DEBRIS-FLOW SUSCEPTIBILITY MODEL OF SLOVENIA AT SCALE 1 : 250,000

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ABSTRACT

For the area of Slovenia (20.000 sqr. km) a debris-flow susceptibility model at scale 1 : 250,000 was produced. To calculate the susceptibility to debris-flow rate using GIS several layers were used (geology – Lithology in combination with the distance from structural elements; 48-hour rainfall intensity; digital elevation model – slope, curvature, energy potential related to elevation; surface water net – distance to surface waters, stream energy potential). Known debris-flow occurrences were used for the models' evaluation. A linear weighted sum model approach was selected on the basis of spatio-temporal factors to simplify the approach and to make the approach transferable to other regions. Based on the calculations of 672 linear models with different weight combinations of spatio-temporal factors and based on results of their debris-flow susceptible areas prediction success, the best factors' weight combination was selected. To avoid over-fitting of the prediction model, an average of weights from the first hundred models was chosen as an ideal combination of factor weights. The presented debris-flow susceptibility model forms a basis for spatial prediction of the debris-flow triggering and transport areas. It also gives a general overview of susceptible areas in Slovenia and gives guidance for further and more detailed research areas.

Key Words: Debris-flow, Susceptibility, Influence factors, Model, Landslides, GIS, Slovenia

INTRODUCTION

Debris-flows are a cause of numerous natural disasters claiming casualties and resulting socio-economic problems of mountainous regions around the globe (Nakagawa *et al.*, 2000, 2001; Takahashi, 1991; Embleton-Hamanu, 1997; Oldnall, 2004; Mikoš, 2001). Since their spatial occurrence is very limited their devastating consequences can be mitigated, maybe even prevented. Paper will present a methodology to derive a debris-flow model of a general scale (1:250,000) for the area of Slovenia, which can be utilised to define more exposed areas where more detailed prediction is necessary in the case of spatial planning.

Debris-flows are processes of slope mass movements of high velocities and predominantly originate in the steep sloped areas of with shallow coarse-grained soil cover. Triggering factor is soil saturation with water, usually a consequence of heavy rainfall (Fleming *et al.*, 1989;

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Mainali & Rajaratnam, 1994; Anderson, 1995; Cruden & Varnes, 1996; Dai *et al.*, 1999; Fiorillo & Wilson, 2004; Lan *et al.*, 2004; Wen & Aydin, 2005). Ribičič (2002) defines debris-flow as a hyper-concentrated gravitational-driven flow consisted of soil (with low proportion of clay particles), gravel, even boulders, water and air that is when triggered "liquefied" and that feeds with material it erodes during transport. Mikoš (2001) explains that based on its origin and evolution a debris-flow can be subdivided into three separate processes, triggering, transport and sedimentation.

Due to complexity of the phenomena numerous approaches have been chosen in the past. Approaches vary from pure empirical (R2 Resource Consultants, 2005), probabilistic (Mazengarb, 2004; Miller and Burnett, 2008), statistical (Zhou *et al.*, 2003; Guinau *et al.*, 2007; Pozzoni *et al.*, 2009) to complex mathematical modelling (Wang *et al.*, 2006; Kowalski & McElwaine, 2008; Christensen *et al.*, 2009).

The primary goal of analyses presented in this paper was merely to spatially delineate the areas susceptible to debris-flow occurrence on national scale and was not focused into detailed analyses related to trigger, transport and sedimentation areas, neither was focused into the hazard assessment i.e. temporal extension or quantifying dimensions of potential debris-flows.

AREA AND DATA USED

The area of Slovenia is due to its complex geological structure (rock types vary from sediments to metamorphic and igneous rocks, while the age ranges from Precambrian to Quaternary), geodynamics (Slovenia lies at the contact of three geotectonic units – Alps, Dinarides and Pannonian Basin), geographical setting that influences regional and local climate (maximum 48-hour rainfall intensity with 50-year return period ranges from 120 to 570 mm) and geomorphology (elevation values in Slovenia range from sea level to 2864 m a.s.l. and terrain types range from flat to steep Alpine valleys and gorges) exposed to several types of slope mass movements including debris-flows. In 2000 a debris-flow stroke the village of Log pod Mangrtom and claimed eight victims (Mikoš, 2001). In 2006 a research project was funded to assess the susceptibility to debris-flow occurrence for the whole of Slovenia.

Based on the previous approaches (Fleming *et al.*, 1989; Rickenmann & Zimmerman, 1993; Mainali & Rajaratnam, 1994; Anderson, 1995; Cruden & Varnes, 1996; Alzate et. al., 1999; Dai *et al.*, 1999; Mikoš, 2001; Lin *et al.*, 2002; Archetti & Lamberti, 2003; Delmonaco *et al.*, 2003; Fiorillo & Wilson, 2004; Lan *et al.*, 2004; Melelli & Taramelli, 2004; Wen & Aydin, 2005; Guinau *et al.*, 2007; Di *et al.*, 2008; Jež *et al.*, 2008; Mergili, 2008; Toyos *et al.*, 2008) and authors' own experiences it was decided to use the data on lithology, distance to faults, slope angle, energy potential related to elevation, rainfall, slope curvature, stream energy potential and distance to streams for the modelling of debris-flow susceptibility prediction. Details are presented in the Table 1.

Table 1 Detailed descriptions of spatio-temporal factors used in the debris-flow susceptibility modelling. Column "Factor" represents descriptions for classes within each factor, "Class area (%)" represents the area proportion for each class, "Normalised susceptibility" represents the relative susceptibility of a given class in relation to other classes. "Weight interval" represents the interval of weight for a given factor and "Step" represents the step of the weight change in the linear weighted model calculation phase.

Factor	Class area (%)	Normalised susceptibility	Weight interval (W_{Min} - W_{Max})	Step
Lithology – (**Litho**) (Buser, in print)			0,14 – 0,23	0,03
Alluvial sediments	17,17%	0		
Soft rocks (claystones, siltstones)	12,11%	0,14		
Igneous rocks (tonalites, etc.)	1,83%	0,29		
Carbonates (without inclusions of other rocks or without alteration with other rocks)	35,32%	0,43		
Clastites*	19,38%	0,57		
Clastites with inclusions of other rocks*	10,10%	0,71		
Gravels, breccias, rock falls, scree deposits	3,05%	0,86		
Slope moraines, till	1,04%	1		
Distance to faults (m) – (**Elem_d**) (Poljak, 2000)		litho + 0,1428		
< 50		(last two lithological classes were excluded		
>= 50		due to post-tectonic sedimentation)		
Rainfall (mm/48-h) – (**Rfall)** (ARSO, 2003)			0,14 – 0,23	0,03
< 120	6,72%	0		
120 – 150	34,06%	0,07		
150 – 180	23,50%	0,13		
180 – 210	12,15%	0,2		
210 – 240	7,55%	0,27		
240 – 270	4,37%	0,33		
270 – 300	3,32%	0,4		
300 – 330	2,46%	0,47		
330 – 360	1,48%	0,53		
360 – 390	0,98%	0,6		
390 – 420	0,89%	0,67		
420 – 450	0,71%	0,73		
450 – 480	0,59%	0,8		
480 – 510	0,60%	0,87		
510 – 540	0,33%	0,93		
540 – 570	0,30%	1		
Slope angle (°) – (**Slp**) (GURS, 2005)			0,14 – 0,23	0,03
< 5; excluded based on Mazengarb (2004), Toyos *et al.* (2008), Melelli & Taramelli (2004), Committee on Alluvial Fan Flooding, (1996).	27,77%	-		
5 - 9 and > 45	15,77%	0		
9 - 15	19,97%	0,17		
15 - 21	15,23%	0,33		
21 - 27	10,02%	0,5		
27 - 33	6,44%	0,67		
33 - 39	3,55%	0,83		
39 - 45	1,25%	1		
Energy potential related to elevation (derived from: a.s.l. elevation zone division (m) based on average slope angle) – (**Ep**)			0,06 – 0,15	0,03
100 – 199 (0° - 5°)	7,6	0		
0 – 99 and 200 – 299 (5° - 10°)	19,17	0,14		

Factor	Class area (%)	Normalised susceptibility	Weight interval (W_{Min} - W_{Max})	Step
300 – 399 (10° - 13°)	14,96	0,29		
400 – 599 (13° - 15°)	23,35	0,43		
600 – 699 (15° - 17°)	8,67	0,57		
700 – 899 (17° - 19°)	11,53	0,71		
900 – 1299 (19° - 21°)	9,98	0,86		
1300 – 2864 (21° - 46°)	4,73	1		
Stream energy potential (º/m2; derived from: adapted quadratic kernel density distribution (Silverman, 1986; ArcGIS Kernel Density tool) of the product of the average slope of a stream segment and segment distance in the 100 m buffer area) – (**Sep**)			0,14 – 0,23	0,03
0 – 0,0138	88,72	0		
0,0138 - 0,048301	5,23	0,125		
0,048301 - 0,089703	2,68	0,25		
0,089703 - 0,134554	1,58	0,375		
0,134554 - 0,182856	0,92	0,5		
0,182856 - 0,238057	0,5	0,625		
0,238057 - 0,310509	0,26	0,75		
0,310509 - 0,424363	0,09	0,875		
0,424363 - 0,883227	0,02	1		
Distance to streams (m) – (**Str_d**) (ARSO, 2005)			0,10 – 0,19	0,03
0 – 25	6,46%	1		
25 – 50	4,08%	0,67		
50 – 75	4,75%	0,33		
> 75	84,71%	0		
Slope curvature – (**Curv**)			0,09 – 0,18	0,03
convex and flat areas (-0,5 > X < -8)	91,68	0		
concave areas (-0,5 < X > -8)	8,32	1		
Debris-flow – (**DF**)	Area	Pixels	Purpose:	
16 known debris-flows occurrences	4 km sqr.	6385	model test population	

* Pixels on the boundary between 5th and 4th Lithology class were classified into the 6th and pixels on the boundary between 5th and 3rd class were classified into the 5th class.

METHODOLOGY

The methodology presented in this paper includes spatial modelling of initial (also triggering) areas and transport areas (transport channels), while accumulation areas (also sedimentation areas or diluvium fans) were not included in the model due to coarse scale of susceptibility modelling and the complex nature of a hyperconcentrated flow modelling. Due to the lack of the representative sample we've founded our susceptibility model (Fig. 1) on the expert decision approach and validated it with 16 debris-flow occurrences in Slovenia, represented with 6385 cells. In this simplified model we've used only the most important spatio-temporal factors, while other parameters related to two- or three-phase nature of debris-flows were excluded. Analyses and modelling were performed on a raster 25×25 m cell grid in GIS using ESRI platform.

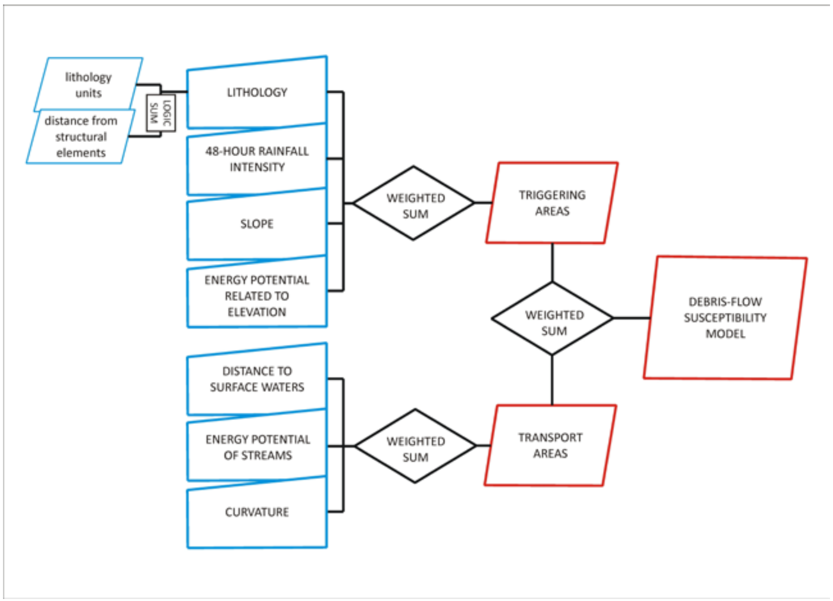

Fig. 1 – Schematic representation of debris-flow susceptibility model.

Modelling of debris-flow susceptibility

Classes of each of the spatio-temporal factor were ordered based on the expert decision. Before the inclusion of relevant factors into the model development, the values of each factor were normalised. It was a necessary step to equalise the different class numbers in factors with a goal that the weights in models represented the real influence of given factor. The normalisation was done using the Eq. 1.

$$NRV = \frac{1-(RV-\min)}{\max-\min}, \tag{1}$$

where *NVR* stands for a new, normalised value, *RV* represents the old (nominal) value, the difference between maximum (*max*) and minimum (*min*) class is always one less than the original number of classes. The normalised values ranged from 0 to 1.

The normalised factors were used to develop the optimum debris-flow susceptibility model. The models were developed using the linear weighted sum (Voogd, 1983). The result is standardised landslide susceptibility, calculated from the Eq. 2:

$$H = \sum_{j=1}^{n} w_j \times f_{ij}, \tag{2}$$

where *H* represents the standardised relative landslide susceptibility (0 – 1), w_j represents the weight for the given factor and f_{ij} represents continuous or discrete variable.

Value intervals for each factor's weight were defined by the expert decision. The subjective factor of the expert decision was minimised by (1) good knowledge of the actual onsite conditions, (2) years of experiences in the field of slope mass movement research and engineering works, and (3) numerous weight combinations.

Altogether 672 models for the whole Slovenia were calculated using different weight combination. In Table 1 W_{Min} represents minimum and W_{Max} maximum weight value used for a given factor in the random combinations calculation and "Step" represents the step, with which the weight values are selected between minimum and maximum value. All models were tested on the debris-flow test set (6385 cells). In order to select the optimum model the comparison of models was necessary. The comparison based on the equal area criterion to avoid the differences between the models debris-flow susceptibility value distributions. In simple, each of the susceptibility classes is supported by the same statistical reliability and hence robustness of the approach is achieved. Each of the evaluated models was classified into 100 classes, according to their debris-flow susceptibility, meaning that the research area was split into 100 classes with one class covering 1 % of the area. The class with the highest l debris-flow susceptibility score, calculated from the (1), was ranked as 100 and the class with the lowest debris-flow susceptibility score was ranked as 1. Descriptive value of debris-flow susceptibility classes was defined only after reclassification procedure for each model.

Prior to modelling all areas with slope angle less than 5° were excluded. 24 cells (0.38 %) from the debris-flow test population were located on the excluded areas and represent a inhered error for each of the models.

RESULTS

Analyses of 672 susceptibility models have shown that among chosen spatio-temporal factors the most important factors (Table 2), which govern the occurrence of debris-flow, are 48-hour rainfall intensity, geological settings and stream energy potential. Despite the fact that other factors – slope angle, distance to surface waters, and slope curvature – are of lesser importance, their contribution is still essential.

Table 2 Average values of weights of spatio-temporal factors, used for the debris-flow susceptibility models calculations. Explanation of spatio-temporal factors (Factors) is given in the Table 1.

Models \ Factors	Name	Litho	Rfall	Slp	Ep	Sep	Str_d	Cur
Best model (over-fitting)	Best	0.2300	0.2200	0.1400	0.0500	0.1400	0.1300	0.0900
10 best models average	AVRG_10	0.1970	0.2200	0.1400	0.0530	0.1550	0.1360	0.0990
25 best models average	AVRG_25	0.1988	0.2116	0.1448	0.0632	0.1556	0.1264	0.0996
50 best models average	AVRG_50	0.1970	0.2044	0.1430	0.0566	0.1706	0.1282	0.1002
100 best models average	AVRG_100	0.1889	0.2029	0.1472	0.0542	0.1706	0.1201	0.1161

Fig. 2 displays the distribution of 6385 cells debris-flow test population for the best 100 susceptibility models for that half of Slovenian area, where the susceptibility is high(er). To avoid over-fitting, average values of 100 best models (AVRG_100) were chosen for the most suitable debris-flow susceptibility model. The distribution of test population for the AVRG_100 model (bold line in Fig. 2) shows that within the top 5 % of the area there are 35 % of the test population, within top 20 % of the area there are more than 76 % of the test population. Model AVRG_100 (shown in Fig. 3) is defined by the following weight values for relevant spatio-temporal factors: 48-hour rainfall intensity (0.2), geology (0.19), stream energy potential (0.17), slope angle (0.15), distance to surface waters (0.12), slope curvature (0.12), and energy potential related to elevation (0.05). The model AVRG_100 represnets the spatial debris-flow susceptibility in Slovenia, where the areas with insignificant or low susceptibility (classes 1 and 2) are shown in green, areas with medium susceptibility (class 3) are shown in yellow, areas with high susceptibility (class 4) are shown in orange, and areas with very high susceptibility (class 5) are shown in red. Areas where debris-flow susceptibility is negligible are shown in grey colours. More detailed analysis indicates an interesting pattern with areas of transport (transport channels where the destruction energy of debris-flow is the highest and hence represents the highest danger) coloured in red and the triggering areas (source of material) shown in orange.

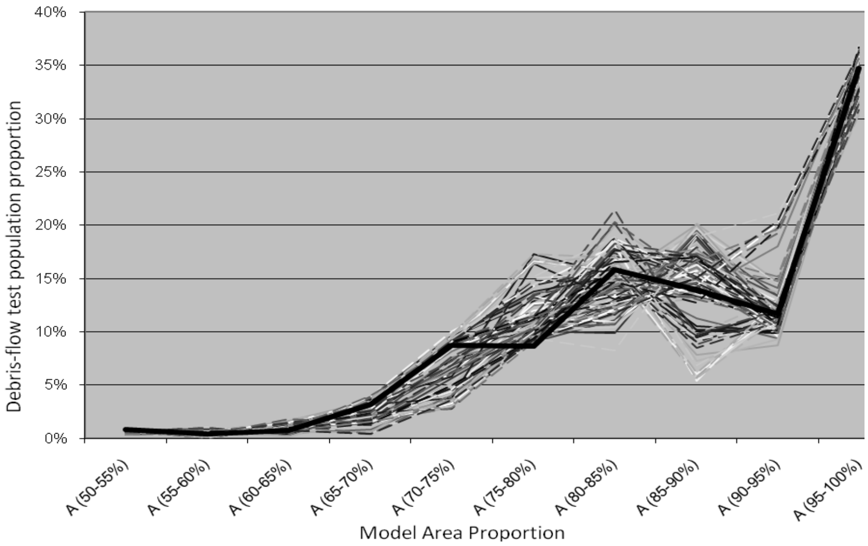

Fig. 2 Test sample area distribution in the upper 50 % of the Slovenian area (the half of the area where the debris-flow susceptibility is higher) divided into ten classes by 5 %. Bold line represents the debris-flow distribution for the chosen model AVRG_100.

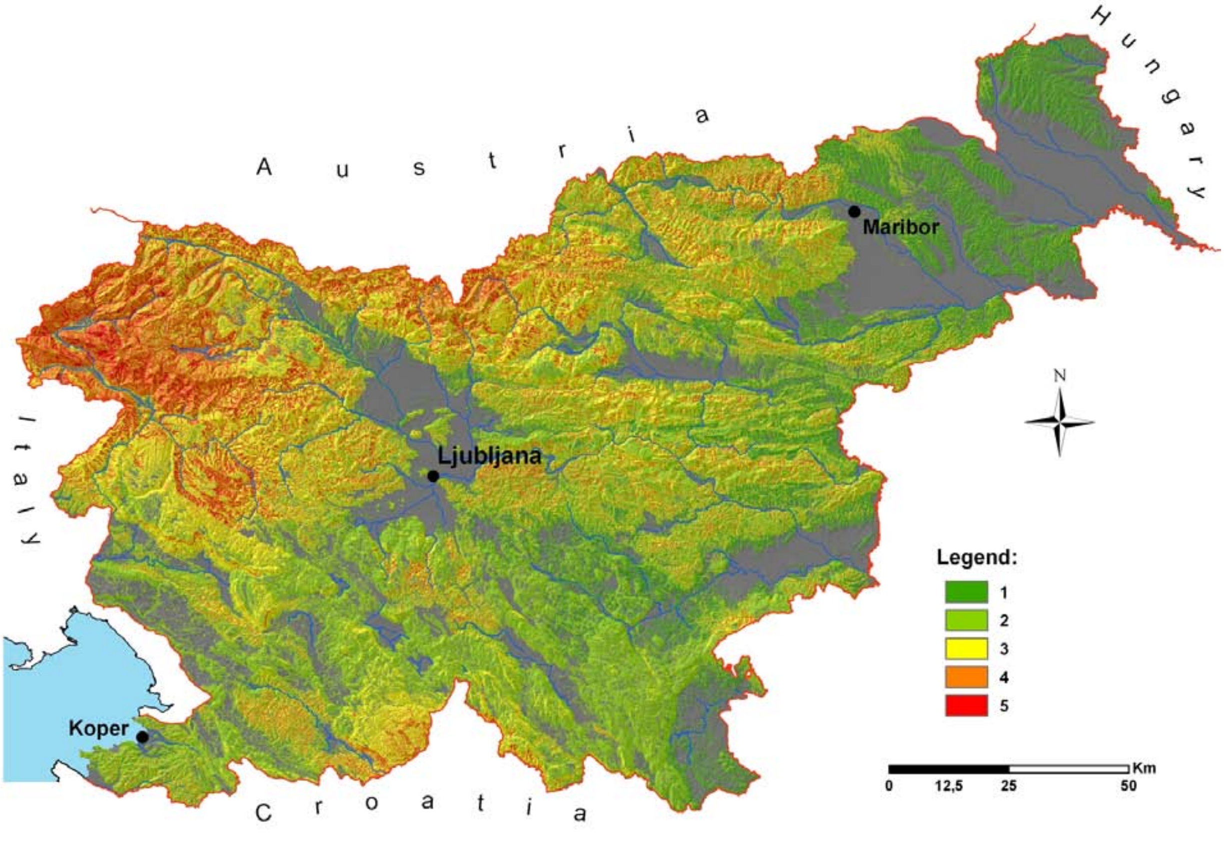

Fig. 3 Most appropriate and real debris-flow susceptibility model for Slovenia (AVRG_100) calculated from the linear function of spatio-temporal factors as described in Table 3. Values in the legend stand for the debris-flow susceptibility: 1 – insignificant; 2 – low; 3 – medium; 4 – high; 5 – very high. The grey areas belong to the areas in Slovenia where the debris-flow susceptibility is negligible.

Table 3 Debris-flow susceptibility classes area distribution in Slovenia for the AVRG_100 model. Column »A« represents the proportion of the area, »Model Values« represents the interval of the AVRG_100 model values that span from 0 to 1, »DF Susceptibility« descriptively represents the debris-flow susceptibility, and »DF Proportion« represents the proportion of the test sample pixels in each susceptibility class.

Class	A (%)	Model Values	DF Susceptibility	DF Proportion (%)
0	27.84	-	Negligible	0.38*
1	10.18	0 – 0.134	Insignificant	0.00
2	27.86	0.134 – 0.243	Low	0.96
3	19.48	0.243 – 0.353	Medium	17.92
4	10.66	0.353 – 0.494	High	43.40
5	3.99	0.494 – 1.00	Very High	37.35

*0,38 % of the testing samples pixels are located in the areas where debris-flow occurrence in negligible.

Based on the properties of the AVRG_100 model and natural brakes in the distribution of its values, the model values were classified into six classes (0 + 5 susceptibility classes) as described in the Table 3. Distribution of model's values should not be confused with the equal area distribution, which is shown with vertical bars in the Fig. 4. Within the very high susceptibility class all areas with 9-times higher probability of debris-flow occurrence than expected were classified. In these areas that cover upper 4 % of the Slovenian area 37.3 % of the debris-flow test population occur. Areas of high susceptibility cover 10.6 % of the area with 43.4 % of debris-flow test population, areas of medium susceptibility cover 19.5 % of the area with 18 % of the debris-flow test population, areas of low susceptibility cover 28 % of the area with less than 1 % of the debris-flow test population, and areas of insignificant susceptibility cover 10 % of the area where no debris-flow from test population occur. In the areas with negligible susceptibility 0.4 % debris-flows occur. Fig. 4 shows cumulative distribution of the debris-flow test population (blue line – DT (kum %)) and the distribution of the area according to the model values (vertical bars; A %). Susceptibility classes are shown in colours circles and boundaries between them are shown with dark vertical bars (CLS). A χ^2 (Chi-square) test (Davis, 1986) was used to statistically test correctness of the susceptibility class definition. The results (χ^2 = 443.068 and p < 0.000) show that the chosen susceptibility classification represents good prediction of debris-flow (Table 4).

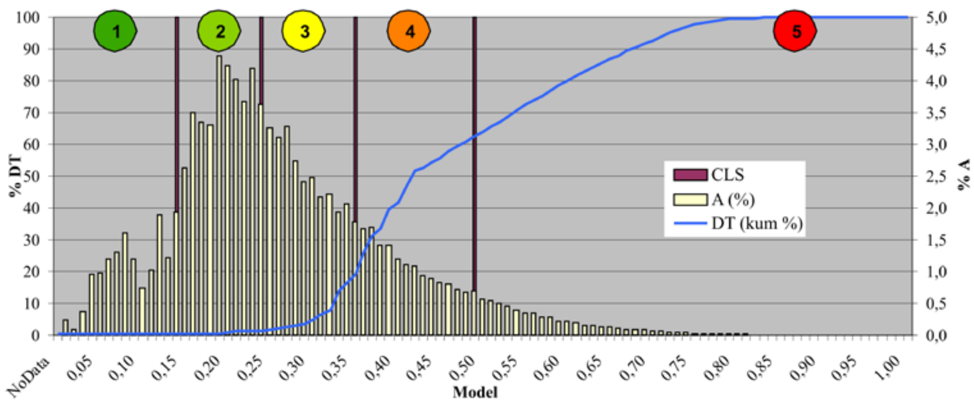

Fig. 4 Cumulative distribution of the debris-flow test sample pixels (DT (kum %)) and distribution of the area (A %) (areas where slope angle is below 5º are excluded) according to values of the AVRG_100 model. Debris-flow susceptibility classes are represented with coloured circles and numbers while boundaries between classes are represented with vertical lines (CLS). Values in the circles stand for the debris-flow susceptibility as described in Fig. 3.

Table 4 Chi square (χ^2) test of model AVRG_100 classification into 6 classes. Column "Observed (O)" represents observed proportion of the test sample pixels in each susceptibility class, column "Expected (E)" represents expected proportion of the test sample pixels in each susceptibility class, if the distribution would be random.

χ^2 = 443.0689	df = 5	p < 0.000000

Class	Observed (O)	Expected (E)	O-E	χ^2=(O-E)^2/E
0	0.3759	27.8358	-27.4599	27.0891
1	0.0000	10.1771	-10.1771	10.1771
2	0.9554	27.8578	-26.9024	25.9798
3	17.9170	19.4799	-1.5629	0.1254
4	43.3986	10.6619	32.7367	100.5158
5	37.3532	3.9876	33.3656	279.1817
Σ	*100.0*	*100.0*	*0.0*	*443.0689*

Geological units that are prone to the debris-flow occurrences (or form triggering areas) can be found all over Slovenia. Beside sediments that are by their composition very similar to debris-flows and are characteristic for Alpine areas (W and N Slovenia) – moraines, scree deposits and (alluvial) fans – and hence form a perfect triggering areas, there are also units consisted of slabbed carbonates with marls or cherts. In Karavanke chain (N Slovenia, bodering Austria) and in western part of central Slovenia the source material for debris-flows is consisted of carbonates with flysch inclusions, units of claystones, siltstones, sandstones, marls and pyroclastic sediments. In NE part of Slovenia, in the areas of igneous and metamorphic rocks the units prone to debris-flow occurrence are tonalities, schists, gneiss, granites with diabase, and slate.

CONCLUSIONS

Debris-flows are complex phenomenon which nature of occurrence and dynamics is difficult to predict and model. The reason for this is the temporal and spatial variability of the influence factors and the complexity of the flow itself. The presented approach is a generalised approximation of the actual conditions. Despite the fact that a quest for an ideal model is never finished, our pragmatic approach is simple, robust, quick and cost-effective. The developed model AVRG_100 predicts potential areas of debris-flow occurrence relatively well as on 15 % of the area 80.7 % debris-flow occur and on 34 % of the area 98.7 % of debris-flow occur. With this model, calculated at scale 1:250.000, for the first time debris-flow susceptibility estimation was done for the area of Slovenia. This analysis forms a basis for the delineation of more susceptible areas and sets directions for further more detailed investigations focused in hazard and risk assessments.

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