successfully several times in Slovenia for these purposes (Mikoš and Majes 2010), i.e. in Log pod Mangartom (Četina et al. 2006), in Koseč (Mikoš et al. 2006), for the official determination of the risk area due to potential debris flows in Log pod Mangartom (Mikoš et al. 2007), and for a potential debris flow in Kropa (Sodnik and Mikoš 2006, 2010).

Flo-2D (O'Brien 2011) is software for two-dimensional mathematical modeling of water movement and fast flowing slope processes including debris flows. This model is in the USA a software tool recommended by the Environmental

Protection Agency (EPA) for analysis of natural hazards that found wide usage in many countries. Modeling 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. Water flow respectively debris-flow modeling depends on the form of the computing model as well as on the roughness of each computing cell. A very important role when modeling 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:

$$\frac{\partial h}{\partial t} + \frac{\partial h V_x}{\partial x} = i \quad (1)$$

and the dynamic equation:

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

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 eight directions (similarly as the directions in the sky are defined; a similar procedure named the D8 algorithm is used for modeling 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 a correspondingly short computing step as a function of the selected computing cell size.

Other Parameters of the Model

Besides topography data and inflow hydrograph with volume concentration and rheological parameters we had to define other model parameters like: computational grid element size, control parameters of the model, manning roughness coefficient and inflow hydrograph position. For better comparison between different topographical data we left all other parameters similar for all the models. Defined values (settings) are: Control parameters (Surface detention 0.03, Percent change in flow depth 0.200, Dynamic wave stability coefficient 5.00), Manning roughness coefficient (forest 0.16, meadow 0.033, building area 0.2, and torrential channel 0.13), computational grid size (5 × 5 m), and inflow hydrograph was positioned on the peak of the fan.

Topographical Data Preparation

The digital elevation models are basically recorded as raster layers in 2.5D, with one attribute of elevation (Podobnikar 2005, 2009). 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 enhanced morphometric analysis of floods or debris flows (Podobnikar 2009). The quality of any spatial analysis 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.

Four DEMs were applied in our study: DEM 12.5, DEM 5, DEM 0.5 and DEM5 derived from DEM0.5 (Table 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 DEM 12.5 was produced by appropriately fusion of various existing data sources of different quality, where their semantically and qualitatively best properties were exposed (Podobnikar 2005, 2010). The final DEM is overall of better quality than any of the used data sources. 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 a 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: (1) mosaicking selected data sources to produce a principal DEM, (2) weighted sum of secondary data sources, (3) (geo)morphologic enhancement, and (4) reference point consideration in the modeling. 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.

Table 1 Characteristics of the DEMs used in this study

Name (produced)	Accuracy (RMSE)	Production method
DEM 12.5 (2001–2005)	3.8 m	Fusion of existing geodetic datasets of different type/quality
DEM 5 (2006–2007)	3.5 m	Resampling of DEM 12.5 + stereo photogrammetry and local adjusting with CAD-tools
DEM 0.5 (2009–2010)	5–10 cm[a]	Datasets of 12 blocks (leaves and snow); different approaches to filtering and interpolation
DEM 5 from DEM 0.5 (2010)	5–10 cm[a]	Resampling of DEM 0.5

[a]In channels gross errors >1 m

The DEM 5 was produced by simply resampling the DEM 12.5, and with further improving the geometrical accuracy on the areas where the previous RMSE was considerably significant (Podobnikar 2008). Aerial photographs and principles of stereo photogrammetry were applied. The areas with significant RMSE were locally adjusted using CAD-tools. The final DEM 5 is geometrically of higher quality than the DEM 12.5, but is quite inhomogeneous with low morphological accuracy (Sodnik et al. 2009). This DEM is unfortunately not very promising for any geomorphometric spatial analysis, i.e. for debris flow modeling, due to its spatial variability in quality.

The DEM 0.5 was captured as a fullwave point cloud in two different periods (2009-05-08 and 2010-04-11), when some snow cover was present in the high mountains and leaves were present on most trees in the lower parts of the study area. Both of these facts make difficulties for the DEM generation. Point density was inhomogeneous, and ranged from 1 to 10 points/m^2. The vertical angle of scanning was 0° to ±30° with laser scanner Litemapper LM 5600 (alias Riegl LMS-Q560). Orthophotos with a resolution of 0.5 m were acquired together with the scanning. The final DEM of 0.5 m 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 with canopies with leaves and buildings, but especially on the areas with streams. The main problems for our debris flow simulation are the areas of streams and their surroundings. Most problematic are stream areas where alluvial plane is covered with canopies with leaves and buildings located just along the streams. Less important, but obvious errors occur due to rough mountain landscape. The produced DEM 0.5 needs further improvement by including more advanced filtering and possible combination and fusion of other data sources. An additional model for the debris flow simulation will be produced, i.e. a digital surface model (DSM) as combination of the DEM 0.5 and buildings (required is LOD 0).

All DEMs were resampled to resolution of 5 and 12.5 m 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.

Table 2 Computational times on an average PC (3.0 GHz dual-core processor) for 15-min simulation time

Model name	DEM used	Computational time
BelaLF7	Classical DEM 12.5	1.9 h
BelaLF6	Classical DEM 5	2.8 h
BelaLF8	LiDAR DEM 0.5	32 h
BelaLF5	LiDAR DEM 5	26 h

Results and Discussion

Modeled Debris-Flow Event Scenario

There is only one written description of past events (the 1789 event), and there are no reliable debris flow magnitude estimations for Koroška Bela torrent. The 100-year peak discharge is 55 m^3/s. We chose a 15-min potential event with a peak discharge of 250 m^3/s and with volume concentration C_v of 0.42. The total magnitude of the potential debris flow event in the study is 155,500 m^3 (water + debris). The event scenario is defined with inflow hydrograph on the peak of the fan. When defining the debris flow scenario, besides peak discharge (inflow hydrograph) we have to define also rheological characteristics of the mixture. Since for a potential debris flow in the test region we do not have precise material rheological data from past debris flow events, we used parameter values gathered when calibrating Flo-2D model for other recent debris flow cases in Slovenia: critical shear stress 20Pa, and Bingham viscosity 19Pa.s for $C_v = 0.42$ (Četina et al. 2006). The goal of the studied models is to test the importance of topographic data used in the model. Apart from the accuracy of the results, also computational times of the Flo-2D models differ a lot with different data (Table 2).

The maximum flow depths of the studied models are shown in Fig. 2. In Fig. 2a the lack of morphologic accuracy of the classic DEM 5 is shown. In the upper part of the fan the torrential channel, 5–7 m wide on average, is poorly expressed. The flow overbanks and the depths all over the fan are practically the same. In the model with DEM 12.5 (Fig. 2b) the channel is more explicit but made wider than in nature due to the DEM resolution. The inundated areas of both models are generally the same. But comparison

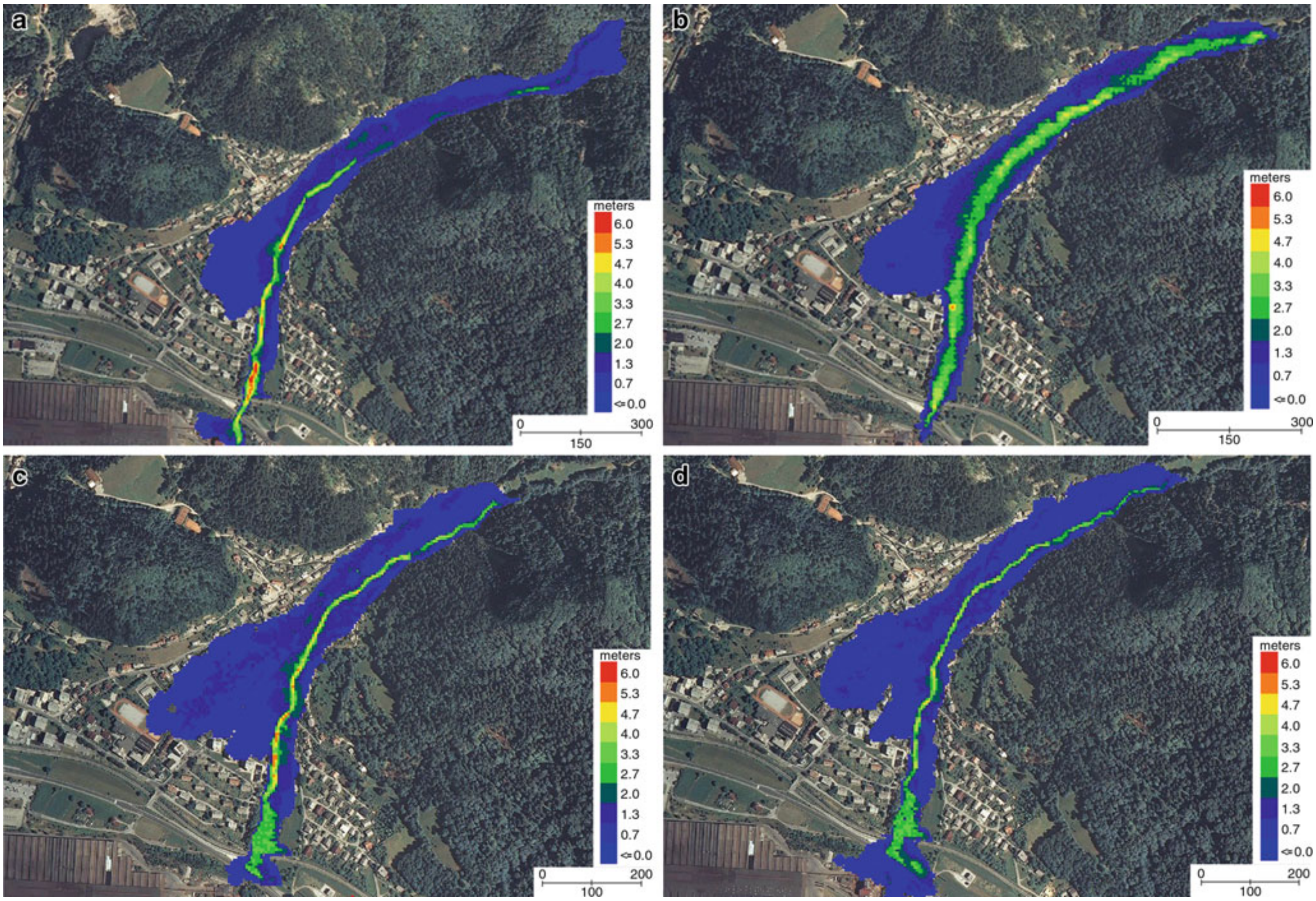

Fig. 2 Comparison of 2D modeling (maximum flow depths in m, uniform scale) using: (**a**) classical DEM 5; (**b**) classical DEM 12.5; (**c**) DEM 0.5 (original LiDAR data); (**d**) DEM 5 (re-sampled LiDAR data); on the Koroška Bela torrential fan

between Fig. 2a and b shows that despite of poor resolution the DEM 12.5 is morphologically more correct and more useful for preliminary hazard assessment. Using DEM 5 in our test area would derive a hazard map with an underestimation of the hazard in the upper part of the fan.

In Fig. 2c, d the comparison between the LiDAR-derived DEM 0.5 and DEM 5 is shown. In both cases the result is geomorphologically more correct (looking at the channel width, even though the channel is rather non-homogenous due to errors in zones covered with broad-leafed trees) than in case of the classic DEM 5 and DEM 12.5. Also the inundation areas are better represented when using LiDAR-derived DEMs. The modeled flow depths outside of the channel are more heterogeneous, because the surface is more agitated due to better topographical input data. In this case the hazard map in the inundated area is more precise. Inter-comparison between the models with LiDAR derived DEMs (Fig. 2c, d) shows that the main difference is the modeled flow depth in the inundation areas outside of channel. The model with DEM 0.5 (grid cell height interpolation integrated in a Flo-2D) derives bigger differences in flow depths in the inundation area when compared to LiDAR derived DEM 5 (bilinear interpolation) which leads to more precise hazard mapping.

Conclusions

From our numerical results it seems obvious that the use of more precise LiDAR data for numerical debris-flow modeling is justified, even if using LiDAR derived DEM 5 instead of classical DEM 5. Better morphological quality of input topographic data assures higher accuracy of the results and therefore also of the resulting hazard maps. The LiDAR data promises better representation of torrential channels on torrential fans (narrow, deep channels) and computed results (velocities, depths) are generally better estimated and therefore delineation of a hazard area into corresponding zones is of higher accuracy for a selected debris-flow scenario. Nevertheless, LiDAR derived data can be potentially further improved, especially in morphological sense.

It also has to be noted that higher resolution topographic data means much longer computational times (not a real problem anymore). For delineation of hazard areas the magnitude of potential debris flow has to be estimated with reasonable certainty, because magnitude, beside topographic data, is one of the most important input data for the model and hazard map preparation.

In 2011, a systematic gathering of LiDAR data in Slovenia is under way; it is rather questionable if the data density (5 m^{-2} on average) will serve all possible applications, including numerical debris-flow modeling.

Acknowledgments We worked within the EU research project PARAmount (www.paramount-project.eu), financially supported by the European Regional Development Fund (ERDF) and by the Research Agency of Slovenia (grant P2-0180 "Hydrotechnics, hydraulics, and geotechnics"). The digital elevation data were kindly provided by the Surveying and Mapping Authority of the Republic of Slovenia and the LiDAR data by the Flycom Company.

References

Bull JM, Miller H, Gravley DM, Costello D, Hikuroa DCH, Dix DK (2010) Assessing debris flows using LIDAR differencing: 18 May 2005 Matata event, New Zealand. Geomorphology 124(1–2):75–84

Cavalli M, Marchi L (2008) Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR, Nat Hazards Earth Syst Sci 8(2):323–333. http://www.nat-hazards-earth-syst-sci.net/8/323/2008/

Četina M, Rajar R, Hojnik T, Zakrajšek M, Krzyk M, Mikoš M (2006) Case study: numerical simulations of debris flow below Stože, Slovenia. J Hydraul Eng 132(2):121–130

Conway SJ, Decaulne A, Balme MR, Murray JB, Towner MC (2010) A new approach to estimating hazard posed by debris flows in the Westfjords of Iceland. Geomorphology 114(4):556–572

Jež J, Mikoš M, Trajanova M, Kumelj Š, Budkovič T, Bavec M (2008) Vršaj Koroška Bela – Rezultat katastrofičnih pobočnih dogodkov = Koroška Bela alluvial fan – The result of the catastrophic slope events (Karavanke Mountains, NW Slovenia). Geologija 51(2):219–227

Lopez Saez J, Corona C, Stoffel M, Gotteland A, Berger F, Liébault F (2011) Debris-flow activity in abandoned channels of the Manival torrent reconstructed with LiDAR and tree-ring data. Nat Hazards Earth Syst Sci 11(5):1247–1257

Mikoš M, Majes B (2010) Mitigation of large landslides and debris flows in Slovenia, Europe. In: Werner ED, Friedman HP (eds) Landslides: causes, types and effects. Nova Science Publishers, New York, pp 105–131. ISBN 978-1-60741-258-8, eISBN 978-1-61470-186-6

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. Nat Hazards Earth Syst Sci 6(2):261–270

Mikoš M, Fazarinc R, Majes B (2007) Delineation of risk area in Log pod Mangartom due to debris flows from the Stože landslide. Acta Geogr Slov 47(2):171–198

O'Brien J (2011) FLO-2D Reference manual, version 2009. http://www.flo-2d.com/wp-content/uploads/FLO-2D-Reference-Manual-2009.pdf. 6 June 2011

Petje U, Mikoš M, Ribičič M (2005) Computer simulation of stone falls and rockfalls. Acta Geogr Slov 45(2):93–120. http://giam.zrc-sazu.si/zbornik/05_AGS_45-2_PetjeRibicicMikos.pdf

Podobnikar T (2005) Production of integrated digital terrain model from multiple datasets of different quality. Int J Geogr Inf Sci 19(1):69–89

Podobnikar T (2008) High-quality data for enhancement of the terrain model of Slovenia. Geod Vestn 52(4):834–853

Podobnikar T (2009) Methods for visual quality assessment of a digital terrain model. SAPIENS 2(2):15–24

Podobnikar T (2010) DEM production/updating based on environmental variables modeling and conflation of data sources. J Civil Eng Archit 4(11):33–44

Scheidl C, Rickenmann D, Chiari M (2008) The use of airborne LiDAR data for the analysis of debris flow events in Switzerland. Nat Hazards Earth Syst Sci 8:1113–1127

Sodnik J, Mikoš M (2006) Estimation of magnitudes of debris flows in selected torrential watersheds in Slovenia. Acta Geogr Slov 46(1):93–123. http://giam.zrc-sazu.si/zbornik/ags46-1-4-SodnikMikos_str-93-123.pdf

Sodnik J, Mikoš M (2010) Modeling of a debris flow from the Hrenovec torrential watershed above the village of Kropa. Acta Geogr Slov 50 (1):59–84. http://giam.zrc-sazu.si/sites/default/files/ags50103.pdf

Sodnik J, Petje U, Mikoš M (2009) Terrain topography and debris-flow modelling Geod Vestn 53(2):305–318. http://www.geodetski-vestnik.com/53/2/gv53-2_305-318.pdf