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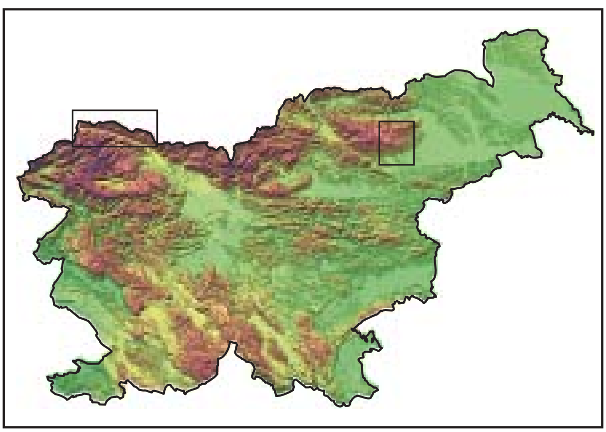
ESTIMATION OF MAGNITUDES OF DEBRIS FLOWS IN SELECTED TORRENTIAL WATERSHEDS IN SLOVENIA

OCENA MAGNITUD DROBIRSKIH TOKOV V IZBRANIH HUDOURNIŠKIH OBMOČJIH V SLOVENIJI

Jošt Sodnik, Matjaž Mikoš

Debris flow in the village of Log pod Mangartom in November 2000 (photograph: authors, November 22, 2000).
Drobirski tok v Logu pod Mangartom novembra 2000 (fotografija: avtorja, 22. november 2000).



Estimation of magnitudes of debris flows in selected torrential watersheds in Slovenia

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ABSTRACT: In this paper the application of different methods for estimation of magnitudes of rainfall-induced debris flows in 18 torrents in the Upper Sava River valley, NW Slovenia, and in 2 torrents in Pohorje, N Slovenia is described. Additional verification of the methods was performed in the torrential watersheds with active debris flows in the recent past (Predelica and Brusnik in the Soča River basin, W Slovenia). For some of the methods, the knowledge of morphometric characteristics of a torrential watershed, torrential channel and torrential fan is enough. For other methods, a mathematical tool (HEC-HMS) had to be applied in order to develop a hydrologic run-off model of precipitation that can trigger debris flows. Computed debris-flow magnitudes were of the order between 6,500 m^3 and 340,000 m^3. Their values are a function of torrential watershed parameters, such as: watershed area, Melton number, fan gradient, and torrential channel gradient. The investigated fans were classified into 3 groups with regard to the debris-flow hazard: debris-flow fans (hazard exists), torrential fans (no hazard), and transitional fans (debris flows are possible, but with low possibility). A limit between debris-flow fans and torrential fans is proposed: Melton number 0.3 and torrential fan gradient 4°, that is, 7%. Out of 24 investigated torrential fans, 13 fans were classified into the group of debris-flow fans, 5 fans were classified into the group of torrential fans, and the rest 6 fans were classified into the group of transitional fans.

KEY WORDS: erosion, mass movements, debris flows, empirical models, hazard estimation, fans, Upper Sava River valley, Pohorje, Slovenia.

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Contents

1 Introduction

Debris flows as a form of mass movements of sediments on slopes or in torrential channels have transformed the relief in Slovenia in the geological past and are becoming more and more frequent recently. Due to the dispersed settlement pattern and dense traffic network in Slovenia, it has become necessary to investigate debris flow hazards into more detail. Debris flows as a form of mass movement of sediments (Skaberne 2001) can develop on slopes or in torrential channels. Knowing their dynamics (Mikoš 2001) makes it possible to plan adequate preventive countermeasures. One of the most frequent questions related to debris flows is related to the location of their initiation. Also, for planning of countermeasures it is necessary to know the process magnitude that can be expected. Using estimated magnitudes one can also estimate the debris flow run-out by modelling debris flow routing as well as their flowing velocities and depths that are usually used with hazard assessment (Mikoš 1997).

Any large-scale planning of preventive countermeasures against different landslide and rockfall processes must tackle each case separately. Each case has its specific characteristics that may greatly effect the course of events. One of the basic data is the catchment area of a torrential watershed under investigation. The ratio between the amount of available debris material and the amount of released debris material varies from one case to another. Nevertheless one tried to develop methods that would be generally applicable for the estimation of debris flow magnitudes in the past. Geomorphic processes on torrential fans have been so far investigated in many field studies. In one of the earliest studies, Melton (1965) suggested a relation between the gradient of a torrential fan (S) and some other topographic parameters:

$$S = a[(H_{max} - H_{min})A^{-0,5}]^n, \qquad (1)$$

where a and n are independent coefficients, H_{max} (km) and H_{min} (km) are elevations of the highest point and the lowest point of the torrential watershed (i. e. highest point of the torrential fan), respectively, and A (km^2) is the catchment area of the torrential watershed. The term $Mel = (H_{max} - H_{min})A^{-0,5}$ is simply called the Melton number after its author. This approach is the ground for investigation of alluvial processes on fans, oriented into a classification of fans on the basis of morphological parameters of torrential watersheds and fans.

There are many methods for estimation of debris flow magnitudes, being one of the bases for debris flow risk estimation, and one can divide them into:

- empirical methods (e. g. Takei 1984, Kronfellner-Kraus 1984, Marchi & D'Agostino 2002) that they provide the estimation of debris-flow magnitudes;
- morphological methods (e. g. Jackson et al. 1987, Marchi et al. 1993, Marchi & D'Agostino 2002, Jakob 2005) that can be divided into those that estimate the magnitude and those that aim at the determination of debris-flow hazard on torrential fans;
- combined methods (e. g. Ceriani et al. 2000) that are a combination of different other methods, which based on statistical analysis determine the relevant torrential watershed parameters in the form of an empirical equation for the estimation of the debris-flow magnitude;
- computer methods (e. g. Schöberl et al. 2004) are computer programs that take into account sediment production in the watershed under investigation and sediment transport capacity of the torrent including sediment deposition in the torrential channel.

A detailed description of these methods is given elsewhere (Sodnik 2005; Sodnik & Mikoš 2005).

For computation of debris flow magnitudes m in selected torrential watersheds in Slovenia the following empirical and morphological methods have been used:

Takei (1984): $Vd = 13600A^{0.61}$ …..[m^3] (2)

Kronfellner-Kraus (1984): $M = K \cdot A \cdot S_c$ …..[m^3] (3)

$K = 1150/e^{0.014A}$ …..[–] (4)

Marchi & D'Agostino (2002):

Method 1: $M = 65000A^{1.35}S^{1.7}$ …..[m^3] (5)

Method 2: $M / V_r = 2,9\,S^2$ …..[–] (6)

Ceriani et al. (2000): $M = k \cdot (A)^a \cdot (M_b)^b \cdot (S_{cl\_c})^c \cdot (I\_F)^{-d}$…..[$10^3$ m^3], (7)

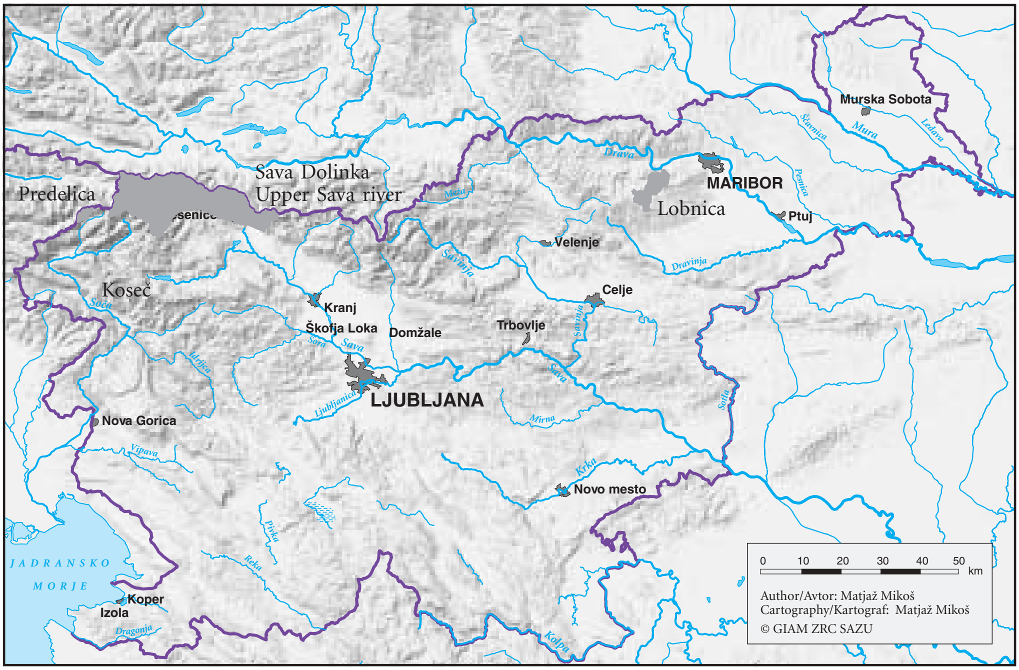

Figure 1: Torrential watersheds in Slovenia treated in this paper.

where the parameters in the equations are follows:
K – coefficient of the torrential watershed, given for separate parts of the Alps in Austria [–];
A – catchment area of the torrential watershed [km^2];
S_c – average gradient of the torrential channel [%];
S – average gradient of the torrential channel [m/m];
V_r – the total run-off volume [m^3];
I_F – landslide index [–];
M_b – Melton number [–];
S_{cl_c} – gradient of the torrential channel on the fan [%].

In this paper, the results of application of the empirical and morphological methods to selected Slovenian torrents are discussed. The purpose of the analysis was to check the possibility of estimating the magnitude of potential debris flows and their distribution in relation to hazard. The estimated values obtained with the chosen methods should be compared to historical records on the volume of past events. Unfortunately, no systematic analysis of past events was ever performed and the comparison of results acquired with the chosen methods with events that occurred in the past is rather the exception, not the rule.

The estimates of magnitudes of debris flows were performed in selected torrential tributaries of the Sava Dolinka (the Upper Sava valley) and two torrents in Pohorje (Figure 1). For additional verification, the methods were tested in the torrents of Predelica and Brusnik, where debris flows have occurred in the recent past (Mikoš et al. 2004; 2006).

2 Hydrological calculations

Before applying some of the methods in the chosen torrential watersheds, the total run-off volume of the precipitation relevant for debris-flow initiation was to be calculated. The modelling was performed with the HEC-HMS program (Hydrologic Modeling System 2000; 2001). The purpose of modelling was to deter-

Table 1. Results of run-off modelling in the torrential watersheds of the Upper Sava River.

Torrential watershed	area [km^2]	slope [%]	channel length [km]	channel length [%]	discharge Q_{100} [m^3/s]	Curve number CN [–]	SCS method T_p [hour]	Clarck-Kirpich method T_c [hour]	Snyder – Riverside County method T_p [hour]	Total run-off [m^3]
UPPER SAVA RIVER										
Trebiža	5.3	38	3.8	8.6	40	67	0.560	0.376	0.432	407,150
Krotnjek	3.7	48	3.2	9.6	36	67	0.435	0.301	0.363	326,000
Suhelj	1.9	57	3.2	16.9	23	71	0.359	0.282	0.351	182,050
Velika Pišnica	37.9	67	9.2	3.3	128	57	1.107	0.598	0.760	2,092,700
Jurežev graben	2	47	2.7	28.6	19	66	0.394	0.267	0.320	158,380
Martuljek	11.4	72	4.1	11.4	82	64	0.468	0.312	0.406	803,620
Hladnik	15	60	6.6	12.1	99	66	0.713	0.483	0.603	1,174,600
Beli potok	5.3	72	3.8	21	39	63	0.452	0.294	0.383	355,690
Belca	17.6	65	7	8.5	107	64	0.756	0.490	0.621	1,307,100
Bistrica	43.7	64	12.6	4	197	61	1.317	0.775	0.974	3,303,100
Mlinca	7.9	59	4.9	17.1	56	60	0.661	0.386	0.482	593,910
Presušnik	4.7	49	4.1	21.2	38	61	0.613	0.362	0.436	387,770
Dobršnik	1.8	45	3.3	24.8	18	63	0.511	0.316	0.376	165,300
Jesenica	20.5	41	7.9	8.7	122	64	1.049	0.642	0.743	1,676,900
Ukova	4.3	37	4.5	14.2	38	68	0.634	0.433	0.494	384,740
Javornik	16.6	42	6.8	7.8	94	61	0.992	0.567	0.660	1,304,400
Bela	6.2	52	3.9	11.9	52	62	0.557	0.340	0.415	479,390
Sevnik	1.9	39	2.9	24.6	16	59	0.548	0.303	0.350	144,660
POHORJE										
Lobnica	44.3	29.6	16.5	6.51	116	54	2.866	0.414	1.383	3,547,000
Lobničica	3	46.2	3.6	19.78	19.5	53	0.696	0.305	0.399	241,200
PREDELICA										
Predelica	9.3	60	6.2	15.7	77	36	1.481	0.316	0.575	1,345,000
KOSEČ										
Brusnik upstream of Koseč	0.56	70	1.5	37.2	8.4	43	0.363	0.297	0.190	82,360
Brusnik upstream of Ročica	0.9	56	2.3	32.5	12.0	43	0.572	0.324	0.274	136,500
Ročica	10.6	60	6.7	14.1	79.0	38	1.488	0.277	0.610	1,313,000

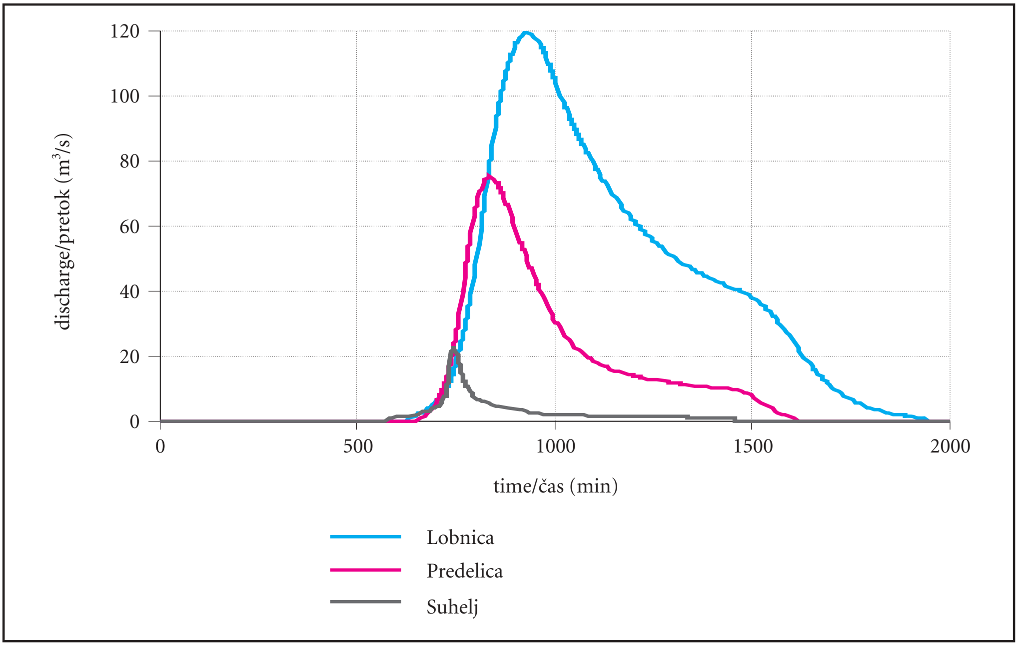

Figure 2: Modelled run-off hydrographs using HEC-HMS model for selected torrential watersheds (Suhelj in the Upper Sava River valley, Lobnica in Pohorje and Predelica in the Soča River basin).

mine the total volume of run-off based on given precipitation and calculated discharge values, since in the method for estimation of magnitude of debris flow the estimate of run-off volume is required.

The morphometric data on torrential areas were taken from hydrological studies (VGI 1993, 1995a, 1995b, 1999, 2002), Table 1.

The data on surface charactersts were taken from the Naravovarstveni atlas (NVA 2005), where the airborne imagery can be acquired. The precipitation data for hydrological modelling were taken from hydrological studies (VGI 1993, 1995b, 1999, 2002) and they are shown in Table 2. Based on the position, an associated precipitation station was attributed to each torrential area, and precipitation data were considered in the analysis. For torrential watersheds in the upstream part of the Upper Sava River, including the Belca Torrent, the data for rainfall station Rateče – Planica were used, and for other areas with the inclusion of the Bistrica Torrent the data from the precipitation station Javorniški Rovt were used. For the Lobnica River and the Lobničica Torrent on Pohorje, the data of the precipitation station Koča nad Šumikom were used, for the Predelica Torrent and the Brusnik Stream the data from Bovec. In the vicinity of torrential areas there are other stations, which, however, are not equipped with raingauges (ombrographs) that would record short heavy rain showers and enable their statistical analysis. Thus in the Upper Sava River valley there are 8 precipitation stations, but only three are equipped with ombrographs. Only stations Rateče – Planica and Javorniški Rovt could therefore be included in the analysis. Hydrological

Table 2. Rainfall data from raingauge stations, used for hydrologic modelling – shown are precipitation totals in mm of showers of short duration between 5 minutes and 1440 minutes with the recurrence interval of 100 years.

Raingauge station/Duration of precipitation [minutes]	5	15	60	120	180	360	720	1440
Javorniški Rovt (1966–1993)	22.5	34.0	57.5	74.5	86.8	112.7	146.3	190.0
Rateče – Planica (1966–1993)	15.1	25.2	48.1	66.5	80.4	110.5	138.9	174.6
Koča nad Šumikom (1975–1997)	21.2	33.6	59.9	80.1	94.9	126.8	169.5	226.5
Bovec (1959–1987)	20.2	41.9	104.9	165.9	217.0	293.3	358.0	437.0

studies provide statistically calculated precipitation of different return periods/recurrence intervals and duration, calculated with the help of measurements for particular periods (see Table 2).

For the preparation of data in the HEC-HMS model there are several methods to choose from, however, the methods are limited by several factors, such as relief gradient, channel gradient, characteristics of terrain, and thus some of them were not applicable. The following methods have proven as suitable: SCS method (Soil Conservation Service), SRC method (Snyder – Riverside County) and Clark-Kirpich method (Brilly & Šraj 2005). The calculated values of the time of concentration T_c or the time delay T_p between precipitation and run-off peak are shown in Table 1. Based on the results we have decided to use the SCS method, which is widely used in practice.

The CN (curve number) as a parameter indicating the soil characteristics (infiltration etc.) was based on surface characteristics, such as ratio of forest, meadows, shrubs and rocks. The initial CN value was based on the data provided by remote sensing. The final value of CN parameter was based by calibrating the hydrological model, so that the peak of the calculated runoff and data on high water with 100-year recurrence period were correlated. The calculated runoffs in the hydrological studies were determined in a similar way, by way of a synthetic hydrograph, computed from assumed precipitation, however, they only give peak values, and not the total volume of the flood wave. The calculated volumes of runoff volume with the SCS method are shown in Table 1, and the synthetic run-off hydrographs for the selected torrential areas in Figure 2.

3 Analysis of hydrological parameters

This was followed by the analysis of the calculated hydrological parameters as a function of the size of the torrential watershed. The basis for determination of empirical equations were the results for 18 torrential areas of the Upper Sava River: Figure 3 shows the relation between the 100-year discharge Q_{100} (m^3/s) and the torrential watershed area A (km^2) and Figure 4 the relation between the run-off volume V_r (m^3) and the torrential watershed area A (km^2). 100-year discharge analysis Q_{100} and run-off analysis V_r give statistically reliable equations (in both cases the regression coefficient is $R^2 > 0.97$ for $n = 18$). These two

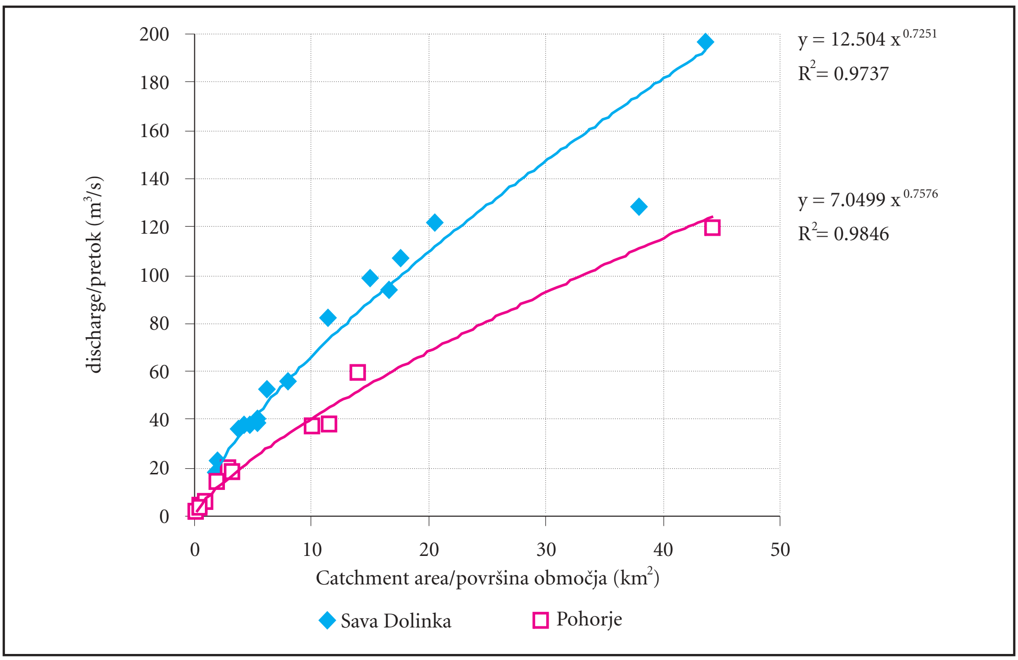

Figure 3: Relation between the 100-year discharge Q_{100} and the catchment area of the torrential watersheds in the Upper Sava River valley ($n = 18$) and in Pohorje ($n = 11$).

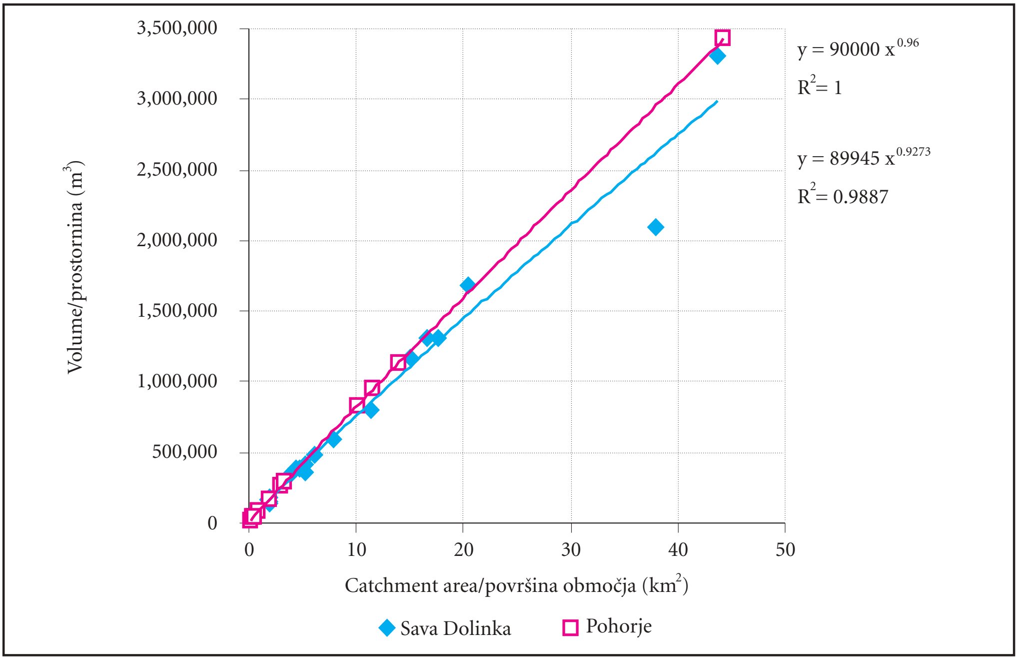

Figure 4: Relation between the volume of the flood hydrograph with a peak discharge of Q_{100} and the catchment area of the torrential watersheds in the Upper Sava River valley (n = 18) and in Pohorje (n = 11).

equations can be used also in other torrential areas of the Upper Sava River valley without previous hydrological modelling. The relation between runoff volume and torrential watershed area accelerates the estimate of magnitude of debris flow using the methods that require the knowledge of runoff volume.

Figure 3 also shows the relation between 100-year discharges Q_{100} and the area of watershed A of single torrents in the Pohorje area. In Pohorje only two torrents (the Lobnica and Lobničica) were used for the analysis of applicability of methods for estimation of magnitude of debris flows, however, for discharge analysis other torrents from SW part of Pohorje were used, which are covered in the hydrological study for this particular area (VGI 1999). Thus, a total of 11 torrential areas (n = 11) of a size of between 0.17 km^2 and 44,3 km^2 were at our disposal.

Based on discharge analysis and run-off volumes the following empirical equations were obtained (Figures 3 and 4):

Q_{100} for torrents on the Upper Sava River: $$Q_{100} = 12.5\,A^{0,72}\ [\mathrm{m^3/s}] \qquad (8)$$

Q_{100} for torrents in the Pohorje area: $$Q_{100} = 7\,A^{0,76}\ [\mathrm{m^3/s}] \qquad (9)$$

Volume of flood wave in the Upper Sava River: $$V_r = 90{,}000\,A^{0,93}\ [\mathrm{m^3}] \qquad (10)$$

Table 3. Computed run-off volumes for the torrential watersheds in Pohorje.

Torrential watershed	area A (km^2)	Upper Sava River (Eq. 10) Volume $V_r = 90{,}000\,A^{0.93}$ (m^3)	Pohorje (Eq. 11) Volume $V_r = 90{,}000\,A^{0.96}$ (m^3)	HEC-HMS method Volume V_r (m^3)
Lobnica	44.3	3,057,722	3,426,022	3,547,000
Lobničica	3.0	250,015	258,392	241,200

The empirical equations for calculation of flood wave volume in Pohorje could not be obtained in the same way as for the torrents on the Upper Sava River, since in the Pohorje area only two torrents (Lobnica

Table 4. Parameters of the torrential watersheds, used for the estimation of debris-flow magnitudes.

Torrential watershed	Area [km^2]	Slope [%]	Channel length [km]	Channel slop [%]	*dH* – height difference [km]	Melton number [–]	Fan gradient [%]	V_r – water run-off [m^3]	Annual sediment yield [m^3/year]
UPPER SAVA RIVER									
Trebiža	5.3	38	3.8	8.6	0.687	0.298	4.157	407,150	No data available
Krotnjek	3.7	48	3.2	9.6	0.592	0.308	5.024	326,000	No data available
Suhelj	1.9	57	3.2	16.9	0.727	0.527	11.828	182,050	No data available
Velika Pišnica	37.9	67	9.2	3.3	1.500	0.244	2.218	2,092,700	69,325
Jurežev graben	2.0	47	2.7	28.6	0.867	0.613	11.842	158,380	265
Martuljek	11.4	72	4.1	11.4	1.066	0.316	4.211	803,620	19,848
Hladnik	15.0	60	6.6	12.1	1.134	0.293	6.496	1,174,600	9,654
Beli potok	5.3	72	3.8	21.0	1.367	0.594	10.010	355,690	7,053
Belca	17.6	65	7	8.5	1.067	0.254	5.182	1,307,100	18,297
Bistrica	43.7	64	12.6	4.0	1.650	0.250	1.448	3,303,100	No data available
Mlinca	7.9	59	4.9	17.1	1.231	0.438	8.100	593,910	11,481
Presušnik	4.7	49	4.1	21.2	1.150	0.530	12.261	387,770	9,521
Dobršnik	1.8	45	3.3	24.8	0.970	0.723	10.000	165,300	2,396
Jesenica	20.5	41	7.9	8.7	1.093	0.241	3.382	1,676,900	10,402
Ukova	4.3	37	4.5	14.2	0.739	0.356	9.348	384,740	885
Javornik	16.6	42	6.8	7.8	1.230	0.302	5.900	1,304,400	7,280
Bela	6.2	52	3.9	11.9	0.570	0.229	9.058	479,390	4,968
Sevnik	1.9	39	2.9	24.6	0.480	0.348	14.500	144,660	No data available
POHORJE									
Lobnica	44.3	29.6	16.5	6.5	0.997	0.150	5.607	3,547,000	5,248
Lobničica	3.0	46.2	3.6	19.8	0.900	0.520	20.000	241,200	386
PREDELICA									
Predelica	9.3	60	6.2	15.7	2.049	0.672	9.200	1,345,000	No data available
KOSEČ									
Brusnik upstream of Koseč	0.56	70	1.5	37.2	0.725	0.969	23.333	82,360	No data available
Brusnik upstream of Ročica	0.9	56	2.3	32.5	0.985	1.038	30.769	136,500	No data available
Ročica	10.6	60	6.7	14.1	1.007	0.309	7.700	1,313,000	No data available

Table 5. Estimated debris-flow magnitudes determined for all torrential watersheds.

	Takei (1984)	Kronfellner-Kraus (1984)		Marchi & D'Agostino (2002)			Ceriani et al. (2000)					
				Method 1		Method 2	Magnitude [m^3]	Magnitude [m^3]	Magnitude [m^3]			
Torrential watershed	Magnitude [m^3]	K [–]	Magnitude [m^3]	Magnitude [m^3]	M/V_r	Magnitude [m^3]	$I\_F = 1$	$I\_F = 2$	$I\_F = 3$	M/V_r	M/V_r	M/V_r
UPPER SAVA RIVER												
Trebiža	37,614	1067.76	48,668	9,535	0.021	8,733	45,221	11,305	5,025	0.111	0.028	0.012
Krotnjek	30,209	1091.95	38,786	7,077	0.027	8,713	39,102	9,775	4,345	0.120	0.030	0.013
Suhelj	20,118	1119.81	35,957	7,527	0.083	15,079	72,742	18,185	8,082	0.400	0.100	0.044
Velika Pišnica	124,885	676.49	84,609	26,641	0.003	6,609	146,677	36,669	16,297	0.070	0.018	0.008
Jurežev graben	20,757	1118.25	63,964	19,730	0.237	37,569	86,468	21,617	9,608	0.546	0.136	0.061
Martuljek	60,014	980.36	127,407	43,299	0.038	30,287	103,057	25,764	11,451	0.128	0.032	0.014
Hladnik	70,950	932.17	169,189	69,402	0.042	49,872	196,955	49,239	21,884	0.168	0.042	0.019
Beli potok	37,614	1067.76	118,842	43,497	0.128	45,489	188,803	47,201	20,978	0.531	0.133	0.059
Belca	78,217	898.85	134,468	47,246	0.021	27,387	164,708	41,177	18,301	0.126	0.032	0.014
Bistrica	136,217	623.73	109,028	44,778	0.005	15,326	112,596	28,147	12,511	0.034	0.009	0.004
Mlinca	47,983	1029.59	139,087	52,578	0.085	50,363	178,510	44,627	19,834	0.301	0.075	0.033
Presušnik	34,956	1076.77	107,289	37,585	0.130	50,541	187,379	46,845	20,820	0.483	0.121	0.054
Dobršnik	19,465	1121.38	50,058	13,431	0.178	29,483	74,985	18,746	8,332	0.454	0.113	0.050
Jesenica	85,844	863.09	153,932	60,390	0.022	36,808	120,105	30,026	13,345	0.072	0.018	0.008
Ukova	33,110	1082.81	66,117	16,865	0.058	22,498	95,085	23,771	10,565	0.247	0.062	0.027
Javornik	75,475	911.52	118,024	37,724	0.018	23,014	202,874	50,718	22,542	0.156	0.039	0.017
Bela	41,390	1054.39	77,793	20,468	0.041	19,687	93,231	23,308	10,359	0.194	0.049	0.022
Sevnik	20,118	1119.81	52,340	14,250	0.175	25,387	63,975	15,994	7,108	0.442	0.111	0.049
POHORJE												
Lobnica	–	–	–	–	0.012	43,593	293,738	73,434	32,638	0.083	0.021	0.009
Lobničica	–	–	–	–	0.113	27,367	191,907	47,977	21,323	0.796	0.199	0.088
PREDELICA												
Predelica	–	–	–	–	0.071	96,143	336,128	84,032	37,348	0.250	0.062	0.028
KOSEČ												
Brusnik upstream of Koseč	–	–	–	–	0.401	33,052	68,794	17,198	7,644	0.835	0.209	0.093
Brusnik upstream of Ročica	–	–	–	–	0.306	41,812	154,101	38,525	17,122	1.129	0.282	0.125
Ročica	–	–	–	–	0.058	75,701	172,382	43,095	19,154	0.131	0.033	0.015

and Lobničica) were modelled with HEC-HMS. So we could only test the applicability of equation (10), which applies for the torrents on the Upper Sava River. Table 3 shows the calculation of flood wave volume for both torrents in Pohorje in 3 different ways. Correlation with results of hydrological modeling with HEC-HMS model are bfollowing term is obtained (Figure 4):

Flood wave volume in Pohorje: $V_r = 90{,}000\ A^{0{,}96}\ [m^3]$ (11)

Torrents Lobnica and Lobničica are fit for comparison, the former having large catchment area ($A = 44.3\ km^2$), and the latter having small catchment area ($A = 3.0\ km^2$). The proposed equation for wider use should be additionally verified with hydrological modelling. The values of coefficients in equations 8 and 9 are consistent with the values employed in engineering practice. The value of exponent 0.76 for torrents in Pohorje may come as a surprise, since this is contrary to the assumed maximum coefficient of 0.75, which should be used/valid in the alpine part of Slovenia.

4 Calculation of magnitudes of debris flows

When estimating the magnitudes with different methods, we first determined the parameters of the methods for each torrential area; the parameters were either taken from hydrological studies, calculated or taken from topographic maps and airborne imagery. In Table 4 total precipitation run-offs are given, obtained by HEC-HMS. At the end of the table, the values of average release of erosion material for specific torrential areas are given, however, this data are not available for all torrents.

In Table 5 the results of the methods used are given. In the 18 torrential areas of the Upper Sava River all the methods were used, while on other torrential areas only the 2nd method Marchi & D'Agostino (2002) and method of Ceriani et al. (2000) were used. The Takei method (1984) and Kronfellner-Krauss method (1984) gave very high values of magnitudes of debris flows for the torrential areas of the Upper Sava River and were therefore not used for other torrential areas. For the method of Ceriani et al. (2000) the results are given for different landslide indices (*I_F*): active landslides or landslides that may re-activate are present (*I_F* = 1);

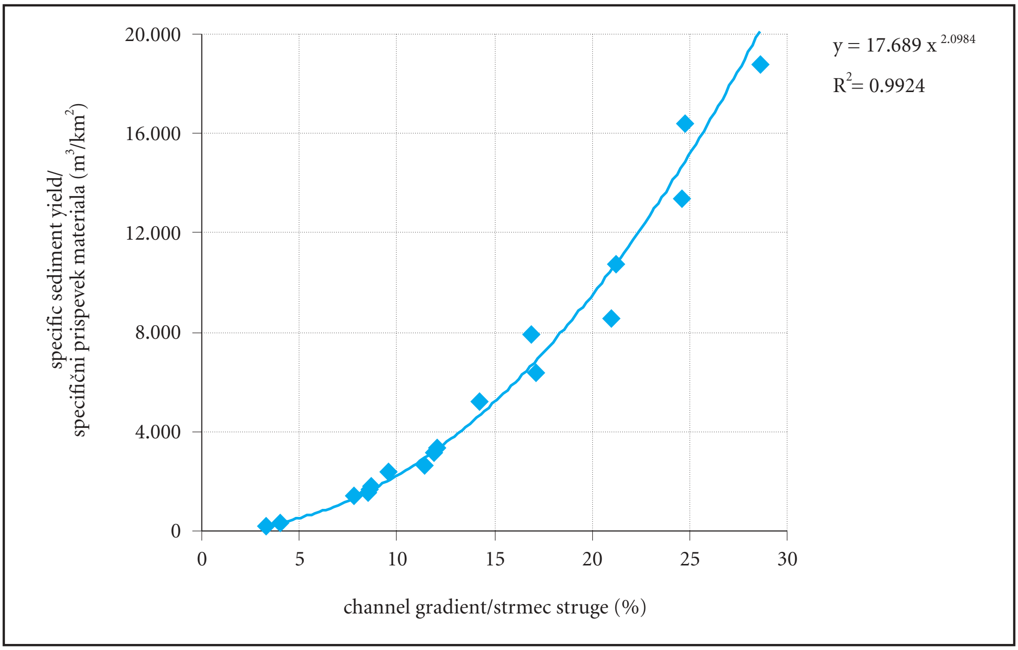

Figure 5: Relation between the specific sediment yield, computed using the method 2 of Marchi & D'Agostino (2002), and the torrential channel gradient in the Upper Sava valley (*n* = 18).

Table 6. Specific sediment yields for torrential watersheds.

	Takei (1984)	Kronfellner-Kraus (1984)	Marchi & D'Agostino (2002)		Ceriani et al. (2000)		
			Method 1	Method 2	a) $l\_F = 1$	b) $l\_F = 2$	c) $l\_F = 3$
Torrential watershed	[m^3/km^2]	[m^3/km^2]	[m^3/km^2]	[m^3/km^2]	[m^3/km^2]	[m^3/km^2]	[m^3/km^2]
UPPER SAVA RIVER							
Trebiža	7096.9	9182.7	1799.1	1647.7	8532.2	2133.0	948.0
Krotnjek	8164.7	10482.7	1912.7	2354.8	10568.0	2642.0	1174.2
Suhelj	10588.3	18924.8	3961.7	7936.1	38285.1	9571.3	4253.9
Velika Pišnica	3295.1	2232.4	702.9	174.4	3870.1	967.5	430.0
Jurežev graben	10378.6	31981.9	9865.0	18784.5	43234.1	10808.5	4803.8
Martuljek	5264.4	11176.1	3798.1	2656.8	9040.1	2260.0	1004.5
Hladnik	4730.0	11279.3	4626.8	3324.8	13130.3	3282.6	1458.9
Beli potok	7096.9	22422.9	8207.0	8582.9	35623.1	8905.8	3958.1
Belca	4444.2	7640.2	2684.4	1556.1	9358.4	2339.6	1039.8
Bistrica	3117.1	2494.9	1024.7	350.7	2576.6	644.1	286.3
Mlinca	6073.9	17606.0	6655.4	6375.1	22596.1	5649.0	2510.7
Presušnik	7437.4	22827.4	7996.8	10753.4	39867.8	9967.0	4429.8
Dobršnik	10813.9	27810.3	7461.5	16379.5	41658.4	10414.6	4628.7
Jesenica	4187.5	7508.9	2945.8	1795.5	5858.8	1464.7	651.0
Ukova	7699.9	15375.9	3922.1	5232.1	22112.9	5528.2	2457.0
Javornik	4546.7	7109.9	2272.5	1386.4	12221.3	3055.3	1357.9
Bela	6675.8	12547.2	3301.3	3175.3	15037.2	3759.3	1670.8
Sevnik	10588.3	27547.4	7500.1	13361.7	33670.8	8417.7	3741.2
POHORJE							
Lobničica	–	–	–	984.1	6630.6	1657.7	736.7
Lobnica	–	–	–	9122.3	63969.0	15992.2	7107.7
PREDELICA							
Predelica	–	–	–	10338.0	36142.8	9035.7	4015.9
KOSEČ							
Brusnik upstream of Koseč	–	–	–	59021.8	122845.6	30711.4	13649.5
Brusnik upstream of Ročica	–	–	–	46457.4	171223.1	42805.8	19024.8
Ročica	–	–	–	7141.6	16262.4	4065.6	1806.9

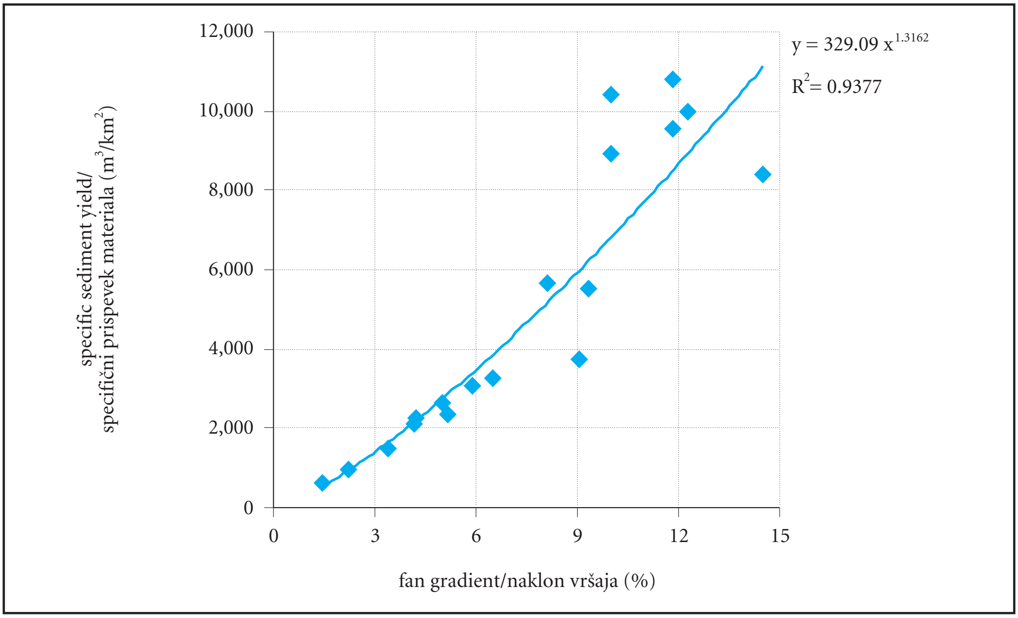

Figure 6: Relation between the specific sediment yield, computed using the method of Ceriani et al. (2000), and the torrential fan gradient in the Upper Sava valley ($n = 18$).

landslides are present though not close to the torrent channel ($I\_F = 2$); no larger or important landslides are present ($I\_F = 3$). For representation purposes, with method 2 of Marchi & D'Agostino (2002) and the method of Ceriani et al. (2000) the ratio between the volume of debris flow (magnitude) and volume of water M/V_r is given. Table 6 also gives specific sediment yield of debris material in single torrential areas.

5 Analysis of magnitudes of debris flows

The next step was the analysis of calculated magnitudes of debris flows as a function of morphological parameters of the torrential area. The analysis was performed for 18 torrents of the Upper Sava River valley for the calculated magnitudes of debris flows, using the method 2 of Marchi & D'Agostino (2002) and the method of Ceriani et al. (2000), with landslide index of $I\_F = 2$. As the most useful relationship was taken the relation/connection between morphological parameters of the torrential area and specific sediment yield of debris material in an area (m^3/km^2). In this way, the effect of size of catchment area was eliminated from the analysis.

Relations with the magnitude of debris flow, calculated to the specific sediment yield, were checked for the following morphological parameters: channel gradient (%), fan gradient (%) and the Melton number. The magnitude of debris flow following the method 2 of Marchi & D'Agostino (2002) was most significantly related to the channel gradient ($R^2 = 0.9924$, $n = 18$; Figure 5):

$$M = 17.7 \cdot I_s^2 \ [\text{m}^3/\text{km}^2], \qquad (12)$$

where I_s is channel gradient [%], while the method Ceriani et al. (2000) showed most significant relations to the fan gradient ($R^2 = 0.9377$, $n = 18$; Figure 6):

$$M = 330 \cdot I_v^{1,3} \ [\text{m}^3/\text{km}^2], \qquad (13)$$

where I_v fan gradient [%]. These two relations enable a quick assessment of magnitudes of debris flow in the Upper Sava River area. The reliability of both relations is a sound one, especially in using method 2

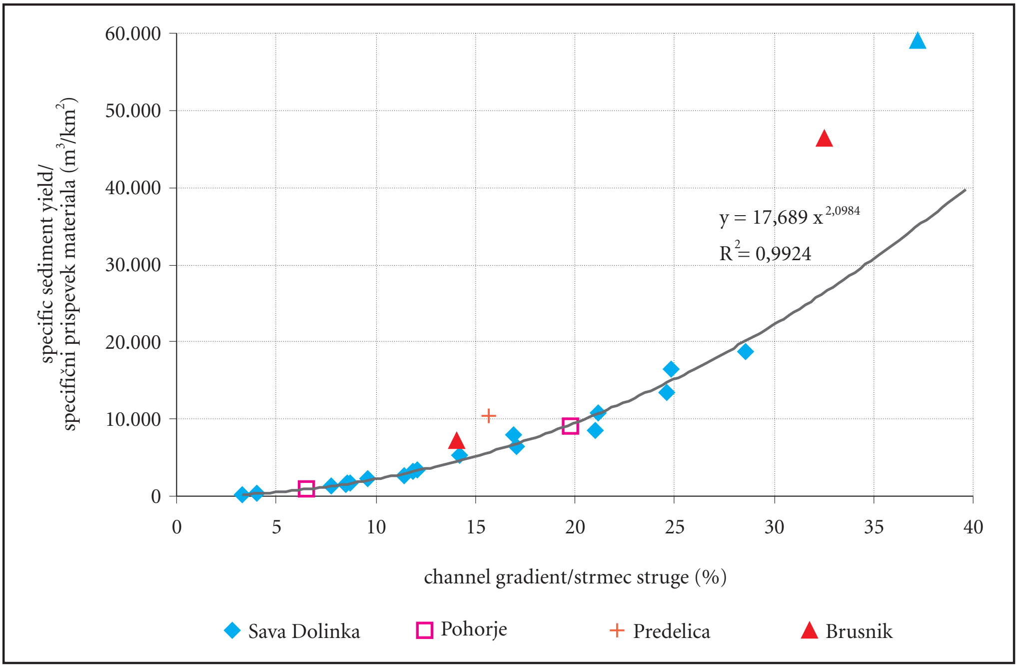

Figure 7: Relation between the specific sediment yield, computed using the method 2 of Marchi & D'Agostino (2002), and the torrential channel gradient for all investigated torrential watersheds (the regression line is Eq. (12)).

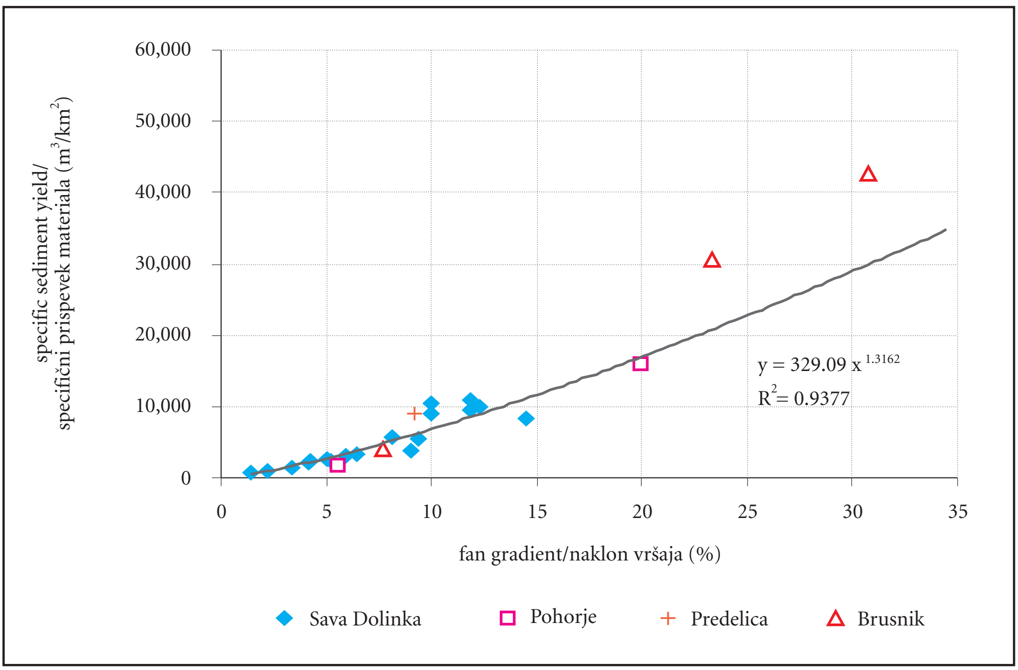

Figure 8: Relation between the specific sediment yield, computed using the Ceriani et al. (2000) method, and the torrential fan gradient for all investigated torrential watersheds (the regression line is Eq. (13)).

of Marchi & D'Agostino (2002) ($R^2 = 0.9924$, $n = 18$). For more exact results a more detailed analysis and calculations are required, taking into consideration all required parameters of the method in the torrential area investigated. The advantage of the empirical connection is that the either the channel gradient or the fan gradient are the basic parameters found in any hydrological study, or they can be easily determined from topographic maps.

Figures 7 in 8 show the results of all investigated torrents, and empirical equations (12) and (13). Clearly evident are the deviations between the estimated values of the specific sediment yield in different torrential areas from the proposed empirical relation. The Brusnik torrent situated in the area up to Koseč shows most significant deviations.

6 Classification of torrential fans

Further, we classified the investigated torrents in terms of the level of danger of occurrence of debris flows. In this respect, two limit values are given in the literature: the Melton number = 0.3 and torrential fan gradient = 4° (7%). Both are based on analysis of past events. These limit values should provide a criterion good enough for classification of torrential fans into three kinds:

- fans that fullfilled both criteria were termed as debris-flow fans, since the hazard of occurrence of debris flows exists;
- fans whose parameters did not exceed any of the limits were termed as torrential fans, with no hazard of occurrence of debris flows;
- fans that fullfil only one criterion were termed as transitional fans, where there is the danger of occurrence of debris flows, but the probability of occurrence is relatively small.

The parameters for this classification are relatively easy to obtain, that is, either from topographic maps or, to achieve higher accuracy, with field investigation. It should be noted that contrary to debris-flow fans, the torrential fans may not be subject to debris flows, however there may still be the danger of torrents or hyperconcetrated flow.

Table 7 shows the classification of the investigated debris-flows based on the value of both limit parameters. The Predelica and Brusnik torrents are included among the torrents investigated, where debris flows occurred in the past. A debris flow triggered in the Predelica torrent strongly affected the village of Log pod Mangartom. In the Brusnik torrent in 2002 debris flows were triggered that posed a threat to the village of Koseč. If the classification of debris flows into classes from 1 to 10 is adopted, as proposed by Jakob (2005) that defines the possible consequences of debris flows of different classes using several debris flow parameters (magnitude, peak discharge, area of deposited sediment), the classification of these debris flows is the following one:

Log pod Mangartom:

Magnitude:	M = 700,000–1,000,000 m^3 (class 5–6)
Peak debris flow discharge:	Q_b = 8000 m^3/s (class 5)
Area of deposited debris flow sediment:	B_b = 250,000 m^2 (class 5)

The debris flow of 17 November 2000 in Log pod Mangartom is classified as class 5.

Koseč:

Magnitude:	M = 100–1000 m^3 (class 2)
Peak debris flow discharge:	Q_b = 15–20 m^3/s (class 2)
Area of deposited debris flow sediment:	B_b = several 100 m^2 (class 2)

Debris flows in 2002 in Koseč are classified as class 2.

Table 8 shows the results of the calculated magnitudes of debris flows with the method 2 of Marchi & D'Agostino (2002) and the Ceriani et al. method (2000). The estimate of magnitude by these two methods gives an estimate of maximum possible events and differs from the actual volumes of investigated debris flows. In the case of Log pod Mangartom, the reason for the difference is the extremeness of event, when the debris flow with recurrence period of over 100 years was initiated in the area in spilled into the Koritnica valley in two phases. To reach the value of debris flow volume of approx. 900,000 m^3 by the Ceriani et al. method (2000) one would have to use the landslide index $I\_F = 0.6$. However, debris

Table 7. Values of parameters and classification of torrential fans in terms of debris flow hazard.

Torrential watershed	Melton number [–]	Fan gradient [%]	Fan classification
UPPER SAVA RIVER			
Trebiža	0.298	4.157	transitional fan
Krotnjek	0.308	5.024	transitional fan
Suhelj	0.527	11.828	debris-flow fan
Velika Pišnica	0.244	2.218	torrential fan
Jurežev graben	0.613	11.842	debris-flow fan
Martuljek	0.316	4.211	transitional fan
Hladnik	0.293	6.496	transitional fan
Beli potok	0.594	10.010	debris-flow fan
Belca	0.254	5.182	torrential fan
Bistrica	0.250	1.448	torrential fan
Mlinca	0.438	8.100	debris-flow fan
Presušnik	0.530	12.261	debris-flow fan
Dobršnik	0.723	10.000	debris-flow fan
Jesenica	0.241	3.382	torrential fan
Ukova	0.356	9.348	debris-flow fan
Javornik	0.302	5.900	transitional fan
Bela	0.229	9.058	transitional fan
Sevnik	0.348	14.500	debris-flow fan
POHORJE			
Lobnica	0.150	5.607	torrential fan
Lobničica	0.520	20.000	debris-flow fan
PREDELICA			
Predelica	0.672	9.200	debris-flow fan
KOSEČ			
Brusnik upstream of Koseč	0.969	23.333	debris-flow fan
Brusnik upstream of Ročica	1.038	30.769	debris-flow fan
Ročica	0.309	7.700	debris-flow fan

Table 8. The estimated debris-flow magnitudes for the Predelica Torrent and the Brusnik Stream upstream of Koseč.

	Marchi & D'Agostino (2002)	Ceriani et al. (2000)		
	Magnitude [m^3]	Magnitude [m^3]	Magnitude [m^3]	Magnitude [m^3]
Torrential watershed		b) *I_F* = 1	a) *I_F* = 2	c) *I_F* = 3
PREDELICA				
Predelica	96,143	336,128	84,032	37,348
KOSEČ				
Brusnik upstream of Koseč	33,052	68,794	17,198	7,644

flows in Koseč were of smaller volume since they were limited by the available quantity of debris material (Mikoš et al. 2005). If the Strug rockfall grew in its intensity, we could expect re-activation of debris flows. For delination of hazard area in Koseč due to occurrence of debris flows under Strug, as the extreme scenario the event with a volume (magnitude) of 25,000 m^3 was taken (Mikoš et al. 2006).

7 Conclusion

The performed analysis showed the applicability of the chosen methods for estimation of magnitudes of debris flows based on the known morphological parameters of the torrential area. For Slovenian conditions two methods have proven adequate: the method 2 of Marchi & D'Agostino (2002) and the method of Ceriani et al. (2000). By way of hydrological modelling of the chosen torrential areas we developed our own empirical equations from the two methods. The decision on the applicability of the methods was based also on comparison of results of both methods with data on debris flows in Koseč in 2002 and on debris flow that devastated the village of Log pod Mangartom on November 17, 2000.

The critical limits for classification of fans into classes are only partly confirmed and require further validation, especially detailed field investigation of fans, which would confirm or adapt the values to Slovenian conditions. The Ceriani et al. method (2000), which uses the landslide index I_F, requires field investigation and determination of the index based on frequency of erosion-related events in the torrential area. The index strongly influences the estimation of debris flow magnitude.

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Ocena magnitud drobirskih tokov v izbranih hudourniških območjih v Sloveniji

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IZVLEČEK: V prispevku je opisana uporaba različnih metod za oceno magnitud drobirskih tokov, sproženih ob padavinah, na 18 hudournikih v Zgornjesavski dolini in na dveh na Pohorju (Lobnica, Lobničica). Dodatno preverjanje metod je bilo opravljeno na hudourniških območjih z aktivnimi drobirskimi tokovi v bližnji preteklosti (Predelica, Brusnik). Za nekatere metode zadošča poznavanje morfometričnih lastnosti hudourniškega območja, hudourniške struge in hudourniškega vršaja. Za druge metode je bilo treba uporabiti matematično orodje (HEC-HMS) in izdelati hidrološki model odtoka izbranih padavin, ki lahko sprožijo drobirske tokove. Izračunane magnitude drobirskih tokov se gibljejo v območju od 6500 m^3 do 340.000 m^3. Vrednosti so odvisne od parametrov hudourniškega območja; najpomembnejši parametri so: površina prispevnega območja, Meltonovo število, naklon vršaja in strmec hudourniške struge. Obravnavane vršaje smo razdelili v tri skupine glede na nevarnost delovanja drobirskih tokov: drobirski vršaji (nevarnost obstaja), hudourniški vršaji (ni nevarnosti) in prehodni vršaji (drobirski tokovi so možni, a malo verjetni). Predlagali smo mejni vrednosti Meltonovega števila (0,3) in naklona hudourniškega vršaja (4° oziroma 7 %) za razdelitev med drobirskimi in hudourniškimi vršaji. Od obravnavanih 24 hudourniških vršajev smo med drobirske vršajev razvrstili 13 vršajev, v hudourniške vršaje pet, ostalih šest vršajev pa smo uvrstili med prehodne vršaje.

KLJUČNE BESEDE: erozija, masna gibanja, drobirski tokovi, empirični modeli, ocena nevarnosti, vršaji, Zgornjesavska dolina, Pohorje, Slovenija.

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Vsebina

1 Uvod

Drobirski tokovi kot oblika masnega gibanja sedimentov po pobočjih ali hudourniških strugah so v preteklosti preoblikovali slovensko površje in so v zadnjem času vse pogostejši. Zaradi razpršene poselitve in goste mreže prometnic je nujna podrobnejša preučitev ogroženosti prostora zaradi njihovega delovanja. Gre za obliko masnega gibanja sedimentov (Skaberne 2001), ki se lahko razvije na pobočjih ali v strugah hudournikov. Poznavanje njihove dinamike (Mikoš 2001) omogoča načrtovanje primernih preventivnih ukrepov. Eno najbolj pogostih vprašanj v zvezi z drobirskimi tokovi je vprašanje, kje lahko nastanejo. Ob tem je za načrtovanje ukrepov nujno poznati obseg (magnitudo) pojava, ki jo lahko pričakujemo. S pomočjo ocenjenih magnitud lahko z modeliranjem gibanja drobirskih tokov ocenimo njihov doseg in pretočne hitrosti ter globine, ki jih običajno uporabimo pri ocenah nevarnosti (Mikoš 1997). Obširnejše načrtovanje ukrepov za varstvo pred različnimi erozijskimi pojavi mora obravnavati vsak primer posebej, saj ima vsak primer svoje specifične lastnosti, ki lahko bistveno vplivajo na potek dogodkov. Eden od bistvenih podatkov je velikost obravnavanega erozijskega območja. Razmerje med količino erozijskega gradiva, ki je na določenem območju na razpolago, in količino materiala, ki se dejansko sproži ob posameznem dogodku, je od primera do primera lahko zelo različno. Kljub temu so v preteklosti skušali razviti metode, ki bi bile splošno uporabne za ocenjevanje magnitude drobirskih tokov. Geomorfne procese na hudourniških vršajih so obravnavale številne terenske študije. V eni prvih je Melton (1965) predlagal zvezo med naklonom hudourniškega vršaja (S) in nekaterimi drugimi topografskimi parametri:

$$S = a[(H_{max} - H_{min})A^{-0,5}]^n, \qquad (1)$$

pri čemer sta a in n neodvisna koeficienta, H_{max} in H_{min} sta višina najvišje točke in najnižje točke hudourniškega območja (t. j. najvišja točka vršaja) [km], A pa je površina hudourniškega območja [km^2]. Člen enačbe $Mel = (H_{max} - H_{min})A^{-0,5}$ po avtorju imenujemo Meltonovo število. Ta pristop je osnova za raziskovanje naplavinskih procesov na vršajih, ki je usmerjeno v klasifikacijo vršajev na podlagi morfoloških parametrov hudourniških območij in hudourniških vršajev.

Metode za ocenjevanje magnitude drobirskih tokov, ki so osnova za ocenjevanje ogroženosti zaradi tega pojava, delimo na:

- empirične metode (npr. Takei 1984, Kronfellner-Kraus 1984, Marchi in D'Agostino 2002), ki so namenjene oceni magnitude drobirskega toka;
- morfološke metode (npr. Jackson s sod. 1987, Marchi s sod. 1993, Marchi in D'Agostino 2002, Jakob 2005), ki jih delimo na tiste, ki ocenjuje magnitudo, in na tiste, ki so namenjene določevanju nevarnosti delovanja drobirskega toka na hudourniškem vršaju;
- kombinirane metode (npr. Ceriani s sod. 2000), ki so kombinacija različnih drugih metod, ki na podlagi statistične obdelave določijo odločilne parametre hudourniškega območja v obliki empirične enačbe za izračun magnitude drobirskega toka;
- računalniške metode (npr. Schöberl s sod. 2004), ki so računalniški programi, ki upoštevajo zalogo erozijskega drobirja v obravnavanem prispevnem območju in premestitveno zmogljivost hudournika z upoštevanjem odlaganja materiala v strugi hudournika.

Podroben opis metod je že bil podan drugje (Sodnik 2005; Sodnik in Mikoš 2005).

Za izračun magnitud drobirskih tokov na izbranih hudournikih v Sloveniji smo uporabili naslednje empirične in morfološke metode:

Takei (1984): $Vd = 13600\mathrm{A}^{0.61}$ ….. (2)

Kronfellner-Kraus (1984): $M = K \cdot A \cdot S_c$ …..[m^3] (3)

$\mathrm{K} = 1150/e^{0.014A}$ …..[–] (4)

Marchi & D'Agostino (2002):

1. metoda: $\mathrm{M} = 65000A^{1.35}S^{1.7}$ …..[m^3] (5)

2. metoda: $\mathrm{M} / V_r = 2,9\,S^2$ …..[–] (6)

Preglednica 1. Rezultati modeliranja odtoka padavin na hudournikih Save Dolinke.

hudourniško območje	površina [km^2]	naklon površja [%]	dolžina vodotoka [km]	vodotok [%]	stoletni pretok Q_{100} [m^3/s]	število CN [–]	SCS metoda *Tp* [ure]	Clarck-Kirpichova metoda *Tc* [ure]	SRC metoda *Tp* [ure]	skupni odtok [m^3]
SAVA DOLINKA										
Trebiža	5,3	38	3,8	8,6	40	67	0,560	0,376	0,432	407.150
Krotnjek	3,7	48	3,2	9,6	36	67	0,435	0,301	0,363	326.000
Suhelj	1,9	57	3,2	16,9	23	71	0,359	0,282	0,351	182.050
Velika Pišnica	37,9	67	9,2	3,3	128	57	1,107	0,598	0,760	2.092.700
Jurežev graben	2	47	2,7	28,6	19	66	0,394	0,267	0,320	158.380
Martuljek	11,4	72	4,1	11,4	82	64	0,468	0,312	0,406	803.620
Hladnik	15	60	6,6	12,1	99	66	0,713	0,483	0,603	1.174.600
Beli potok	5,3	72	3,8	21	39	63	0,452	0,294	0,383	355.690
Belca	17,6	65	7	8,5	107	64	0,756	0,490	0,621	1.307.100
Bistrica	43,7	64	12,6	4	197	61	1,317	0,775	0,974	3.303.100
Mlinca	7,9	59	4,9	17,1	56	60	0,661	0,386	0,482	593.910
Presušnik	4,7	49	4,1	21,2	38	61	0,613	0,362	0,436	387.770
Dobršnik	1,8	45	3,3	24,8	18	63	0,511	0,316	0,376	165.300
Jesenica	20,5	41	7,9	8,7	122	64	1,049	0,642	0,743	1.676.900
Ukova	4,3	37	4,5	14,2	38	68	0,634	0,433	0,494	384.740
Javornik	16,6	42	6,8	7,8	94	61	0,992	0,567	0,660	1.304.400
Bela	6,2	52	3,9	11,9	52	62	0,557	0,340	0,415	479.390
Sevnik	1,9	39	2,9	24,6	16	59	0,548	0,303	0,350	144.660
POHORJE										
Lobnica	44,3	29,6	16,5	6,51	116	54	2,866	0,414	1,383	3.547.000
Lobničica	3	46,2	3,6	19,78	19,5	53	0,696	0,305	0,399	241.200
PREDELICA										
Predelica	9,3	60	6,2	15,7	77	36	1,481	0,316	0,575	1.345.000
KOSEČ										
Brusnik do Koseča	0,56	70	1,5	37,2	8,4	43	0,363	0,297	0,190	82.360
Brusnik do Ročice	0,9	56	2,3	32,5	12,0	43	0,572	0,324	0,274	136.500
Ročica	10,6	60	6,7	14,1	79,0	38	1,488	0,277	0,610	1.313.000

Ceriani s sod. (2000):

$$M = k \cdot (A)^a \cdot (M_b)^b \cdot (S_{cl\_c})^c \cdot (I\_F)^{-d} \ldots\ldots [10^3 \, m^3], \qquad (7)$$

kjer so parametri v enačbah naslednji:
K – koeficient lastnosti hudourniškega območja, podan za posamezna območja Alp v Avstriji [–];
A – površina prispevnega območja hudournika [km²];
S_c – povprečen strmec hudourniške struge [%];
S – povprečen strmec hudourniške struge [m/m];
V_r – celoten odtok vode [m³];
I_F – indeks plazljivosti [–];
M_b – Meltonovo število [–];
S_{cl_c} – strmec hudourniške struge na vršaju [%].

V tem prispevku prikazujemo rezultate uporabe omenjenih empiričnih in morfoloških metod na slovenskih hudournikih. Namen analize je bil preveriti možnosti podajanja ocene magnitude morebitnih drobirskih tokov in njihovega razvrščanja glede na nevarnost delovanja drobirskih tokov. Ocenjene količine po izbranih metodah je treba primerjati z zgodovinskimi zapisi o količinah preteklih dogodkov. Žal sistematične analize zgodovinskih dogodkov ni in je primerjanje rezultatov po izbranih metodah z dogajanjem v preteklosti prej izjema kakor pravilo.

Ocene magnitud drobirskih tokov smo opravili na hudourniških pritokih Save Dolinke in na dveh hudournikih na Pohorju (slika 1). Za dodatno preverjanje smo metode preizkusili tudi na hudournikih Predelica in Brusnik, kjer so se drobirski tokovi pojavljali v bližnji preteklosti (Mikoš in sod. 2004; 2006).

Slika 1: V tem prispevku obravnavana hudourniška območja v Sloveniji.
Glej angleški del prispevka.

2 Hidrološki računi

Na izbranih hudourniških območjih je bilo treba za uporabo nekaterih metod najprej izračunati celotno prostornino odtoka za nastanek drobirskih tokov relevantnih padavin. Modelirali smo s programom HEC-HMS (Hydrologic Modeling System 2000; 2001). Namen modeliranja je bil določiti celotno prostornino odtoka vode na podlagi podanih padavin in izračunanih pretokov, saj metoda za oceno magnitude drobirskega toka kot parameter zahteva oceno prostornine odtekle vode.

Morfometrične podatke o hudourniških območjih smo privzeli po hidroloških študijah (VGI 1993; 1995a; 1995b; 1999; 2002) in so prikazani v preglednici 1.

Podatke o značilnostih površja smo privzeli po Naravovarstvenem atlasu (NVA 2005), kjer so dostopni aerofoto posnetki. Padavinske podatke za hidrološko modeliranje smo povzeli iz hidroloških študij (VGI 1993; 1995b; 1999; 2002) in so prikazani v preglednici 2.

Preglednica 2. Podatki z dežemernih postaj, uporabljeni pri hidrološkem modeliranju – prikazane so višine kratkotrajnih nalivov v mm s povratno dobo 100 let in trajanja od 5 minut do 1440 minut.

Dežemerna postaja	5	15	60	120	180	360	720	1440
Javorniški Rovt (1966–1993)	22,5	34,0	57,5	74,5	86,8	112,7	146,3	190,0
Rateče – Planica (1966–1993)	15,1	25,2	48,1	66,5	80,4	110,5	138,9	174,6
Koča nad Šumikom (1975–1997)	21,2	33,6	59,9	80,1	94,9	126,8	169,5	226,5
Bovec (1959–1987)	20,2	41,9	104,9	165,9	217,0	293,3	358,0	437,0

Vsakemu hudourniškemu območju smo glede na lego določili pripadajočo padavinsko postajo, katere padavine smo upoštevali v analizi. Za hudourniška območja Save Dolinke vključno z Belco smo uporabili podatke za dežemerno postajo Rateče – Planica, za ostala območja od vključno Bistrice pa podatki dežemerne postaje Javorniški Rovt. Za Lobnico in Lobničico smo uporabili podatke dežemerne postaje Koča nad Šumikom, za Predelico in Brusnik pa podatke iz Bovca. Sicer so v bližini nekaterih hudourniških območij tudi druge postaje, vendar niso opremljene z ombrografi, ki bi merili kratkotrajne nalive in omogočili njihovo statistično analizo. Tako je v porečju Save Dolinke osem padavinskih postaj, a so le tri opremljene z ombrografi. Za analizo smo tako lahko uporabili le postaji Rateče – Planica in Javorniški Rovt. V hidroloških študijah so podane statistično izračunane padavine različnih povratnih dob in trajanja, izračunane s pomočjo meritev za določeno obdobje (glej preglednico 2).

Za pripravo podatkov v modelu HEC-HMS je na voljo veliko število metod, a ker so posamezne metode omejene z različnimi faktorji, kot so naklon terena, strmec struge, lastnosti obravnavanega površja, so nekatere neuporabne. Kot primerne so se izkazale metode: metoda SCS (*Soil Conservation Service*), metoda SRC (metoda *Snyder – Riverside County*) in Clark-Kirpichova metoda (Brilly & Šraj 2005). Izračunane vrednosti kritičnega časa stekanja T_c oziroma časa zamika T_p med težiščem padavin in konico odtoka so prikazane v preglednici 1. Na podlagi rezultatov smo se odločili za uporabo metode SCS, ki se v praksi tudi sicer široko uporablja.

Število CN (angl.: *curve number*) je parameter, ki določa lastnosti tal (infiltracija ipd.). Določili smo ga na podlagi značilnosti površja, kot so delež gozdov, travnikov, grmovja in skal. Začetno vrednost za CN smo določili na osnovi podatkov daljinskega zaznavanja. Končno vrednost CN smo določili s pomočjo umerjanja hidrološkega modela, tako da sta se ujemala konica izračunanega odtoka in podatek o visoki vodi s 100-letno povratno dobo. Izračunane pretoke v hidroloških študijah smo določili na podoben način, s pomočjo sintetičnega hidrograma, izračunanega iz predpostavljenih padavin. Vendar izračuni podajajo le konico, ne pa tudi celotne prostornine visokovodnega vala. Izračunane prostornine odtoka vode po metodi SCS so prikazane v preglednici 1, sintetični hidrogrami odtoka za izbrana hudourniška območja pa na sliki 2.

Slika 2: Z uporabo programa HEC-HMS modelirani hidrogrami odtoka za izbrana hudourniška območja (Suhelj v Zgornjesavski dolini, Lobnica na Pohorju in Predelica).

Glej angleški del prispevka.

3 Analiza hidroloških parametrov

Sledila je analiza izračunanih hidroloških parametrov v odvisnosti od velikosti hudourniškega območja. Kot osnovo za določitev empiričnih enačb smo vzeli rezultate za 18 hudourniških območij Save Dolinke: na sliki 3 je prikazana zveza med stoletnim pretokom Q_{100} (m^3/s) in površino hudourniškega območja A (km^2) ter na sliki 4 zveza med prostornino odtoka V_r (m^3) in površino hudourniškega območja A (km^2). Analiza stoletnih pretokov Q_{100} in odtokov vode V_r daje statistično zanesljivi enačbi (v obeh primerih je regresijski koeficient $R^2 > 0{,}97$ za $n = 18$). Ti dve enačbi lahko torej uporabimo tudi na drugih hudourniških območjih Zgornjesavske doline brez predhodnega hidrološkega modeliranja. Predvsem zveza med prostornino odtoka in površino hudourniškega območja je pomembna za oceno magnitude drobirskega toka po metodah, ki zahtevajo poznavanje prostornine odtoka vode.

Na sliki 3 je prikazana tudi zveza med pretoki Q_{100} in površino prispevnega območja A posameznega hudournika na Pohorju. Za analizo uporabnosti metod za oceno magnitude drobirskih tokov sta bila na Pohorju obravnavana samo dva hudournika (Lobnica in Lobničica), za analizo pretokov pa smo uporabili še druge hudournike iz JZ dela Pohorja, obravnavane v hidrološki študiji tega območja (VGI 1999). Tako smo imeli na razpolago skupaj 11 hudourniških območij ($n = 11$) velikosti od 0,17 km^2 do 44,3 km^2.

Na podlagi analize pretokov Q_{100} in prostornin odtokov V_r smo torej prišli do naslednjih empiričnih enačb (sliki 3 in 4):

Q_{100} za hudournike na Savi Dolinki [m^3/s]: $$Q_{100} = 12{,}5\, A^{0{,}72} \quad (8)$$

Q_{100} za hudournike na Pohorju [m^3/s]: $$Q_{100} = 7\, A^{0{,}76} \quad (9)$$

Prostornina poplavnega vala na Savi Dolinki [m^3]: $$V_r = 90.000\, A^{0{,}93} \quad (10)$$

Slika 3: Zveza med stoletnimi pretoki Q_{100} in površino prispevnega območja posameznega hudournika v Zgornjesavski dolini ($n = 18$) in na Pohorju ($n = 11$).

Glej angleški del prispevka.

Slika 4: Zveza med prostornino poplavnega hidrograma s konico Q_{100} in površino prispevnega območja posameznega hudournika v Zgornjesavski dolini (n = 18) in na Pohorju (n = 11).
Glej angleški del prispevka.

Preglednica 3. Izračun prostornin odtoka vode za hudourniška območja Pohorja.

hudourniško območje	površina A (km^2)	Sava Dolinka (en. 10) prostornina $V_r = 90.000\,A^{0,93}$ (m^3)	Pohorje (en. 11) prostornina $V_r = 90.000\,A^{0,96}$ (m^3)	HEC-HMS metoda prostornina V_r (m^3)
Lobnica	44,3	3.057.722	3.426.022	3.547.000
Lobničica	3,0	250.015	258.392	241.200

Empirične enačbe za izračun prostornine poplavnega vala za Pohorju na način kot smo to storili za hudournike na Savi Dolinki, ni bilo mogoče dobiti, saj smo s pomočjo HEC-HMS modelirali na Pohorju le dva hudournika (Lobnico in Lobničico). Zato smo lahko le preizkusili uporabnost enačbe (10), ki velja za hudournike na Savi Dolinki. V preglednici 3 je prikazan izračun prostornine poplavnega vala V_r za oba hudournika na Pohorju na 3 različne načine. Ujemanje z rezultati hidrološkega modeliranja s programom HEC-HMS dobimo tako, da eksponent v empirični enačbi (10) spremenimo z 0,93 na 0,96 in tako dobimo enačbo (slika 4):

Prostornina poplavnega vala na Pohorju: $V_r = 90.000\,A^{0,96}\ [m^3]$ (11)

Hudournika Lobnica in Lobničica sta primerna za primerjavo, saj ima prvi veliko (A = 44,3 km^2), slednji pa majhno prispevno površino (A = 3,0 km^2). Predlagano enačbo je za širšo uporabo treba dodatno preveriti s pomočjo hidrološkega modeliranja. Vrednosti koeficientov v enačbah 8 in 9 so konsistentne z vrednostmi, ki so se uveljavile v inženirski praksi, morda preseneča vrednost eksponenta 0,76 za hudournike na Pohorju, saj velja domneva, da je maksimalni koeficient 0,75, ki naj bi veljal v alpskem delu Slovenije.

4 Izračun magnitude drobirskih tokov

Pri oceni magnitud po posameznih metodah smo najprej določili parametre metode za vsako hudourniško območje, ki smo jih povzeli po hidroloških študijah, izračunali ali povzeli iz topografskih kart in aerofoto posnetkov. V preglednici 4 so podani tudi celotni odtoki padavin, dobljeni s programom HEC-HMS. Na koncu preglednice so podane še količine povprečnega sproščanja erozijskega materiala za posamezno hudourniško območje, vendar ta podatek ni na voljo za vse hudournike.

V preglednici 5 so rezultati uporabljenih metod. Na 18 hudourniških območjih Save Dolinke smo uporabili vse navedene metode, medtem ko smo na ostalih hudourniških območjih uporabili le 2. metodo Marchi & D'Agostino (2002) in metodo Ceriani s sod. (2000). Metoda Takei (1984) in metoda Kronfellner-Krauss (1984) sta za hudourniška območja Save Dolinke dali primerjalno zelo visoke vrednosti magnitud drobirskih tokov in ju zato nismo uporabili tudi na drugih hudourniških območjih. Za metodo Ceriani s sod. (2000) so rezultati podani za različne indekse plazljivosti (I_F): prisotnost aktivnih plazov ali plazov z možnostjo ponovnega aktiviranja ($I\_F = 1$); prisotnost plazov, ampak ne neposredno ob strugi ($I\_F = 2$); ni večjih oziroma pomembnih plazov ($I\_F = 3$). Pri 2. metodi Marchi & D'Agostino (2002) in metodi Ceriani s sod. (2000) je za boljšo predstavljivost podano tudi razmerje med prostornino drobirskega toka (magnitudo) in prostornino vode M/V_r. V preglednici 6 sledijo še specifični prispevki drobirskega materiala za posamezno hudourniško območje.

5 Analiza magnitud drobirskih tokov

Sledila je analiza izračunanih magnitud drobirskih tokov v odvisnosti od morfoloških parametrov hudourniškega območja. Opravili smo jo za 18 hudournikov v Zgornjesavski dolini za izračunane magnitude drobirskih tokov po 2. metodi Marchi & D'Agostino (2002) in metodi Ceriani s sod. (2000) ob upoštevanju faktorja plazljivosti $I\_F = 2$. Kot najbolj uporabno zvezo smo privzeli povezavo med morfološkimi

Preglednica 4. Parametri hudourniških območij, uporabljeni pri oceni magnitud drobirskih tokov.

	površina	naklon površja	dolžina in naklon vodotoka		*dH*	Meltonovo število	naklon vršaja	prostornina V_r (odtok vode)	letno sproščanje gradiva
Hudourniško območje	[km^2]	[%]	[km]	[%]	[km]	[–]	[%]	[m^3]	[m^3/leto]
SAVA									
Trebiža	5,3	38	3,8	8,6	0,687	0,298	4,157	407.150	ni podatka
Krotnjek	3,7	48	3,2	9,6	0,592	0,308	5,024	326.000	ni podatka
Suhelj	1,9	57	3,2	16,9	0,727	0,527	11,828	182.050	ni podatka
Velika Pišnica	37,9	67	9,2	3,3	1,500	0,244	2,218	2.092.700	69.325
Jurežev graben	2,0	47	2,7	28,6	0,867	0,613	11,842	158.380	265
Martuljek	11,4	72	4,1	11,4	1,066	0,316	4,211	803.620	19.848
Hladnik	15,0	60	6,6	12,1	1,134	0,293	6,496	1.174.600	9.654
Beli potok	5,3	72	3,8	21,0	1,367	0,594	10,010	355.690	7.053
Belca	17,6	65	7	8,5	1,067	0,254	5,182	1.307.100	18.297
Bistrica	43,7	64	12,6	4,0	1,650	0,250	1,448	3.303.100	ni podatka
Mlinca	7,9	59	4,9	17,1	1,231	0,438	8,100	593.910	11.481
Presušnik	4,7	49	4,1	21,2	1,150	0,530	12,261	387.770	9.521
Dobršnik	1,8	45	3,3	24,8	0,970	0,723	10,000	165.300	2.396
Jesenica	20,5	41	7,9	8,7	1,093	0,241	3,382	1.676.900	10.402
Ukova	4,3	37	4,5	14,2	0,739	0,356	9,348	384.740	885
Javornik	16,6	42	6,8	7,8	1,230	0,302	5,900	1.304.400	7.280
Bela	6,2	52	3,9	11,9	0,570	0,229	9,058	479.390	4.968
Sevnik	1,9	39	2,9	24,6	0,480	0,348	14,500	144.660	ni podatka
POHORJE									
Lobnica	44,3	29,6	16,5	6,5	0,997	0,150	5,607	3.547.000	5.248
Lobničica	3,0	46,2	3,6	19,8	0,900	0,520	20,000	241.200	386
PREDELICA									
Predelica	9,3	60	6,2	15,7	2,049	0,672	9,200	1.345.000	ni podatka
KOSEČ									
Brusnik do Koseča	0,56	70	1,5	37,2	0,725	0,969	23,333	82.360	ni podatka
Brusnik do Ročice	0,9	56	2,3	32,5	0,985	1,038	30,769	136.500	ni podatka
Ročica	10,6	60	6,7	14,1	1,007	0,309	7,700	1.313.000	ni podatka

Preglednica 5. Rezultati izračuna magnitud drobirskih tokov na vseh hudournikih.

	Takei (1984)	Kronfellner-Kraus (1984)		Marchi in D'Agostino (2002)			Ceriani s sod. (2000)					
				1. metoda		2. metoda	magnituda	magnituda [m^3]	magnituda [m^3]	[m^3]		
Hudourniško območje	magnituda [m^3]	K [–]	magnituda [m^3]	magnituda [m^3]	M/V_r	magnituda [m^3]	$I\_F = 1$	$I\_F = 2$	$I\_F = 3$	M/V_r	M/V_r	M/V_r
SAVA												
Trebiža	37.614	1.067,76	48.668	9.535	0,021	8.733	45.221	11.305	5.025	0,111	0,028	0,012
Krotnjek	30.209	1.091,95	38.786	7.077	0,027	8.713	39.102	9.775	4.345	0,120	0,030	0,013
Suhelj	20.118	1.119,81	35.957	7.527	0,083	15.079	72.742	18.185	8.082	0,400	0,100	0,044
Velika Pišnica	124.885	676,49	84.609	26.641	0,003	6.609	146.677	36.669	16.297	0,070	0,018	0,008
Jurežev graben	20.757	1.118,25	63.964	19.730	0,237	37.569	86.468	21.617	9.608	0,546	0,136	0,061
Martuljek	60.014	980,36	127.407	43.299	0,038	30.287	103.057	25.764	11.451	0,128	0,032	0,014
Hladnik	70.950	932,17	169.189	69.402	0,042	49.872	196.955	49.239	21.884	0,168	0,042	0,019
Beli potok	37.614	1.067,76	118.842	43.497	0,128	45.489	188.803	47.201	20.978	0,531	0,133	0,059
Belca	78.217	898,85	134.468	47.246	0,021	27.387	164.708	41.177	18.301	0,126	0,032	0,014
Bistrica	136.217	623,73	109.028	44.778	0,005	15.326	112.596	28.147	12.511	0,034	0,009	0,004
Mlinca	47.983	1.029,59	139.087	52.578	0,085	50.363	178.510	44.627	19.834	0,301	0,075	0,033
Presušnik	34.956	1.076,77	107.289	37.585	0,130	50.541	187.379	46.845	20.820	0,483	0,121	0,054
Dobršnik	19.465	1.121,38	50.058	13.431	0,178	29.483	74.985	18.746	8.332	0,454	0,113	0,050
Jesenica	85.844	863,09	153.932	60.390	0,022	36.808	120.105	30.026	13.345	0,072	0,018	0,008
Ukova	33.110	1.082,81	66.117	16.865	0,058	22.498	95.085	23.771	10.565	0,247	0,062	0,027
Javornik	75.475	911,52	118.024	37.724	0,018	23.014	202.874	50.718	22.542	0,156	0,039	0,017
Bela	41.390	1.054,39	77.793	20.468	0,041	19.687	93.231	23.308	10.359	0,194	0,049	0,022
Sevnik	20.118	1.119,81	52.340	14.250	0,175	25.387	63.975	15.994	7.108	0,442	0,111	0,049
POHORJE												
Lobnica	–	–	–	–	0,012	43.593	293.738	73.434	32.638	0,083	0,021	0,009
Lobničica	–	–	–	–	0,113	27.367	191.907	47.977	21.323	0,796	0,199	0,088
PREDELICA												
Predelica	–	–	–	–	0,071	96.143	336.128	84.032	37.348	0,250	0,062	0,028
KOSEČ												
Brusnik do Koseča	–	–	–	–	0,401	33.052	68.794	17.198	7.644	0,835	0,209	0,093
Brusnik do Ročice	–	–	–	–	0,306	41.812	154.101	38.525	17.122	1,129	0,282	0,125
Ročica	–	–	–	–	0,058	75.701	172.382	43.095	19.154	0,131	0,033	0,015

Preglednica 6. Podatki o specifičnih prispevkih drobirskega materiala za posamezna hudourniška območja.

	Takei (1984)	Kronfellner-Kraus (1984)	Marchi in D'Agostino (2002)		Ceriani s sod. (2000)		
			1. metoda	2. metoda	a) *I_F* = 1	b) *I_F* = 2	c) *I_F* = 3
Hudourniško območje	(m^3/km^2)	(m^3/km^2)	(m^3/km^2)	(m^3/km^2)	(m^3/km^2)	(m^3/km^2)	(m^3/km^2)
SAVA							
Trebiža	7.096,9	9.182,7	1.799,1	1.647,7	8.532,2	2.133,0	948,0
Krotnjek	8.164,7	10.482,7	1.912,7	2.354,8	10.568,0	2.642,0	1.174,2
Suhelj	10.588,3	18.924,8	3.961,7	7.936,1	38.285,1	9.571,3	4.253,9
Velika Pišnica	3.295,1	2.232,4	702,9	174,4	3.870,1	967,5	430,0
Jurežev graben	10.378,6	31.981,9	9.865,0	18.784,5	43.234,1	10.808,5	4.803,8
Martuljek	5.264,4	11.176,1	3.798,1	2.656,8	9.040,1	2.260,0	1.004,5
Hladnik	4.730,0	11.279,3	4.626,8	3.324,8	13.130,3	3.282,6	1.458,9
Beli potok	7.096,9	22.422,9	8.207,0	8.582,9	35.623,1	8.905,8	3.958,1
Belca	4.444,2	7.640,2	2.684,4	1.556,1	9.358,4	2.339,6	1.039,8
Bistrica	3.117,1	2.494,9	1.024,7	350,7	2.576,6	644,1	286,3
Mlinca	6.073,9	17.606,0	6.655,4	6.375,1	22.596,1	5.649,0	2.510,7
Presušnik	7.437,4	22.827,4	7.996,8	10.753,4	39.867,8	9.967,0	4.429,8
Dobršnik	10.813,9	27.810,3	7.461,5	16.379,5	41.658,4	10.414,6	4.628,7
Jesenica	4.187,5	7.508,9	2.945,8	1.795,5	5.858,8	1.464,7	651,0
Ukova	7.699,9	15.375,9	3.922,1	5.232,1	22.112,9	5.528,2	2.457,0
Javornik	4.546,7	7.109,9	2.272,5	1.386,4	12.221,3	3.055,3	1.357,9
Bela	6.675,8	12.547,2	3.301,3	3.175,3	15.037,2	3.759,3	1.670,8
Sevnik	10.588,3	27.547,4	7.500,1	13.361,7	33.670,8	8.417,7	3.741,2
POHORJE							
Lobničica	–	–	–	984,1	6.630,6	1.657,7	736,7
Lobnica	–	–	–	9.122,3	63.969,0	15.992,2	7.107,7
PREDELICA							
Predelica	–	–	–	10.338,0	36.142,8	9.035,7	4.015,9
KOSEČ							
Brusnik do Koseča	–	–	–	59.021,8	122.845,6	30.711,4	13.649,5
Brusnik do Ročice	–	–	–	46.457,4	171.223,1	42.805,8	19.024,8
Ročica	–	–	–	7.141,6	16.262,4	4.065,6	1.806,9

parametri hudourniškega območja in specifičnim prispevkom drobirskega materiala za posamezno območje (m^3/km^2). Na ta način smo iz analize izključili vpliv velikosti prispevnega območja.

Slika 5: Zveza med specifičnim prispevkom drobirskega materiala, izračunanim po 2. metodi Marchi & D'Agostino (2002), in padcem struge hudournika v Zgornjesavski dolini ($n = 18$).
Glej angleški del prispevka.

Povezave z magnitudo drobirskega toka oziroma specifičnim prispevkom drobirskega materiala smo iskali za naslednje morfološke parametre: strmec vodotoka [%], naklon vršaja [%] in Meltonovo število [–]. Magnituda drobirskega toka po 2. metodi Marchi in D'Agostino (2002) je imela najboljšo povezavo s padcem struge hudournika ($R^2 = 0,9924$, $n = 18$; slika 5):

$$M = 17,7 \cdot I_s^2 \ [m^3/km^2], \qquad (12)$$

pri čemer je I_s strmec struge [%], medtem ko je metoda Ceriani s sod. (2000) najboljšo zvezo pokazala z naklonom vršaja ($R^2 = 0,9377$, $n = 18$; slika 6):

$$M = 330 \cdot I_v^{1,3} \ [m^3/km^2], \qquad (13)$$

pri čemer je I_v naklon vršaja [%]. Ti dve zvezi omogočata hitro oceno magnitud drobirskih tokov na območju Save Dolinke. Zanesljivost teh dveh zvez je dobra, predvsem po 2. metodi Marchi & D'Agostino (2002) ($R^2 = 0,9924$, $n = 18$). Za točnejše rezultate bi bila nujna podrobnejša analiza in izračun z upoštevanjem vseh zahtevanih parametrov metode na obravnavanem hudourniškem območju. Prednost te empirične zveze je, da je strmec struge oziroma naklon vršaja mogoče preprosto določiti s pomočjo topografskih kart.

Na slikah 7 in 8 so prikazani rezultati za vse obravnavane hudournike in empirični enačbi (12) in (13). Vidna so odstopanja med ocenjenimi količinami specifičnega prispevka drobirskega materiala na različnih hudourniških območjih od predlagane empirične zveze. Najbolj izrazito odstopa hudournik Brusnik na območju do Koseča.

Slika 6: Zveza med specifičnim prispevkom drobirskega materiala, izračunanim po metodi Ceriani s sod. (2000), in naklonom hudourniškega vršaja v Zgornjesavski dolini ($n = 18$).
Glej angleški del prispevka.

Slika 7: Zveza med specifičnim prispevkom drobirskega materiala, izračunanim po 2. metodi Marchi & D'Agostino (2002), in strmcem struge hudournika za vsa obravnavana hudourniška območja (regresijska črta je enačba (12)).
Glej angleški del prispevka.

Slika 8: Zveza med specifičnim prispevkom drobirskega materiala, izračunanim po metodi Ceriani s sod. (2000), in naklonom hudourniškega vršaja za vsa obravnavana hudourniška območja (regresijska črta je enačba (13)).
Glej angleški del prispevka.

6 Klasifikacija hudourniških vršajev

Obravnavane hudournike smo nato razvrstili glede na nevarnost nastanka drobirskih tokov. V literaturi sta pogosti dve mejni vrednosti, določeni iz analize preteklih dogodkov, ki sta dovolj dober kriterij za razvrstitev hudourniških vršajev v tri razrede: Meltonovo število = 0,3 in naklon hudourniškega vršaja = 4° (7 %). Vršaje, ki so ustrezali obema kriterijema, smo označili kot drobirske vršaje, saj na njih obstaja nevarnost delovanja drobirskih tokov. Vršaje, katerih parametri niso presegli nobene od obeh mej, smo označili kot hudourniške vršaje. Na hudourniških vršajih ni nevarnosti delovanja drobirskih tokov. Vršaje, ki ustrezajo samo enemu kriteriju od obeh, smo označili kot prehodne vršaje. Na njih sicer obstaja nevarnost delovanja drobirskih tokov, vendar je verjetnost tega dogodka relativno majhna.

Parametri za takšno klasifikacijo lahko enostavno določimo bodisi na podlagi topografskih kart bodisi z natančnejšimi terenskimi meritvami. Opozoriti moramo, da hudourniški vršaj za razliko od drobirskega vršaja morda res ni podvržen delovanju drobirskih tokov, še vedno pa na njem obstaja nevarnost delovanja hudournika in toka, prenasičenega s sedimenti (hiperkoncentriranega toka).

Preglednica 7. Vrednosti parametrov in določena ogroženost vršaja posameznega hudournika z drobirskimi tokovi.

hudourniško območje	Meltonovo število [–]	naklon vršaja [%]	uvrstitev vršajev v razrede
SAVA			
Trebiža	0,298	4,157	prehodni primer
Krotnjek	0,308	5,024	prehodni primer
Suhelj	0,527	11,828	ogrožen vršaj
Velika Pišnica	0,244	2,218	ni ogroženosti
Jurežev graben	0,613	11,842	ogrožen vršaj
Martuljek	0,316	4,211	prehodni primer
Hladnik	0,293	6,496	prehodni primer
Beli potok	0,594	10,010	ogrožen vršaj
Belca	0,254	5,182	ni ogroženosti
Bistrica	0,250	1,448	ni ogroženosti
Mlinca	0,438	8,100	ogrožen vršaj
Presušnik	0,530	12,261	ogrožen vršaj
Dobršnik	0,723	10,000	ogrožen vršaj
Jesenica	0,241	3,382	ni ogroženosti
Ukova	0,356	9,348	ogrožen vršaj
Javornik	0,302	5,900	prehodni primer
Bela	0,229	9,058	prehodni primer
Sevnik	0,348	14,500	ogrožen vršaj
POHORJE			
Lobnica	0,150	5,607	ni ogroženosti
Lobničica	0,520	20,000	ogrožen vršaj
PREDELICA			
Predelica	0,672	9,200	ogrožen vršaj
KOSEČ			
Brusnik do Koseča	0,969	23,333	ogrožen vršaj
Brusnik do Ročice	1,038	30,769	ogrožen vršaj
Ročica	0,309	7,700	ogrožen vršaj

Med obravnavanimi hudourniki sta tudi Predelica in Brusnik, kjer so se drobirski tokovi v preteklosti že zgodili. Na hudourniku Predelica se je sprožil drobirski tok, ki je močno prizadel vas Log pod Mangartom. Na hudourniku Brusnik pa so se leta 2002 prožili drobirski tokovi, ki so ogrožali Koseč. Če privzamemo delitev drobirskih tokov v razrede od 1 do 10, kot jo je predlagal Jakob (2005), ki določa možne posledice drobirskih tokov različnih razredov z uporabo več parametrov drobirskega toka (magnituda, maksimalni pretok, površina odloženega toka), so poglavitne značilnosti teh dveh drobirskih tokov naslednje:

Log pod Mangartom:
Magnituda: M = 700.000–1.000.000 m^3 (razred 5–6)
Maksimalni pretok drobirskega toka: Q_b = 8.000 m^3/s (razred 5)
Površina odloženega drobirskega toka: B_b = 250.000 m^2 (razred 5)
Drobirski tok 17. 11. 2000 v Logu pod Mangartom lahko uvrstimo v razred 5.

Koseč:
Magnituda: M = 100–1000 m^3 (razred 2)
Maksimalni pretok drobirskega toka: Q_b = 15–20 m^3/s (razred 2)
Površina odloženega drobirskega toka: B_b = nekaj 100 m^2 (razred 2)
Drobirske tokove leta 2002 v Koseču lahko uvrstimo v razred 2.

Rezultati izračunanih magnitud drobirskih tokov z 2. metodo Marchi & D'Agostino (2002) in metodo Ceriani s sod. (2000) so prikazani v preglednici 8. Ocenjena magnituda je obenem tudi ocena maksimalnih možnih dogodkov, ki pa se razlikuje od dejanskih prostornin opazovanih drobirskih tokov. V primeru Loga po Mangartom je vzrok razlike ekstremnost dogodka, ko je drobirski tok s povratno dobo prek sto

Preglednica 8. Magnitude drobirskih tokov za Predelico in Brusnik do Koseča.

	Marchi in D'Agostino (2002)	Ceriani s sod. (2000)		
	magnituda [m^3]	magnituda [m^3]	magnituda [m^3]	magnituda [m^3]
Hudourniško območje		a) $I\_F = 2$	b) $I\_F = 1$	c) $I\_F = 3$
PREDELICA				
Predelica	96.143	84.032	336.128	37.348
KOSEČ				
Brusnik do Koseča	33.052	17.198	68.794	7.644

let nastal na pobočju in se razlil v dolini Koritnice v dveh fazah. Da bi dosegli prostornino dejanskega drobirskega toka iz leta 2000 (npr. 900.000 m^3) z metodo Ceriani s sod. (2000), bi morali uporabiti indeks plazljivosti $I\_F = 0{,}6$.

Drobirski tokovi v Koseču so bili manjših dimenzij, ker so bili omejeni z razpoložljivo količino drobirskega materiala (Mikoš s sod. 2005). Če bi se plaz Strug znova intenziviral, lahko pričakujemo vnovično aktiviranje drobirskih tokov. Kot ekstremni scenarij za določitev nevarnega območja v Koseču zaradi delovanja drobirskih tokov izpod Struga smo privzeli dogodek s prostornino (magnitudo) 25.000 m^3 (Mikoš s sod. 2006).

7 Sklep

Analiza je pokazala uporabnost izbranih metod za oceno magnitud drobirskih tokov na osnovi znanih morfoloških parametrov hudourniškega območja. Za slovenske razmere sta se kot primerni pokazali: 2. metoda Marchi in D'Agostino (2002) ter metoda Ceriani s sod. (2000). S pomočjo hidrološkega modeliranja izbranih hudourniških območij smo s pomočjo dveh metod razvili lastne empirične enačbe. Odločitev o primernosti metod je slonela tudi na primerjavi rezultatov teh dveh metod s podatki o drobirskih tokovih v Koseču v letu 2002 in o drobirskem toku, ki je 17. novembra 2000 prizadel Log pod Mangartom.

Rezultati le deloma potrjujejo kritični meji za razvrščanje vršajev v posamezne tipe, zato je njuno nadaljnje preverjanje, predvsem podrobne terenske raziskave vršajev. Tkao bi ju lahko potrdili in prilagodili slovenskim razmeram. Metoda Ceriani s sod. (2000), ki vsebuje indeks plazljivosti, zahteva terenski ogled in določanje tega indeksa na osnovi razširjenosti erozijskih pojavov v hudourniškem območju. Omenjeni indeks močno vpliva na oceno magnitude drobirskega toka.

8 Viri in literatura

Glej angleški del prispevka.