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MODELING OF A DEBRIS FLOW FROM THE HRENOVEC TORRENTIAL WATERSHED ABOVE THE VILLAGE OF KROPA

MODELIRANJE DROBIRSKEGA TOKA V HUDOURNIŠKEM OBMOČJU HRENOVEC NAD KROPO

Jošt Sodnik, Matjaž Mikoš

A street or a torrent? Torrential deposits in the village of Kropa
a day after the storm on September 18, 2007.
Ulica ali hudournik? Hudourniške naplavine v Kropi dan po neurju 18. 9. 2007.

Modeling of a debris flow from the Hrenovec torrential watershed above the village of Kropa

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ABSTRACT: In this paper, debris-flow modeling is shown specifically on the basis of a potential debris flow from the Hrenovec torrential watershed above the village of Kropa in NW Slovenia. This site was chosen, because in this particular torrential watershed a small surficial landslide turned into a debris flow during a storm on September 18, 2007. Fortunately, the debris flow stopped inside the torrential channel above the village of Kropa. Using public available data on rainfall and topography, we developed two scenarios of debris-flow triggering with an estimated magnitude of 50,000 m^3. According the first scenario, a debris flow triggers during rainfall with the 100-year return period, and according the second one, it triggers during extreme rainfall as measured during the storm on September 18, 2007. For both scenarios, we used for debris-flow modeling a commercial two-dimensional mathematical model Flo-2d. The obtained results are shown in the form of computed flow depths and velocities over a cartographic background. The results show to possible catastrophic consequences in the village of Kropa, much worse that set in by torrential flood during the storm on September 18, 2007.

KEY WORDS: slope processes, debris flows, risk assessment, mathematical modeling, Kropa, Slovenia

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ADDRESSES:
Jošt Sodnik, M. Sc.
Vodnogospodarsko podjetje d. d.
Mirka Vadnova 5, SI – 4000 Kranj, Slovenia
E-mail: jost.sodnik@vgp-kranj.si

Matjaž Mikoš, Ph. D.
University of Ljubljana
Faculty of Civil and Geodetic Engineering
Jamova cesta 2, SI – 1000 Ljubljana, Slovenia
E-mail: matjaz.mikos@fgg.uni-lj.si

Contents

1 Introduction

When assessing debris-flow risk, a possible source area should be determined first. It is followed by an assessment of a possible debris-flow magnitude and about appropriate methods we have already reported in this journal (Sodnik and Mikoš 2006). We finish a risk assessment by modeling debris flow movement from a source area and by determining debris-flow runout.

In Slovenia, year 2007 was otherwise an average year with regard to precipitation amount (ARSO 2009), however very intense precipitation on September 18 stood out, when the storm engulfed wide parts of Slovenia and caused altogether close to 200 million Euro in damage respectively the damage exceeded 0.5 percentage of the annual GDP (Gross domestic product; SURS 2009). Main consequences of strong precipitation were fast surface run-off, very fast increasing of small torrents and flooding of numerous rivers (Sušnik et al. 2007; Kobold 2008, Rusjan et al. 2009). The worst situation was in Železniki and its close neighbourhood, especially in the valley of the Davča torrent (Klabus 2007) and in the village of Kropa. Among geomorphological and hydrological processes, torrential floods were prevailing related to local bank erosion and local aggradation due to sedimentation of torrential deposits and related to local dammings of abundant floating wooden debris; such events are frequently also decribed as torrential outburst (Klabus 2007; Mikoš 2007, Rusjan et al. 2009). Fundamentally less frequent were landsliding events, shown by field examination as well as by an analysis of possibilities of using satellite images as a help for recognizing landsliding events (Jemec and Mikoš 2008). The cause for relatively small number of slope instabilities was in intense short-term precipitation, when soils had not enough time to soak to such an extent to come to frequent and deep-seated landslides. So only a few soil slips triggered on steep unforested (grassy) slopes. There were also not many debris flows observed, we should mention only the case of a debris flow in the village of Zali log in the valley of the Selška Sora River. In this case, a local several meters high damming in

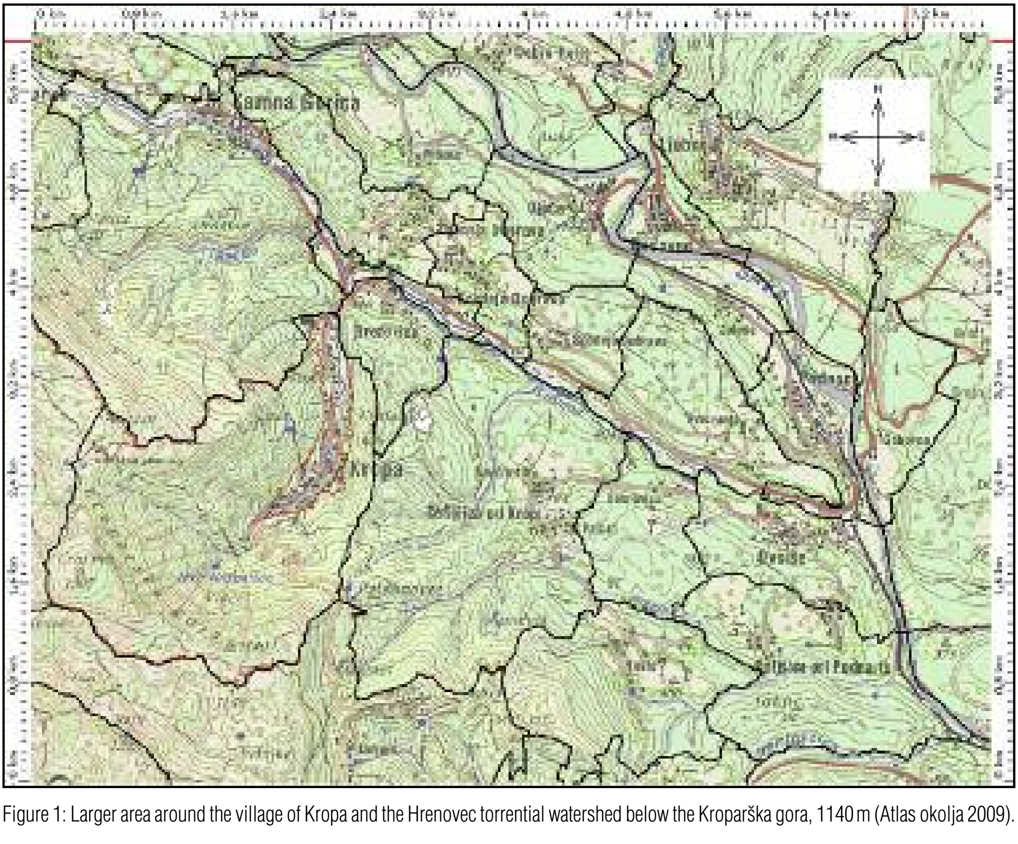

Figure 1: Larger area around the village of Kropa and the Hrenovec torrential watershed below the Kroparška gora, 1140 m (Atlas okolja 2009).

the channel of the Pruharica torrent just upstream of the village suddenly broke and released a debris flow that burried part of the village and caused one casualty (Klabus 2007; Mikoš 2007, Rusjan et al. 2009).

Luckier was the village of Kropa that was otherwise flooded but not hit by a debris flow that was triigered in the Hrenovec torrential watershed above the village of Kropa (the area below the Vodiška planina and the Kroparška gora, 1140 m; Figure 1). The majority of debris was deposited in the torrential channel in its middle course where the channel is locally less steep and where it locally widens. The assessment after the storm was that there is around 50,000 m^3 of potentially unstable material that can be triggered as a debris flow. After a field examination of the whole Hrenovec torrential channel in September 2007, a retention basin was dig out in 2008 in the lower part of the torrent close to its outflow into the Kroparica torrent. Its function is to cause sedimentation of torrential sediments that are triggered in the hinterland during strong precipitation. The size of this retention basin is nevertheless not big enough for a full capture of a potential debris flow. Due to this fact, not only this technical measure but also an analysis of a potential hazard along the Kroparica torrential channel due to a potential debris flow from the Hrenovec torrential watershed was performed.

As a part of the risk assessment we developed a mathematical model of a debris flow triggered in the Hrenovec torrential watershed above the village of Kropa. We used it for simulation of debris flow movement in the lower part of the Hrenovec torrent upstream of its confluence with the Kroparica torrent and further downstream in the upper reach of the Kroparica torrent through the densly populated part of the village of Kropa. It is this part of this old village that was hit at most during the storm on September 18, 2007. This investigation showed what would be the consequences in the village of Kropa if a potential debris flow had triggered in the Hrenovec torrential watershed that would not stop in the Hrenovec torrential channel as it had happened in September 2007 but would have travelled along the Kroparica channel through the village of Kropa. We used for debris-flow modeling a commercial model Flo-2d that has been applied successfully several times in Slovenia for these purposes, i.e. in the village of Log pod Mangartom (Rajar et al. 2001; Četina et al. 2006), in the village of Koseč above Kobarid (Mikoš et al. 2006) and for the determination of the risk area due to potential debris flows in the village of Log pod Mangartom (Mikoš et al. 2007).

2 Hydrologic bases for modeling

2.1 Description of the Hrenovec torrential watershed above the village of Kropa

The Hrenovec torrent is a tributary of the Kroparica torrent that springs below the Vodiška Planina on Jelovica. The catchment area of this torrent is very steep (Figure 2), as well as its channel. In the past, two check dams were built in its lower course, some 300 m upstream of its confluence with the Kroparica torrent. Because both are completely filled with sediments, they only have a stabilising function. The Hrenovec channel itself is natural and not regulated in any respect. Due to badly nursing of neighbouring forests, the channel is full of fallen trees that in some places form weirs and further worsen run-off conditions in the torrent. The torrential watershed area is 1.065 km^2. The average slope inclination is 30°. The area is mainly forested, as it can be seen from the ortho-photo on Figure 3.

2.2 Rainfall

A hydrologic study was done for the near-by Lipnica river (VGI 1996), in which rainfall data from the following raingauge stations: Dražgoše, Tržič-elektrarna, and Lesce-Hlebce were treated. For the Hrenovec torrential watershed, the raingauge station in Dražgoše is relevant as it is the closest one to the considered area. The maximum daily rainfall data are presented in Table 1. For the analysis of debris-flow movement from the Hrenovec torrential watershed above the village of Kropa, we used daily rainfall with the 100-year return period. Beside the 100-year event, we used for the mathematical model of a debris flow also a potential scenario of September 18, 2007, when in the raingauge station in Dražgoše 216.4 mm rainfall was measured. A preliminary statistical analysis of this rainfall event using Gumbel

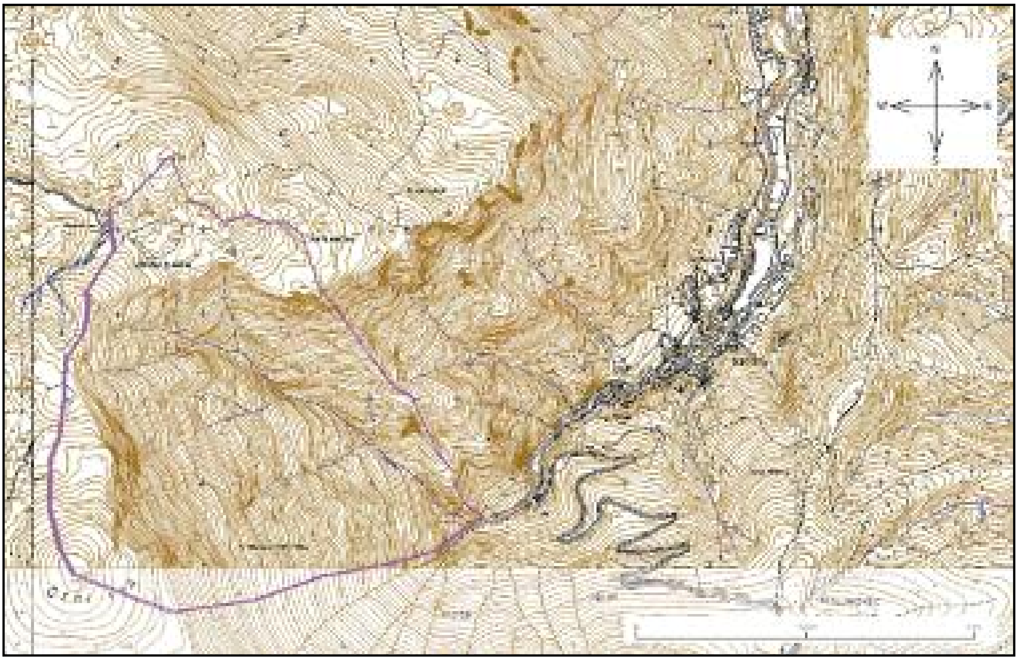

Figure 2: Contributing area of the Hrenovec torrent (on the basis of the topographic map in the scale 1 : 5,000 sheet D2503 and topographic map in the scale 1 : 10,000 sheet D0717 (Geodetska uprava Republike Slovenije 2008).

Figure 3: Digital ortho-photo of the considered area (GURS 2008).

distribution and a daily-rainfall data series of 47 years estimated the return period of this event to 120 years (Meze 2008).

Table 1: Maximum daily rainfall for the raingauge station in Dražgoše for the period of measurements 1929–1993 (VGI 1996).

Return period in years	2	5	10	20	25	50	100
Maximum daily rainfall in mm	86.6	103.8	115.2	126.1	129.6	140.2	150.9

2.3 Modeling of surface run-off

For rainfall-runoff modeling we applied a hydrologic model HEC-HMS (*Hydrologic Modeling System*; HEC 2000; 2008) that was successfully applied when modeling surface run-off as a part of the determination of debris-flow magnitudes in selected torential watersheds in Slovenia (Sodnik and Mikoš 2006). Input data for the model were daily rainfalls (Table 1) and topographic data that were gained from the topographic maps in the scale of 1 : 5,000 and the digital ortho-photo maps as follows: contributing area 1.065 km^2, average slope inclination 30°, watercourse length (of the torrential channel) 1.37 km, average watercourse slope (of the torrential channel) 30°. On the basis of the digital ortho-photo (soil cover) and using experiences with run-off modeling in other torrents in Slovenia (Sodnik and Mikoš 2006), we determined for the Hrenovec torrential watershed with regard to soil cover the run-off coefficient CN (*Curve Number*) = 66. For determining the direct input data into the hydrologic model HEC-HMS we applied the SCS (*Soil Conservation Service*) method that proved to be adequate also in other torrential watersheds in Slovenia (Sodnik and Mikoš 2006).

For the modeled 100-year run-off hydrogram, the peak discharge Q_{100} is 14.065 m^3/s and the total run-off volume is 65,267 m^3. In Figure 4, the modeled run-off hydrogram for measured rainfall on September 18, 2007, is shown. The peak discharge Q_{MAX} is 26.55 m^3/s and the total run-off volume is 120,750 m^3.

So, the result of the hydrologic modeling is a run-off hydrogram of 100-year rainfall and a run-off hydrogram for rainfall on September 18, 2007. The computed run-off hydrogram is an important input data for debris-flow modeling. In the cases, when in the hydrologic study rainfall-runoff and corresponding discharges are given for different return periods, we can use these discharges for the validation of our model. Since the hydrologic study of the Lipnica river only treats the Kroparica torrent, but not also discharges of the Hrenovec torrent as the Kroparica tributary, we used for the model validation an empirical equation for run-off estimation. By applying this method we checked the computed 100-year run-off. By such

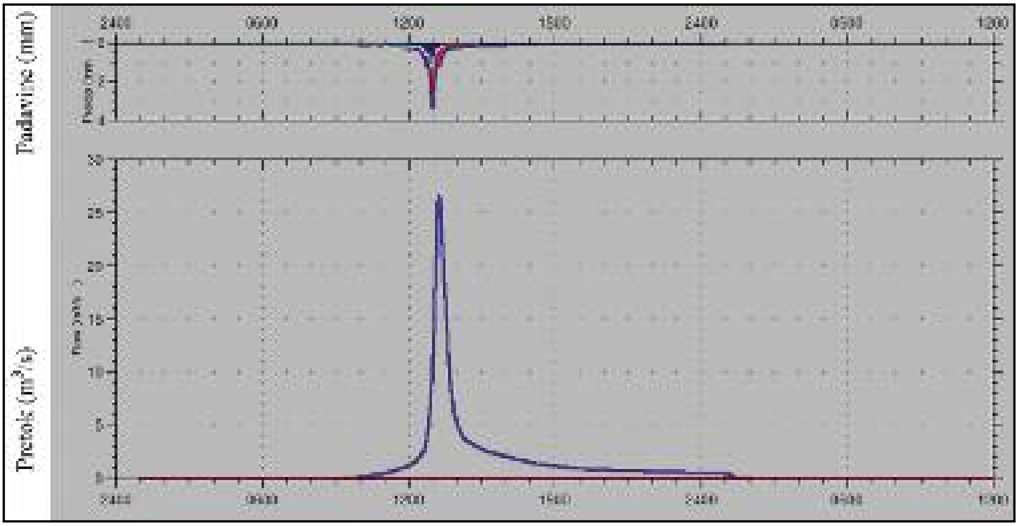

Figure 4: The modeled run-off hydrogram Q_{MAX} for measured rainfall on September 18, 2007, using the HEC-HMS model for the Hrenovec torrential watershed above the village of Kropa (above: hietogram in mm, below: hydrogram in m^3/s).

a validation we determined the watershed parameters that may be further used for other rainfall events. For validation purposes we used the empirical Kresnik equation that is frequently used in Slovenia in torrential watersheds for the determination of extreme run-off:

$$Q_{100}=\frac{\alpha FW 32}{0.5+\sqrt{FW}}=\frac{0.63*1.06*32}{0.5+\sqrt{1.06}}=13.97 m^3 s^{-1}$$

where FW is cathment area (of the torrential watershed) [km^2] and α is an empirical run-off coefficient [–] that goes from 0.4 (forested, well permeable (karst) surfaces of lower inclination) to 1.0 (bare surfaces (up to 25% forested), very steep and impermeable surfaces with high elevation differences).

3 Description of the mathematical model Flo-2d

3.1 Model description and model operation

Flo-2d (O'Brien 2006) is software for two-dimensional mathematical modeling 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. In Slovenia, we successfully used it for the analysis of debris flows in the village of Koseč (Mikoš et al. 2006) and for the determination of the risk area in the village of Log pod Mangartom (Mikoš et al. 2007). 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 rheologic 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:

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

and the dynamic equation:

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

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 [–] (flow energy is used to overcome flow friction and the slope is a function of the Manning friction coefficient n_g), and S_{ox} is the channel (relief) slope [–]. Part of the equations are also pressure gradient i [–] and local accelerations.

The dynamic equation is used in such a way that we compute the depth-averaged flow velocity in each computing cell separately for all of the eight directions (similarly as the directions in the sky are defined; a similar procedure named the D8 algoritm 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 correspondingly short computing step as a function of the selected computing cell size.

3.2 Debris-flow modeling using Flo-2d

Debris flows are non-homogenous (anizotropic) 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 modeling a debris-flow:

- the resistance parameter for laminar flow;
- specific weigth;
- 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 modeling of debris flows its calibrated value is 2285 (O'Brien 2006). In Table 2, the values of the resistance parameter for laminar flow K for different surfaces are shown.

Table 2: The values of the resistance parameter for laminar flow K for different surfaces, over which the debris flow moves (O'Brien 2006).

surface	range of K
concrete/asphalt	24–108
bare sand	30–120
graded surface	90–400
bare clay – loam soil, eroded	100–500
spare vegetation	1,000–4,000
short prairie grass	3,000–10,000

Debris specific weight [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 mixture. The mixture's flow characteristics on the slope strongly depend on the specific weight of the mixture. We used the specific weight of 27 kN/m^3 when modeling the debris flow from the Hrenovec torrential watershed.

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: $\tau_y = \alpha e^{\beta C_v}$ [dyn/cm^2 = 10^{-5} N/cm^2].

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

4 Debris-flow models from the Hrenovec torrential watershed

4.1 Input data and geometry

Topographic input data were the data gained from the Digital Elevation Model (DEM) 5 × 5 m. The data were made available by the Surveying and Mapping Authority of the Republic of Slovenia (GURS 2008). On the basis of the DEM data we developed the computing grid and made its height interpolation. On the grid we defined computing area, i. e. cells, which were incorporated into computing the movement of the debris flow, and furthermore, on the border of the computing area we defined corresponding border conditions. The computing area includes the lower part of the Hrenovec torrent as well as the upper part of the Kroparica torrent through the village of Kropa (Figure 5). This is the area, where the storm of September 2007 caused the majority of damages. The computing area includes 11,811 computing cells. The debris flow enters the upper part of the computing area according to the input hydrograph computed

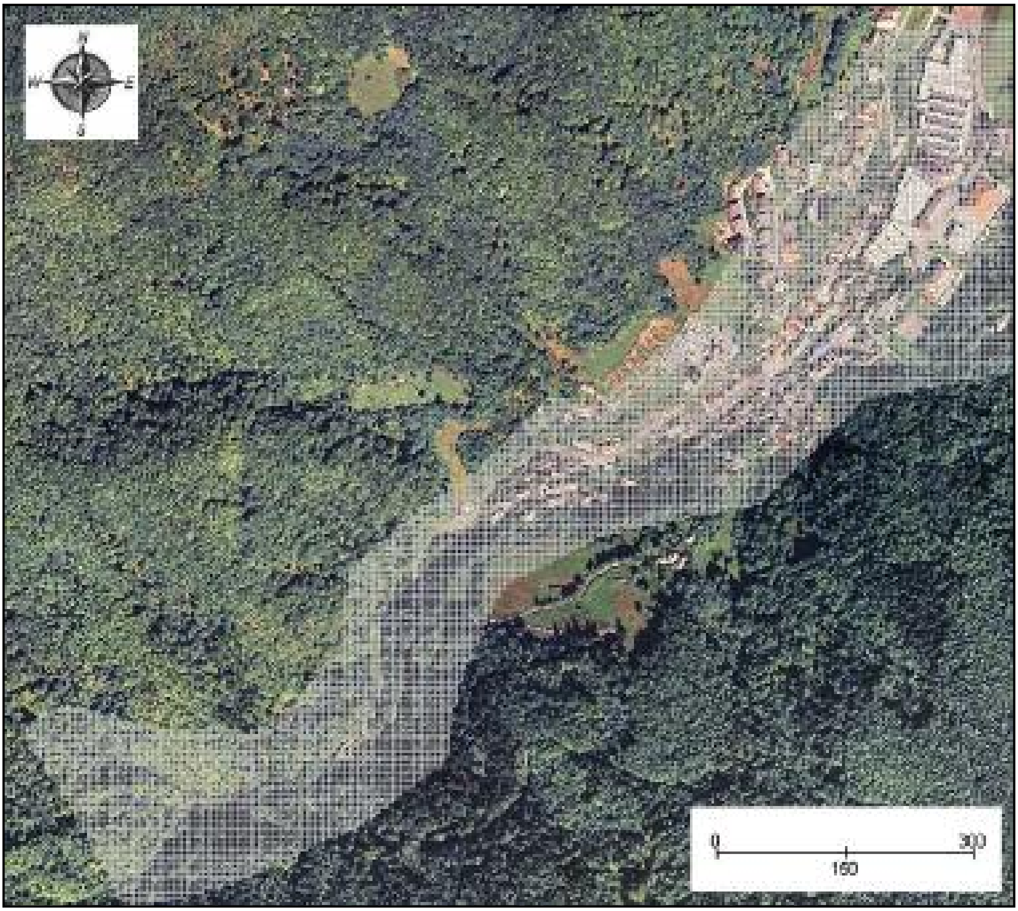

Figure 5: The computing grid 5m × 5m for theHrenovec torrent and the village of Kropa.

by the HEC-HMS model. For the final computation, we also need to determine the volumetric concentration of the debris flow. In the case of modeling debris flow in the village of Log pod Mangartom, the following two values for C_v were applied: 0.42 for a wet, and 0.5 for a dry debris flow, respectively. In the Hrenovec torrent case was on the basis of the availability of debris in hinterland (field investigation) and water quantities (rainfall) determined the value of $C_v = 0.5$; the same value that was used to calibrate the rheologic properties in the village Log pod Mangartom.

4.2 Rheological parameters

The rheological characteristics are very important when modeling debris flows (O'Brien, 2006): debris specific weight, mixture yield stress and mixture viscosity. The last two ones are dependent on the volumetric concentration C_v. With respect to prevaling geological composition of the hinterland, where limestone prevails, and the Hrenovec torrential banks are built out of volcanic rocks, among those mainly keratophyr, porphyrit, diabas, tuff, and tuffit is prevailing, we chose for the specific weight of the debris material the value of 27 kN/m^3. The selected value corresponds to that for limestone; furthermore, this value was determined in the nearby stone quarry of Brezovica, where limestone is the prevailing rock type. For the selection of values for yield stress and mixture viscosity it would be the most advantageous to sample debris flow that was triggered on September 8, 2007, and to determine its rheological properties in a large enough shear cell under laboratory conditions. Because such an apparatus doesn't exist in Slovenia, we do use only much smaller viscometers, we had to help ourselves using past experiences with modeling of debris flows. The only case of modeling debris flows in Slovenia, where the values of yield stress and viscosity were calibrated, was the case of the village of Log pod Mangartom, where the elevations of the real debris flow that had hit this area were determined. After the field measurements, the debris flow model was calibrated using the measured debris-flow levels in the gorge of the Predelica torrent and the debris flow run-out in the Koritnica river valley (Fazarinc 2002). The calibrated values for the case of the village Log pod Mangartom are: yield stress $\tau_y = 2000$ N m^{-2} and viscosity $\eta = 156$ Pa s. These values were back-calculated into the non-dimensional coefficients α and β that are input parameters in the model, namely for yield stress: $\alpha = 0.0525$ and $\beta = 25.7$, and for viscosity: $\alpha = 0.0248$ and $\beta = 22.1$.

4.3 Other model parameters

Alongside the rheologic parameters, further important parameters are also the Manning roughness coefficient n_g and the resistance parameter for laminar flow K. The Manning roughness coefficient n_g was determined from literature, because the only other way would be to determine it from a mathematical model calibrated on an observed natural event. In the case of assessing risk for potential events this coefficient can not be measured, it can only be chosen on the basis of experiences, an analysis of similar cases elsewhere or on the values suggested in literature. We chose the last option (O'Brien 2006), where values are suggested for different surfaces, over which a debris flow moves. The values used for modeling of a debris flow on a fan are slightly different from ordinary values for channel flow. For the treated Hrenovec torrential watershed the value of $n_g = 0.2$ was determined. The sensitivity study of the mathematical model on the model parameter selection, among others also on the Manning roughness coefficient, showed for the case of the Koroška Bela fan that changing values of this coefficient does not elementarily influence the modeling results (Sodnik et al. 2009). The resistance parameter for laminar flow K was also taken out of literature (O'Brien 2006) that suggests for debris flows the value of $K = 2285$. The software allows the choice to compute the K value during the computation directly from the Manning n_g for each computing field separately, but such a selection very prolongs the computing time needed.

4.4 Treated numerical cases

As already stated in the chapter on hydrological bases of modeling, we treated two potential events (Table 3). The first one is a 100-year event; the second one is an event taking into account rainfall on September 18, 2007. The mentioned cases are interesting ones; the 100-year event is of interest because in torrent control as a professional activity of controlling torrential watersheds, all measures and structures should withstand a 100-year event. The second event is of interest, because it simulates respectively shows the event that might have happened on September 18, 2007.

Table 3: The main characteristics of the two scenarios, used for simulating debris flow movement from the Hrenovec torrential watershed above the village of Kropa.

Parameter	100-year scenario	Scenario with the rainfall of September 18, 2007
Peak discharge	21.09 m^3/s	39.82 m^3/s
Magnitude	32,633 m^3	60,375 m^3
Volumetric concentration	0.5	0.5

5 Modeling results

5.1 100-year event

For the 100-year event the maximum discharge $Q_{100} = 21.09$ m^3/s, and the released debris-flow magnitude $M_{100} = 32{,}633$ m^3. The maximum flow depths in this case are up to 2.6 m (Figure 6). In the area of the Kropa

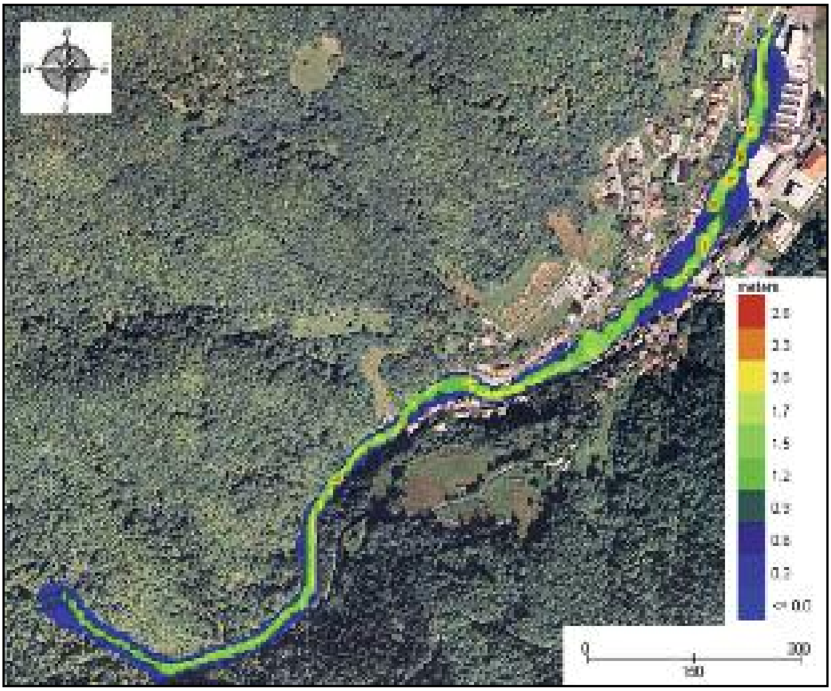

Figure 6: The maximum flow depths of the debris flow from the Hrenovec torrential watershed above the village of Kropa for the 100-year event.

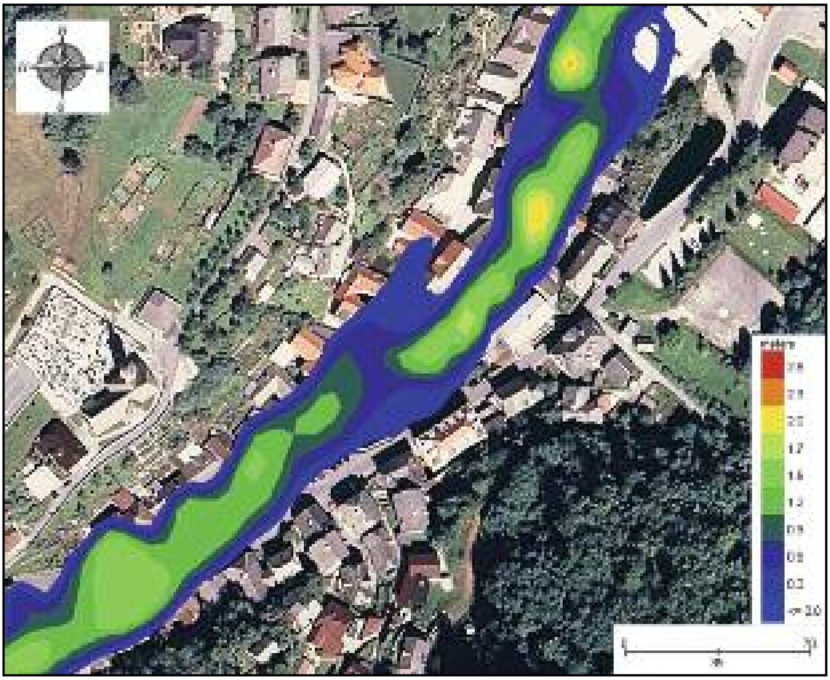

Figure 7: The maximum flow depths of the debris flow from the Hrenovec torrential watershed above the village of Kropa for the 100-year event, given for the Main square in the village of Kropa.

Figure 8: The maximum flow depths of the debris flow from the Hrenovec torrential watershed above the village of Kropa for the 100-year event, given for the Viganca area in the village of Kropa.

center, where the situation during floods is the worse, the maximum flow depth for this case is 1.7 m and the flow would spread across the square and the old village center (Figure 7), and would cover the square and the surrounding buildings. On the square, the maximum flow depth is between 1.2 and 1.5 m, respectively.

The flow depth are high also in the Viganca area (Figure 8), where the September 2007 storm caused high damages. Downstream of the village center, along the UKO and Novi Plamen factories, the conditions are less critical, because the channel is deep and along the Kroparica banks there are no buildings and in the area of the factories the banks are protected by walls, respectively. In this area, a bridge blockage happened on September 18, 2007, and the torrential water overspill the banks and was flowing on the road towards the main square. The debris-flow velocities in the channel are on average between 3 and 4 m/s.

The modeling has shown that flow velocities on flood plains are essentially smaller compared to those in the torrent channel. This is an essential advantage of two-dimensional hydraulic models compared to one-dimensional ones that are not capable of showing such flow details due to simplified velocity computation in only one direction.

5.2 Possible scenario of September 18, 2007

When modeling a potential event on September 18, 2007, where we took into account the rainfall measured on that day, the peak discharge was $Q_{18.9.2007} = 39.82$ m^3/s, and the debris-flow magnitude was $M_{18.9.2007} = 60{,}375$ m^3. At this event it is about almost twice the 100-year discharge ($Q_{100} = 21.09$ m^3/s) and almost twice the debris-flow magnitude ($M_{100} = 32{,}633$ m^3). The flow depths in this case are up to 3.1 m. In the channel, the flow depths are on average between 2.0 and 2.4 m. The maximum flow depths appear in the same parts as with the 100-year event, only that they are in this case for around 20% higher. Precisely this difference means in many places essential worsening of conditions. In the Main square, the flow depths are around 2.0 m that is more than the windowsills' height in ground floor (Figure 9).

Also heavily flooded is the square on the right bank, whereas it is not flooded at the 100-year event, at the scenario of September 18, 2007, the flow depths on the square are over 1.5 m (Figure 10). As it was the case with debris-flow depths, also debris-flow velocities are much higher as with ther 100-year event. On average, in the upper part of the flow, they are larger for 25%, and in lower part, where the channel slope is small; the differences are small (Figure 11).

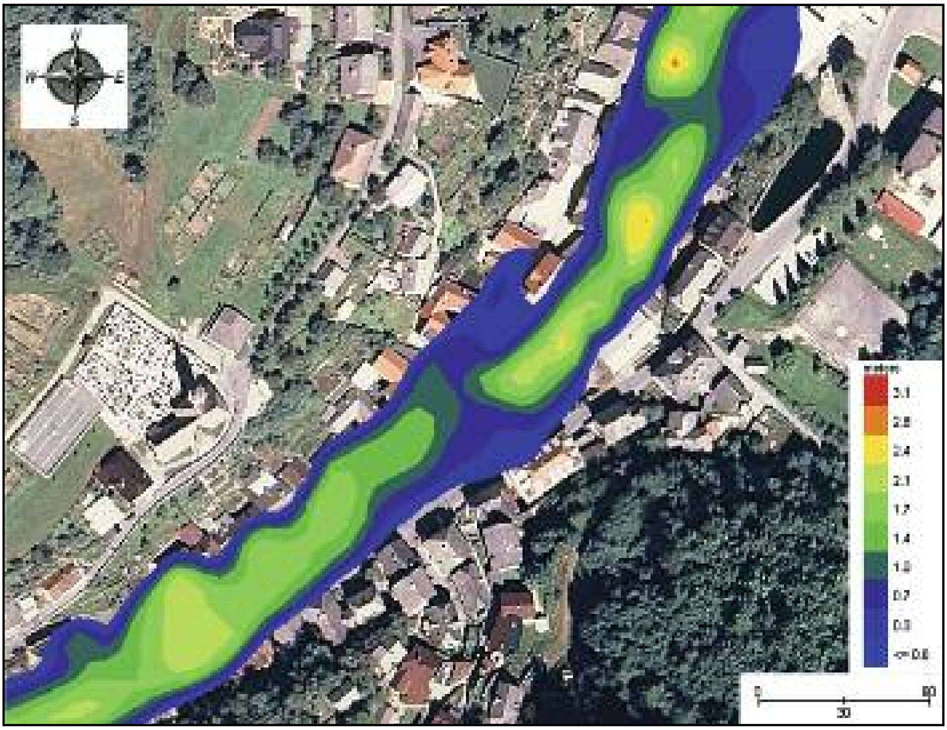

Figure 9: The maximum flow depths of the debris flow from the Hrenovec torrential watershed above the village of Kropa for the potential event of September 18, 2007, given for the Main square in the village of Kropa.

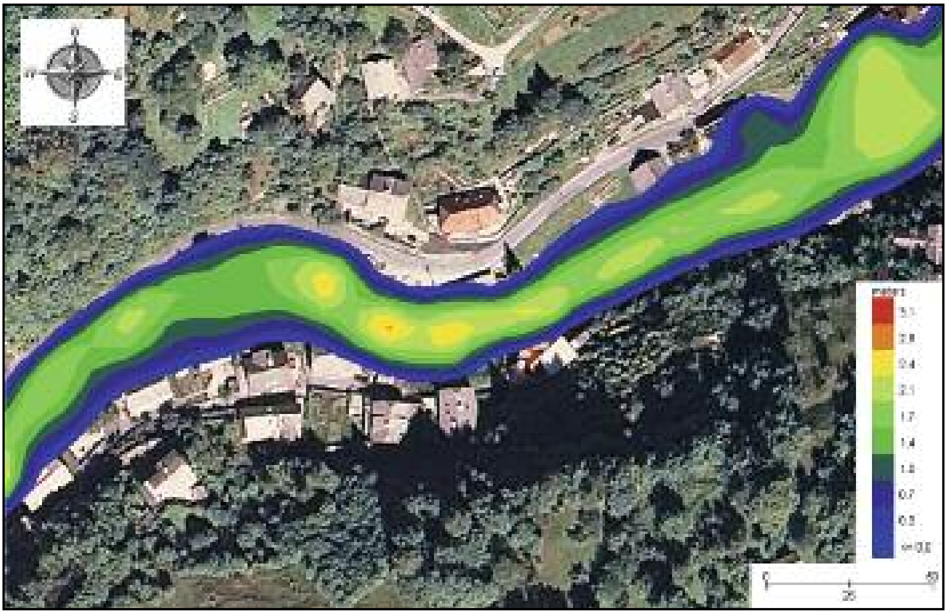

Figure 10: The maximum flow depths of the debris flow from the Hrenovec torrential watershed above the village of Kropa for the potential event of September 18, 2007, given for the flooded area of the millrace in Kropa that are under the monument care and preservation.

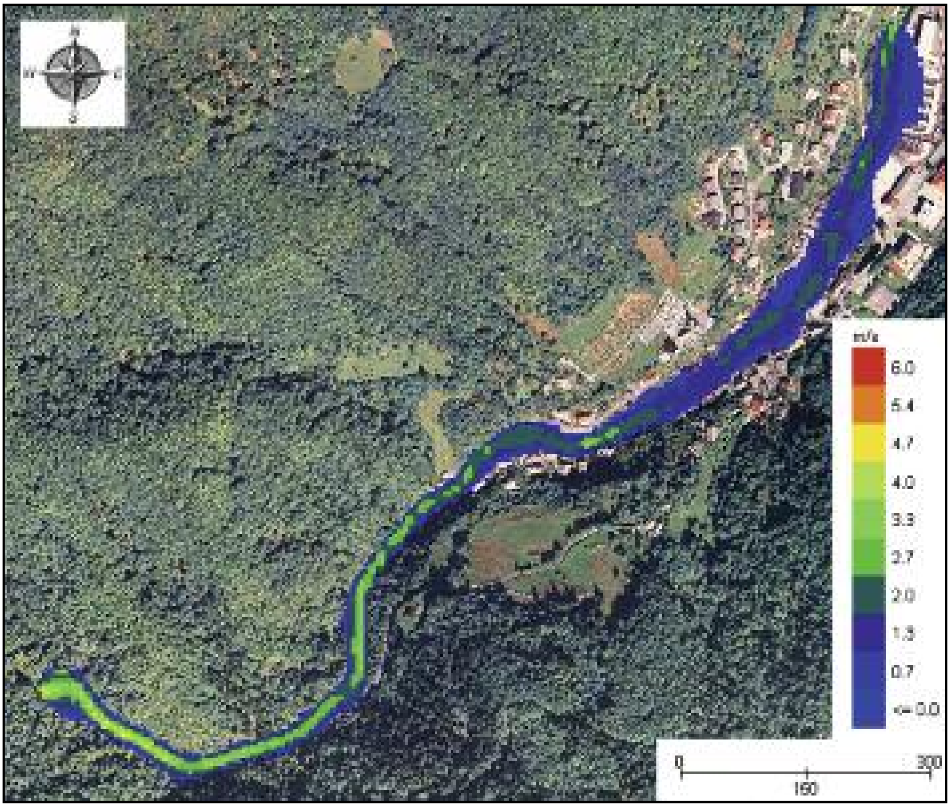

Figure 11: The maximum flow velocities of the debris flow from the Hrenovec torrential watershed above the village of Kropa for the potential event of September 18, 2007.

6 Conclusion

The modeling of a debris flow from the Hrenovec torrential watershed above the village of Kropa is a topical problem, because during the storm on September 18, 2007, a debris flow was released in the upper reach of the torrent after a smaller landslide below the Vodiška planina had triggered. The majority luckily stopped in the upper part of the torrential channel. The unstable mass was assessed to be approximately 50.000 m^3. Because of its activation in September 2007, the Hrenovec torrential watershed above the village of Kropa was classified as a potential triggering area of debris flows and as such was used as one of the bases for assessment of debris flow susceptibility in Slovenia (CRP 2009).

The debris flow models after both scenarios have shown that the Kroparica torrent channel, the recepient of the Hrenovec torrent, is considerably under-dimensioned for an event shown in this paper. After the storm in September 2007, for mitigation of consequences and for retention of smaller debris flows, a retention basin with the volume of around 1500 m^3 was formed close to the confluence of the Hrenovec torrent with the Kroparica torrent. The mentioned retention basin has no essential role with the events of the magnitudes as modeled in the treated scenarios. But it could have an important role during events with smaller magnitudes.

For a more exact risk determination in the sense of defining risk zones, one should incorporate into the model a more detailed survey of the torrential channels of the Hrenovec and Kroparica torrents, respectively. The study showed that on the basis of publicly available topographic data (DEM5; the Surveying and Mapping Authority of the Republic of Slovenia) and rainfall data (Environmental Protection Agency of the Republic of Slovenia), we can work out a detailed enough model for movement of potential debris flows, by which we can define hazard that threatens the treated area. Such an approach to preventive protection is legally binding and implemented in many alpine countries. In Slovenia, we have more than 10 years ago written on the necessity of taking such steps (Mikoš 1997). Eventhough such an approach is mentioned in the Water law (Zakon o vodah 2002), necessary legislation is still missing. As a best practice case we may mention the governmental decree that, as a part of the mitigation of conditions in the village of Log pod Mangartom after the debris flow of November 2000, prescribed conditions of use of space due to hazard of new debris flows from the Stože landslide (Mikoš et al. 2007).

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Modeliranje drobirskega toka v hudourniškem območju Hrenovec nad Kropo

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IZVLEČEK: V članku je prikazan postopek modeliranja gibanja drobirskega toka na konkretnem primeru možnega drobirskega toka iz hudourniškega območja Hrenovec nad Kropo v severozahodni Sloveniji. Lokacija je bila izbrana zato, ker se je v tem hudourniškem območju med neurjem 18. 9. 2007 iz manjšega površinskega zemljinskega plazu razvil drobirski tok, ki se je na srečo ustavil v strugi hudournika nad naseljem Kropa. S pomočjo javno dostopnih podatkov o padavinah in površju smo razvili dva scenarija proženja drobirskega toka z ocenjeno prostornino gradiva 50.000 m^3. Po prvem scenariju se drobirski tok sproži ob padavinah s 100-letno povratno dobo, po drugem pa pri intenzivnih padavinah, kot so bile izmerjene med neurjem 18. 9. 2007. Za gibanje drobirskega toka smo za oba scenarija uporabili komercialni dvodimenzijski matematični model Flo-2D. Prikazani so rezultati v obliki izračunanih globin in hitrosti toka, prikazani na kartografski podlagi. Izračuni kažejo na možne katastrofalne posledice v Kropi, precej hujše kakor so nastopile ob hudourniški poplavi v času neurja 18. 9. 2007.

KLJUČNE BESEDE: pobočni procesi, drobirski tokovi, ocena ogroženosti, matematično modeliranje, Kropa, Slovenija.

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NASLOVA:
mag. Jošt Sodnik
Vodnogospodarsko podjetje Kranj, d. d.
Mirka Vadnova 5, SI – 4000 Kranj, Slovenija
E-pošta: jost.sodnik@vgp-kranj.si

dr. Matjaž Mikoš
Univerza v Ljubljani
Fakulteta za gradbeništvo in geodezijo
Jamova cesta 2, SI – 1000 Ljubljana, Slovenija
E-pošta: matjaz.mikos@fgg.uni-lj.si

Vsebina

1 Uvod

Pri oceni ogroženosti zaradi delovanja drobirskih tokov je najprej treba določiti območje možnega proženja. Sledi ocena možne magnitude drobirskega toka in o ustreznih metodah smo v tej reviji že poročali (Sodnik in Mikoš 2006). Oceno ogroženosti zaključimo z modeliranjem gibanja drobirskega toka iz območja proženja in določitvijo območja dosega drobirskega toka.

Leto 2007 je bilo sicer padavinsko povprečno (ARSO 2009), vendar so izstopale zelo intenzivne padavine 18. 9. 2007, ko je neurje zajelo obsežne dele Slovenije in povzročilo skupaj blizu 200 milijonov evrov škode oziroma je škoda presegla 0,5 odstotka letnega bruto domačega proizvoda (SURS 2009). Glavne posledice močnih padavin so bili hiter površinski odtok, zelo hitro naraščanje manjših hudournikov in poplavljanje številnih rek (Sušnik in ostali 2007; Kobold 2008; Rusjan in ostali 2009). Najhuje je bilo v Železnikih in bližnji okolici, predvsem dolini hudournika Davščica (Klabus 2007) ter v Kropi. Med geomorfološkimi in hidrološkimi pojavi so prevladovale hudourniške poplave z lokalno bočno erozijo in lokalnim odlaganjem hudourniških plavin ter lokalnimi zajezitvami zaradi obilnega plavja; take pojave pogosto imenujemo tudi hudourniški izbruh (Klabus 2007; Mikoš 2007; Rusjan in ostali 2009). Bistveno manj je bilo pojavov plazenja tal, kakor je razen terenskih ogledov pokazala tudi analiza možnosti uporabe satelitskih posnetkov kot pomoč pri njihovem prepoznavanju (Jemec in Mikoš 2008). Vzrok za relativno majhno število pojavov nestabilnosti tal je v intenzivnih kratkotrajnih padavin, ko se zemljina ni uspela dovolj razmočiti, da bi lahko prišlo do številnejših in globokih zemljinskih plazov. Tako se je pojavilo le nekaj plitvejših usadov na strmih in z gozdom neporaslih (travnatih) vesinah. Tudi drobirskih tokov ni bilo veliko, omeniti velja primer oblikovanja drobirskega toka v Zalem logu v dolini Selške Sore, kjer je zaradi lokalne zajezitve višine več metrov v strugi hudournika Pruharica tik nad naseljem po porušitvi te zajezitve v Zali log udaril drobirski tok in zasul del vasi ter zahteval smrtno žrtev (Klabus 2007; Mikoš 2007; Rusjan in ostali 2009).

Več sreče je imela Kropa, ki je bila poplavljena, vendar v naselje ni prodrl drobirski tok, ki se je sprožil v hudourniškem območju Hrenovca nad Kropo (območje pod Vodiško planino in Kroparško goro, 1140 m; slika 1). Večina gradiva se je odložila v strugi hudournika in sicer v njegovem srednjem toku, kjer je struga mestoma bolj položna in kjer so lokalne razširitve. Ocena po neurju je bila, da je potencialno nevarnega gradiva za sprožitev drobirskega toka okoli 50.000 m^3. Po ogledu celotne struge Hrenovca septembra 2007, je bil leta 2008 v iztočnem delu hudournika pred njegovim izlivom v Kroparico skopan zaplavni prostor, ki služi za odlaganje hudourniških plavin, ki se sproščajo v zaledju ob močnejših nalivih. Velikost zaplavnega prostora vseeno ne zadošča za popolno prestrezanje možnega drobirskega toka in zato se je razen tega ukrepa opravila tudi analiza možne nevarnosti vzdolž struge Kroparice zaradi možnega drobirskega toka v hudourniškem območju Hrenovca.

Slika 1: Širše območje Krope in hudourniško območje Hrenovec pod Kroparško goro, 1140 m (Atlas okolja 2009).
Glej angleški del prispevka.

Kot del analize ogroženosti smo izdelali matematični model drobirskega toka iz hudourniškega območja Hrenovca nad Kropo ter z njim simulirali gibanje drobirskega toka na izlivnem odseku hudournika Hrenovec ter v zgornjem toku Kroparice, ki teče skozi gosto poseljeno območje Krope. Gre za tisti del tega starega naselja, ki je bil najbolj prizadet med ujmo septembra 2007. Omenjena raziskava je pokazala, kakšne bi bile posledice v Kropi, če bi se v hudourniškem območju Hrenovca sprožil drobirski tok, ki se ne bi ustavil v hudourniški strugi Hrenovca, kakor se je zgodilo septembra 2007, ampak bi potoval po strugi Kroparice skozi Kropo. Za modeliranje gibanja drobirskega toka je bil uporabljen komercialni model Flo-2D, ki je bil v Sloveniji že večkrat uspešno uporabljen za matematično modeliranje gibanja drobirskih tokov in sicer v Logu pod Mangartom (Rajar in ostali 2001; Četina in ostali 2006) in skozi vasico Koseč nad Kobaridom (Mikoš in ostali 2006) ter za določitev ogroženega območja pred možnim drobirskimi tokovi v Logu pod Mangartom (Mikoš in ostali 2007).

2 Hidrološke podlage modeliranja

2.1 Opis hudourniškega območja Hrenovec nad Kropo

Hudournik Hrenovec je pritok Kroparice, ki izvira pod Vodiško Planino na Jelovici. Prispevno območje hudournika je zelo strmo (slika 2). Prav tako je strma tudi njegova hudourniška struga. V preteklosti sta bili na Hrenovcu zgrajeni dve zaplavni pregradi v njegovem spodnjem delu, približno 300 m gorvodno od sotočja s Kroparico. Ker sta popolnoma zaplavljeni, opravljata le še ustalitveno vlogo. Sama hudourniška struga Hrenovca je naravna in tehnično neurejena. Zaradi slabo vzdrževanih okoliških gozdov je struga polna podrtega drevja, ki mestoma tvorijo jezove in še dodatno poslabšujejo odtočne razmere na hudourniku. Površina prispevnega območja je 1,065 km^2. Povprečni naklon območja znaša 30°. Površina je večinoma gozd, kar je razvidno iz ortofoto posnetka na sliki 3.

Slika 2: Prispevno območje hudournika Hrenovec (obdelava karte temeljnega topografskega načrta v merilu 1 : 5000 list D2503 in temeljnega topografskega načrta v merilu 1 : 10.000 list D0717 (Geodetska uprava Republike Slovenije 2008).
Glej angleški del prispevka.

Slika 3: Digitalni ortofoto posnetek obravnavanega območja (GURS 2008).
Glej angleški del prispevka.

2.2 Padavine

Za Lipnico je bila izdelana hidrološka študija (VGI 1996), v kateri so obdelane padavine padavinskih postaj: Dražgoše, Tržič-elektrarna, Lesce-Hlebce. Postaja, merodajna za Hrenovec, je postaja v Dražgošah, saj je najbližja obravnavnemu območju. Podatki o maksimalnih dnevnih padavinah so podani v preglednici 1. Za analizo gibanja drobirskega toka iz hudourniškega območja Hrenovec nad Kropo smo uporabili dnevne padavine s stoletno povratno dobo. Poleg dogodka s stoletno povratno dobo je bil za matematični model drobirskega toka uporabljen tudi možen scenarij z dne 18. 9. 2007, ko je na padavinski postaji Dražgoše padlo kar 216,4 mm dežja. Preliminarna statistična analiza tega padavinskega dogodka je z uporabo navadne Gumbelove porazdelitve in vzorca dnevnih padavin dolgega 47 let ocenila povratno dobo dogodka na 120 let (Meze 2008).

Preglednica 1. Maksimalne dnevne padavine za padavinsko postajo Dražgoše za obdobje meritev 1929–1993 (VGI 1996).

Povratna doba v letih	2	5	10	20	25	50	100
maksimalne dnevne padavine v mm	86,6	103,8	115,2	126,1	129,6	140,2	150,9

2.3 Modeliranje padavinskega odtoka

Za modeliranje odtoka padavin je bil uporabljen hidrološki model HEC-HMS (*Hydrologic Modeling System*; HEC 2000; 2008), ki je bil uspešno uporabljen za modeliranje površinskega odtoka v okviru določanja magnitud drobirskih tokov v izbranih hudourniških območjih Slovenije (Sodnik in Mikoš 2006). Vhodni podatek za model so bile dnevne padavine (preglednica 1) ter podatki o reliefu, ki so bili pridobljeni iz kart temeljnega topografskega načrta v merilu 1 : 5000 in digitalnega ortofoto načrta in sicer kot sledi: prispevna površina 1065 km^2, povprečni naklon 30°, dolžina vodotoka (hudourniške struge) 1,37 km, povprečni strmec vodotoka (hudourniške struge) 30°. Na podlagi digitalnega ortofoto posnetka (pokrovnost tal) in izkušenj z modeliranjem odtoka na drugih hudournikih po Sloveniji (Sodnik in Mikoš 2006), je bil za hudourniško območje Hrenovca določen koeficient odtoka, odvisen od pokrovnosti tal – število CN (*Curve Number*) = 66. Za izračun neposrednih vhodnih podatkov v hidrološki model HEC-HMS je bila uporabljena metoda SCS (*Soil Conservation Service*), ki se je izkazala za primerno tudi v drugih hudourniških območjih Slovenije (Sodnik in Mikoš 2006).

Modelirani hidrogram odtoka s stoletno povratno dobo da ob Q_{100} 14,065 m^3/s celotni odtok vode 65.267 m^3. Na sliki 4 je prikazan hidrogram odtoka za izmerjene padavine dne 18. 9. 2007. Ob Q_{MAX} 26,55 m^3/s je celotni odtok vode 120.750 m^3.

Slika 4: Modelirani hidrogram odtoka Q_{MAX} za izmerjene padavine dne 18. 9. 2007 s programom HEC-HMS (zgoraj je prikazan hietogram v mm, spodaj pa hidrogram v m^3/s).
Glej angleški del prispevka.

Rezultat hidrološkega modeliranja je torej hidrogram odtoka stoletnih padavin in hidrogram za odtok padavin z dne 18. 9. 2007. Računski hidrogram odtoka je pomemben vhodni podatek za model drobirskega toka. V primerih, kadar so v hidrološki študiji obdelani tudi odtoki padavin in s tem pretoki z različnimi povratnimi dobami, lahko podane pretoke uporabimo za preverbo modela. Ker pa hidrološka študija Lipnice obravnava samo Kroparico, ne obdeluje pa pretokov Hrenovca, ki je pritok Kroparice, je bila za preverbo modela odtoka uporabljena empirična enačba za izračun odtoka. Z omenjeno metodo je bil preverjen izračun odtoka za stoletno povratno dobo. S preverbo tega so določeni parametri porečja, ki so lahko uporabljeni tudi za druge primere padavin. Za preverbo smo uporabili empirični Kresnikov obrazec, ki se pogosto v slovenskih hudourniških območjih uporablja za določanje ekstremnih odtokov:

$$Q_{100} = \frac{\alpha FW 32}{0{,}5+\sqrt{FW}} = \frac{0{,}63 * 1{,}06 * 32}{0{,}5+\sqrt{1{,}06}} = 13{,}97 m^3 s^{-1}$$

kjer je *FW* velikost prispevne površine (hudourniškega območja) [km^2] in α je empirični odtočni koeficient odtoka [–], ki ga izbiramo v razponu od 0,4 (gozdnate, dobro prepustne (kraške) površine z manjšim naklonom) do 1,0 (ogolele površine (do 25% gozda), zelo strme in neprepustne površine z veliko višinsko razliko).

3 Opis matematičnega modela Flo-2d

3.1 Opis in delovanje modela

Flo-2d (O'Brien 2006) je programsko orodje za dvodimenzijsko matematično modeliranje gibanja vode in hitrih pobočnih procesov, med katere sodijo tudi drobirski tokovi. Model je v Združenih državah Amerike s strani Agencije za varovanje okolja (EPA) priporočeno programsko orodje za analizo naravnih tveganj, ki je našlo široko uporabo v mnogih državah. V Sloveniji smo ga uspešno uporabili za analizo gibanja drobirskih tokov v vasici Koseč (Mikoš in ostali 2006) in za določitev ogroženega območja v Logu pod Mangartom (Mikoš in ostali 2007). Modeliranje temelji na fizikalnih zakonitostih toka in je uporabno v različnih geografskih razmerah – posebnosti vsakega posameznega obravnavanega problema upoštevamo z izbiro različnih koeficientov v modelu in seveda vnosom podatkov o površju. Za opis geometrije območja uporablja mrežo kvadratnih računskih celic izbrane velikosti. Gibanje vode oziroma modeliranje drobirskega toka je razen od oblike računskega modela odvisno tudi od hrapavosti posameznih računskih celic. Pri modeliranju gibanja drobirskih tokov imajo zelo pomembno vlogo tudi reološki parametri mešanice vode in drobirja, ki so podrobneje opisane v nadaljevanju prispevka. Osnovni enačbi modela v vsaki smeri (prikazana sta le enačbi za smer *x*) sta kontinuitetna enačba:

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

in dinamična enačba:

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

kjer je *h* globina toka [m], V_x globinsko povprečna komponenta hitrosti toka [m/s], S_{fx} je padec energijske črte [–] (energija toka se porablja za premagovanje trenja v toku in padec je odvisen od Manningovega koeficienta hrapavosti n_g), in S_{ox} je naklon terena [–]. V enačbah nastopata še gradient tlaka *i* [–] in členi lokalnih pospeškov.

Dinamično enačbo vrednotimo tako, da izračunamo globinsko povprečno hitrost toka v vsaki računski celici posebej za vsako od osmih smeri (podobno kot so določene smeri neba, podoben postopek imenovan algoritem D8 se uporablja pri modeliranju gibanja skalnih gmot po pobočju; Petje in sodelavci 2005). Hitrost je v vsaki smeri izračunana kot enodimenzionalna in neodvisna od ostalih hitrosti. Stabilnost računske numerične sheme je zagotovljena tako, da izberemo ustrezno kratek računski korak glede na izbrano velikost računske celice.

3.2 Modeliranje drobirskih tokov s Flo-2d

Drobirski tokovi so nehomogene (anizotropne) in ne-newtonske tekočine (Mikoš 2000/2001). Gibanje drobirskih tokov je odvisno od reoloških lastnosti mešanice, reliefa, naklona in hrapavosti površja. Mešanica drobirskega toka je sestavljena iz vode in drobirja različnih velikosti, torej gre pri gibanju drobirskega toka dejansko za večfazni tok, ki ima lahko tudi primesi lesa (grmičevja, drevja, panjev, vej). Količina oziroma koncentracija materiala določa specifično težo, strižno odpornost in viskoznost mešanice. Koncentracija gradiva v mešanici je izražena s prostorninsko koncentracijo C_v, ki je izražena kot razmerje med prostornino drobirja in prostornina mešanice vode in drobirja. Omenjena koncentracija je pomembna pri nadaljnji obravnavi gibanja drobirskih tokov, saj s tem podatkom določamo celotno magnitudo drobirskega toka. Od koncentracije mešanice vode in drobirja je odvisna vrsta gibanja. Zato so poleg prostorninske koncentracije za model drobirskega toka nujni še naslednji podatki:

- koeficient laminarnega odpora;
- specifična teža drobirja;
- podatki o strižni odpornosti;
- podatki o viskoznosti.

Koeficient laminarnega odpora [–] odraža hrapavost reliefa, po kateri se giblje tok. Ta vrednost je pomembna za območja oz. faze, ko je tok laminaren ali v prehodnem režimu. Pri strogo turbulentnih tokovih je ta faktor manj odločilen. Vrednost koeficienta *K* se giblje od 24 za gladka pravilna korita pa vse do 50.000 pri bolj hrapavih in geometrijsko bolj zapletenih primerih. Za modeliranje drobirskih tokov je bila umerjena vrednost 2285 (O'Brien 2006). V preglednici 2 so prikazane vrednosti tega koeficienta za različne vrste reliefa.

Preglednica 2. Vrednost koeficienta laminarnega odpora *K* za različne vrste reliefa, po katerih se giblje drobirski tok (O'Brien 2006).

vrsta reliefa	vrednost *K*
beton /asfalt	24–108
pesek	30–120
pobočja v naklonu	90–400
glina	100–500
redka vegetacija	1000–4000
travniki	3000–10.000

Specifična teža erozijskega drobirja [N/m^3] je pomemben podatek za določanje specifične teže mešanice, ki je odvisna od specifične teže gradiva in volumske koncentracije mešanice C_v. Od specifične teže mešanice so močno odvisne lastnosti, ki jih ima mešanice pri gibanju po pobočju. Uporabljena vrednost pri modelu drobirskega toka iz hudourniškega območja Hrenovec znaša 27 kN/m^3.

Strižna odpornost je odvisna od volumske koncentracije C_v gradiva v mešanici. Podati je treba dva koeficienta in sicer α in β, ker se strižna odpornost računa po enačbi: $\tau_y = \alpha e^{\beta C_v}$ [dyn/cm^2 = 10^{-5} N/cm^2].

Viskoznost mešanice je odvisna od volumske koncentracije C_v materiala v mešanici. Prav tako je potrebno podati dva koeficienta α in β. Ker se viskoznost računa po enačbi: $\eta = \alpha e^{\beta C_v}$ [P = g cm^{-1} s-$^{-1}$ = 10^{-1} Pa.s].

4 Model drobirskega toka iz hudourniškega območja Hrenovec

4.1 Vhodni podatki in geometrija

Vhodni podatki o reliefu so bili podatki digitalnega modela višin (DMV) 5 m krat 5 m. Podatki so bili pridobljeni z Geodetske uprave Republike Slovenije (GURS 2008). Na podlagi podatkov DMV smo izdelali računsko mrežo in jo tudi višinsko interpolirali. Na mreži smo še določili računsko območje, torej celice, ki so vključene v računanje gibanja toka in na mejah računskega območja nastavili ustrezne robne pogoje. Na sliki 5 je prikazano računsko območje, ki zajema spodnji del hudournika Hrenovec ter zgornji tok Kroparice skozi naselje Kropa. To je območje, kjer je ujma septembra 2007 povzročila največ škode. Računsko območje zajema 11.811 računskih celic. V zgornjem delu računskega območja priteka drobirski tok ustrezno izračunanemu vhodnemu hidrogramu z modelom HEC-HMS. Za dokončen izračun je treba določiti še prostorninsko koncentracijo drobirskega toka. V primeru modeliranja drobirskega toka v Logu pod Mangartom sta bili uporabljeni dve vrednosti C_v in sicer 0,42 za moker drobirski tok in 0,5 za suh drobirski tok. V primeru Hrenovca je bil glede na količino razpoložljivega materiala v zaledju (terenski ogled) in količino vode (padavine) izbrana vrednost $C_v = 0{,}5$, za katero so bile umerjene reološke karakteristike v Logu pod Mangartom.

Slika 5: Računska mreža 5m × 5m na območju Hrenovca in Krope.
Glej angleški del prispevka.

4.2 Reološki parametri

Pri modeliranju drobirskih tokov so zelo pomembne reološke lastnosti (O'Brien, 2006): specifična teža gradiva, strižna odpornost mešanice in viskoznost mešanice. Strižna odpornost in viskoznost sta odvisni od koncentracije C_v. Za specifično težo drobirskega gradiva smo glede na prevladujočo geološko sestavo zaledja, kjer prevladujejo apnenci, hudourniške brežine pa gradijo kamnine vulkanskega nastanka, med katerimi prevladujejo keratofirji, porfiriti, diabazi, tufi in tufiti, izbrali vrednost 27 kN/m^3. Izbrana vrednost je ustrezna za apnence, poleg tega pa je omenjena vrednost izmerjena v bližnjem kamnolomu Brezovica, kjer med kamninami prevladuje predvsem apnenec. Glede izbora vrednosti koeficientov strižne odpornosti in viskoznosti mešanice bi bilo najugodneje odvzeti vzorec drobirskega toka, ki je nastal 18. 9. 2007 ter določiti njegove reološke lastnosti v ustrezno veliki strižni celici v laboratorijskih pogojih. Ker te naprave v Sloveniji ni, uporabljamo namreč le manjše viskozimetre, smo si morali pomagati z dosedanjimi izkušnjami pri modeliranju drobirskih tokov. Edini primer modeliranja drobirskih tokov v Sloveniji, kjer sta bili vrednosti strižne odpornosti in viskoznosti umerjeni, je bil primer Loga pod Mangartom, kjer so bile zabeležene gladine drobirskega toka, ki je prizadel to območje. Po meritvah na terenu je bil model gibanja drobirskega toka umerjen na izmerjene gladine toka v soteski Predelice in na doseg toka v dolini Koritnice (Fazarinc 2002). Umerjene vrednosti za Log pod Mangartom znašajo: strižna odpornost $\tau_y = 2000\ \mathrm{N\,m^{-2}}$ in viskoznost $\eta = 156\ \mathrm{Pa\,s}$. Te vrednosti so bile nato preračunane v brezdimenzijska koeficienta α in β, ki sta zahtevana kot vhodna podatka v modelu in sicer za strižno odpornost: $\alpha = 0{,}0525$ in $\beta = 25{,}7$ ter za viskoznost: $\alpha = 0{,}0248$ in $\beta = 22{,}1$.

4.3 Ostali parametri modela

Poleg reoloških parametrov sta pomembna parametra tudi Manningov koeficient hrapavosti n_g in koeficient laminarne odpornosti K. Manningov koeficient hrapavosti n_g je bil izbran na podlagi literature, saj bi ga sicer lahko le določili iz matematičnega modela, ki bi ga umerili na opazovani naravni dogodek. V primeru ocenjevanja tveganja za možne dogodke torej tega koeficienta ne moremo izmeriti, lahko ga izberemo na osnovi izkušenj, analize podobnih primerov na drugih mestih ali pa na osnovi v literaturi predlaganih vrednosti. Izbrali smo zadnjo možnost (O'Brien 2006), kjer so priporočene vrednosti za posamezne vrste površine, po kateri se giblje drobirski tok. Vrednosti za modeliranje gibanja toka po vršaju so rahlo različne od običajnih vrednosti za gibanje toka v strugi. Za obravnavano hudourniško območje Hrenovec je bila določena vrednost $n_g = 0{,}2$. Študija občutljivosti matematičnega modela na izbiro modelnih parametrov, med njimi tudi Manningovega koeficienta hrapavosti je za primer vršaja Koroške Bele pokazala, da spreminjanje vrednosti tega koeficienta ne vpliva bistveno na rezultate modeliranja (Sodnik in ostali 2009). Koeficient laminarne odpornosti toka K je bil prav tako povzet po literaturi (O'Brien 2006), ki za drobirske tokove predlaga vrednost $K = 2285$. Program dopušča možnost, da se med računom vrednost K izračuna iz vrednosti n_g za vsako računsko polje posebej, vendar taka izbira zelo podaljša čas računanja.

4.4 Obravnavani računski primeri

Kot je bilo navedeno v poglavju o hidroloških podlagah modeliranja, sta bila obravnavana dva možna dogodka (preglednica 3). Prvi je dogodek s stoletno povratno dobo, drugi pa je dogodek v katerem so upoštevane padavine z dne 18. 9. 2007. Omenjena primera sta zanimiva, saj je pojav s stoletno povratno dobo zanimiv zato, ker se običajno vsi ukrepi in ureditve v hudourništvu kot strokovni dejavnosti urejanja hudourniških območij dimenzionirajo na stoletno povratno dobo. Drugi dogodek pa je zanimiv, ker simulira oziroma prikazuje dogodek, ki bi se lahko zgodil 18. 9. 2007.

Preglednica 3: Glavne značilnosti dveh scenarij, uporabljenih za simuliranje gibanja drobirskega toka iz hudourniškega območja Hrenovec nad Kropo.

parameter	scenarij s stoletno povratno dobo	scenarij s padavinami 18. 9. 2007
maksimalni pretok	21,09 m^3/s	39,82 m^3/s
količina sproženega gradiva	32.633 m^3	60.375 m^3
prostorninska koncentracija mešanice	0,5	0,5

5 Rezultati modeliranja

5.1 Dogodek s stoletno povratno dobo

Pri dogodku s stoletno povratno dobo je maksimalni pretok Q_{100} 21,09 m^3/s. Količina sproščenega gradiva znaša M_{100} 32.633 m^3. Maksimalne globine toka v tem primeru znašajo do 2,6 m (slika 6). Na območju jedra Krope, kjer so ponavadi ob visokih vodah razmere najslabše, je maksimalna globina toka ob dogodku 1,7 m in bi se tok razlil po trgu in starem jedru naselja (slika 7) ter bi zalil trg in bližnje objekte. Na trgu je maksimalna globina toka od 1,2 do 1,5 m.

Velike globine so tudi na območju Viganca (slika 8), kjer je ujma septembra 2007 povzročila veliko škode. Dolvodno od mestnega jedra, mimo tovarne UKO in Novi Plamen so razmere manj kritične, saj je struga globoka in so brežine nenaseljene oziroma na območju tovarn zavarovane z zidovi. Na tem območju je dne 18. 9. 2007 prišlo do zajezitve na mostu in je hudourniška voda prestopila bregove in tekla po cesti proti glavnemu trgu. Hitrosti drobirskega toka znašajo v strugi v povprečju okrog 3 do 4 m/s.

Modeliranje je pokazalo, da je hitrost na poplavnih ravnicah bistveno nižja kot v strugi hudournika, kar je pomembna prednost računanja z dvodimenzijskimi modeli v primerjavi z enodimenzijskimi, ki takih podrobnosti toka zaradi poenostavljenega računa hitrosti v samo eni dimenziji ne morejo prikazati.

Slika 6: Maksimalne globine drobirskega toka iz hudourniškega območja Hrenovec nad Kropo pri dogodku s stoletno povratno dobo.
Glej angleški del prispevka.

Slika 7: Maksimalne globine drobirskega toka iz hudourniškega območja Hrenovec nad Kropo s 100-letno povratno dobo na osrednjem trgu v Kropi.
Glej angleški del prispevka.

Slika 8: Maksimalne globine drobirskega toka iz hudourniškega območja Hrenovec nad Kropo s 100-letno povratno dobo na območju pod Vigancem v Kropi.
Glej angleški del prispevka.

5.2 Možni scenarij 18. 9. 2007

Pri modeliranem možnem dogodku z dne 18. 9. 2007, kjer so upoštevane padavine izmerjene tega dne, je maksimalni pretok $Q_{18.9.2007}$ 39,82 m^3/s, količina sproščenega gradiva pa $M_{18.9.2007}$ 60.375 m^3. Pri dogodku gre za skoraj dvakratni stoletni pretok (Q_{100} 21,09 m^3/s) in skoraj dvakratno količino sproščenega gradiva (M_{100} 32.633 m^3). Maksimalne globine v tem primeru znašajo do 3,1 m. V strugi je globina toka v povprečju od 2,0 do 2,4 m. Maksimalne globine se pojavljajo na istih delih kot pri dogodku s stoletno povratno dobo, a so v tem primeru za približno 20 % višje. Ravno ta razlika na mnogih mestih pomeni bistveno poslabšanje razmer. Na glavnem trgu znašajo maksimalne globine toka okrog 2,0 m, kar je več kot je višina okenskih polic v pritličju (slika 9).

Prav tako je močno poplavljen trg na desnem bregu, ki v dogodku s stoletno povratno dobo ni poplavljen, pri danem scenariju 18. 9. 2007 pa maksimalne globine presegajo 1,5 m (slika 10). Tudi hitrosti drobirskega toka so poleg globin precej večje kot pri dogodku s stoletno povratno dobo. V povprečju so v zgornjem toku večje za 25 %, v spodnjem delu, kjer je padec struge manjši, pa so razlike manjše (slika 11).

Slika 9: Stanje na območju glavnega trga v Kropi v primeru drobirskega toka iz hudourniškega območja Hrenovec nad Kropo pri potencialnem dogodku 18. 9. 2007.

Glej angleški del prispevka.

Slika 10: Območje spomeniško zaščitenih rak v Kropi, ki so v primeru drobirskega toka iz hudourniškega območja Hrenovec nad Kropo pri potencialnem dogodku 18. 9. 2007 preplavljene.

Glej angleški del prispevka.

Slika 11: Maksimalne hitrosti toka v primeru drobirskega toka iz hudourniškega območja Hrenovec nad Kropo pri potencialnem dogodku 18. 9. 2007.

Glej angleški del prispevka.

6 Sklep

Modeliranje drobirskega toka v hudourniškem območju Hrenovec nad Kropo je aktualen problem, saj je med neurjem septembra 2007 prišlo sproženja drobirskega toka v zgornjem toku hudournika po sprožitvi manjšega zemeljskega plazu pod Vodiško planino. Večina se je na srečo zaustavila v zgornjem delu hudourniške struge. Po oceni je bilo nestabilnega približno 50.000 m^3 gradiva. Zaradi aktivnosti septembra 2007, je bilo hudourniško območje Hrenovca nad Kropo uvrščeno med možna območja drobirskih tokov in je kot tako služilo kot podlaga za oceno možnosti proženja drobirskih tokov v Sloveniji (CRP 2009).

Modela obeh scenarijev sta pokazala, da je struga Kroparice, v katero se na območju vodnega zajetja zliva hudournik Hrenovec, občutno pod-dimenzionirana za dogodek, ki je predstavljen v članku. Za blaženje posledic in lovljenje manjših drobirskih tokov je bil po ujmi septembra 2007 na območju vodnega zajetja oblikovan zaplavni prostor s prostornino okoli 1500 m^3. Omenjen zaplavni prostor pri dogodkih z magnitudo, kot je bila modelirana v obravnavanih scenarijih, nima bistvene vloge. Pomembno vlogo pa bi imel pri dogodkih z manjšo magnitudo.

Za natančnejšo določitev ogroženosti v smislu coniranja območij ogroženosti bi morali v model vključiti še natančnejšo geodetsko izmero hudourniške struge Hrenovca in Kroparice. Študija je pokazala, da lahko na podlagi javno dostopnih podatkov o reliefu (digitalni model višin 5, Geodetska uprava Republike Slovenije) in o padavinah (Agencija Republike Slovenije za okolje) izdelamo dovolj natančen model gibanja možnih drobirskih tokov, s katerim lahko opredelimo nevarnost, ki grozi obravnavanem območju. Tovrstni pristop k preventivnemu varstvu je v mnogih alpskih državah uzakonjen in se izvaja. V Sloveniji smo sicer že pred več kot desetimi leti pisali o nujnosti takšnega ukrepanja (Mikoš 1997). Toda čeprav tak pristop omenja Zakon o vodah (2002), nujne podzakonske regulative še vedno niso sprejete. Kot primer dobre prakse omenimo vladno uredbo, ki je v postopku sanacije razmer v Logu pod Mangartom po drobirskem toku novembra 2000 predpisala pogoje rabe prostora zaradi nevarnosti novih drobirskih tokov s plazu Stože (Mikoš in ostali 2007).

7 Zahvala

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8 Literatura

Glej angleški del prispevka.