10.2478/v10066-012-0035-2

ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN – POLONIA

VOL. LXIX, 1 SECTIO B 2014

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Assessment of slope covers vulnerability to shallow mass movements using SINMAP

Ocena podatności pokryw stokowych na powstawanie płytkich osuwisk
przy użyciu modelu SINMAP

Keywords: landslide, SINMAP, south Poland
Słowa kluczowe: osuwiska, SINMAP, Polska południowa

INTRODUCTION

In Flysch Carpathians mass movements are a significant factor that causes changes in the morphology of slopes and, in many cases, causes also economic damage. A complicated geological structure of the area, high height differences and high rainfall, which is the main factor initiating mass movements, are mainly listed among the basic conditions for such type of processes to occur. Infiltration of rainfall in the soil profile can lead to a loss of stability in two ways (Crosta 1998). Infiltration process can cause an increase in the groundwater level when there are low intensity rainfalls. High intensity rainfalls can cause creating of perched water table in the area of moving quench front, therefore in many publications in the field of geotechnics and engineering geology (among others: Crosta 1998; Li et al. 2006; Rahardjo et al. 2007, 2010; Tu et al. 2009) assessment of vulnerability of slope covers to mass movements does not focus only on the strength parameters of the soil, but it also takes infiltration of rainfall into consideration.

Because of a recent development of spatial information systems, slope stability evaluation is more often done in relation to large areas, comprising river basins or even regions (Montgomery and Dietrich 1994; Morrissey et al. 2001; Meisina and Scarabelli 2007). One of the generally used in GIS environment physical model of water distribution in the soil profile that allows to determine slope stability is SINMAP (Pack et al. 1999).

An attempt to do a preliminary assessment of vulnerability of surface slope covers from the area of Nowy Wiśnicz commune to mass movements using SINMAP model was made and presented in the paper, along with the verification of modeling results with actual existing landslides.

STUDY AREA

According to the geomorphological classification (Starkel 1972), the area of Nowy Wiśnicz commune is entirely in the Wiśnicz Foothills, within river basins of Raba and Uszwica. The morphology of this area has a low foothill character, the heights do not exceed 440 m above sea level. The main rocks at this area are Krosno layers, melinit shale, Ciężkowice sandstones, variegated shale and upper and lower Istebna beds of Silesian and SubSilesian Units. In this area mainly folding structures of Carpathian flysch interpenetrate and then smoothly transform into Miocene structures that lie below.

The morphology of this part of Foothills is characterized by occurring of parallel, extended and wide humps and divisions, referring to the course of the main geological structures. Long, convexo-concave slopes of the foothills do not exceed the inclination of 25°. The main distinguishing elements in the morphology of this area are two levels of flattening: higher (350–430 m above sea level) and lower (300–320 m above sea level) (Starkel 1972). Higher level is traversed with narrow depressions in the form of erosion-denudation valleys and ravine forms.

Slope covers were developed on the loess, loess-like and silt forms of flysch Carpathian eluvium. Lessive, lessive groundwater gley soils and – less often – brown, alluvial or colluvial soils were created (Skiba 1995). Mechanical constitution of slope covers is characterized by low sand content (up to 10%), a significant silt fraction content (50–70%) and a high percentage of colloidal clay fraction (8–18%) (Święchowicz 2012). In relation to climate the area of Nowy Wiśnicz commune is classified as moderate warm level (Hess 1965). Data from IGiGP (Institute of Geography and Spatial Management) Meteorological Station in Łazy (located 7 km from the center of the commune) from 1987 to 1994 showed that the average annual temperature was 8.6°C. The coldest month was January with the average temperature of about -0.4°C. The hottest month was July with the temperature of 18.4°C. An average annual rainfall was 665.9 mm based on the period from 1987–2009 (on average 168 days with rain). Maximum daily rainfall was from 27.9 to 83.4 mm (Święchowicz 2012).

Within the scope of SOPO program (Anti-landslide Protection System) in the area of Nowy Wiśnicz commune a detailed landslide charting was performed and places where there is a great danger of mass movement were distinguished. Within the boundaries of the commune about 280 landslides were counted. An average density of landslides incidence was 3.4 per 1 km^2. In the area close to Królówka village the density of incidence rises up to 20 landslides per 1 km^2. Among all landslides almost 90% are formed in the slope covers (landslides from weathered material on the bed-rock, earth landslides). Only 10% are deep landslides that reach to the deep Paleogene and Neogene rocks (source: SOPO).

METHODOLOGY

SINMAP (Stability INdex MAPping) model, created by Pack et al. (1999), was used in the evaluation of vulnerability of slopes in the analyzed area. The infinite plane slope stability model was used to describe the equilibrium state of slope. Therefore stability evaluation includes the vulnerability of the slope to translational landslides, which are triggered by rainfall infiltration and inducing subsurface flows. According to publication by Abramson et al. (2002), a rain-induced shallow landslides can be understood as slides up to 3 m deep, whereas according to Crosta and Frattini (2003), this type of mass movement can reach only 2 m BGL (below the ground level).

Initial formula for the factor of safety is:

$$FS = \frac{c_r + c_s + \cos^2\alpha \cdot \left[\rho_s \cdot g \cdot (D - D_w) + (\rho_s \cdot g - \rho_w \cdot g) \cdot D_w\right] \cdot \tan\phi'}{D \cdot \rho_s \cdot g \cdot \sin\alpha \cdot \cos\alpha} \quad (1)$$

where: c_r – root cohesion, c_s – soil cohesion, α – slope angle, D – vertical soil depth, D_w – vertical height of the water table within the soil layer, g – gravitational acceleration, ρ_s – wet soil density, ρ_w – density of water, ϕ' – effective internal friction angle of the soil, *r* – water to soil density ratio.

Assuming that:

$$w = \frac{D_w}{D} \quad (2)$$

$$r = \frac{\rho_w}{\rho} \quad (3)$$

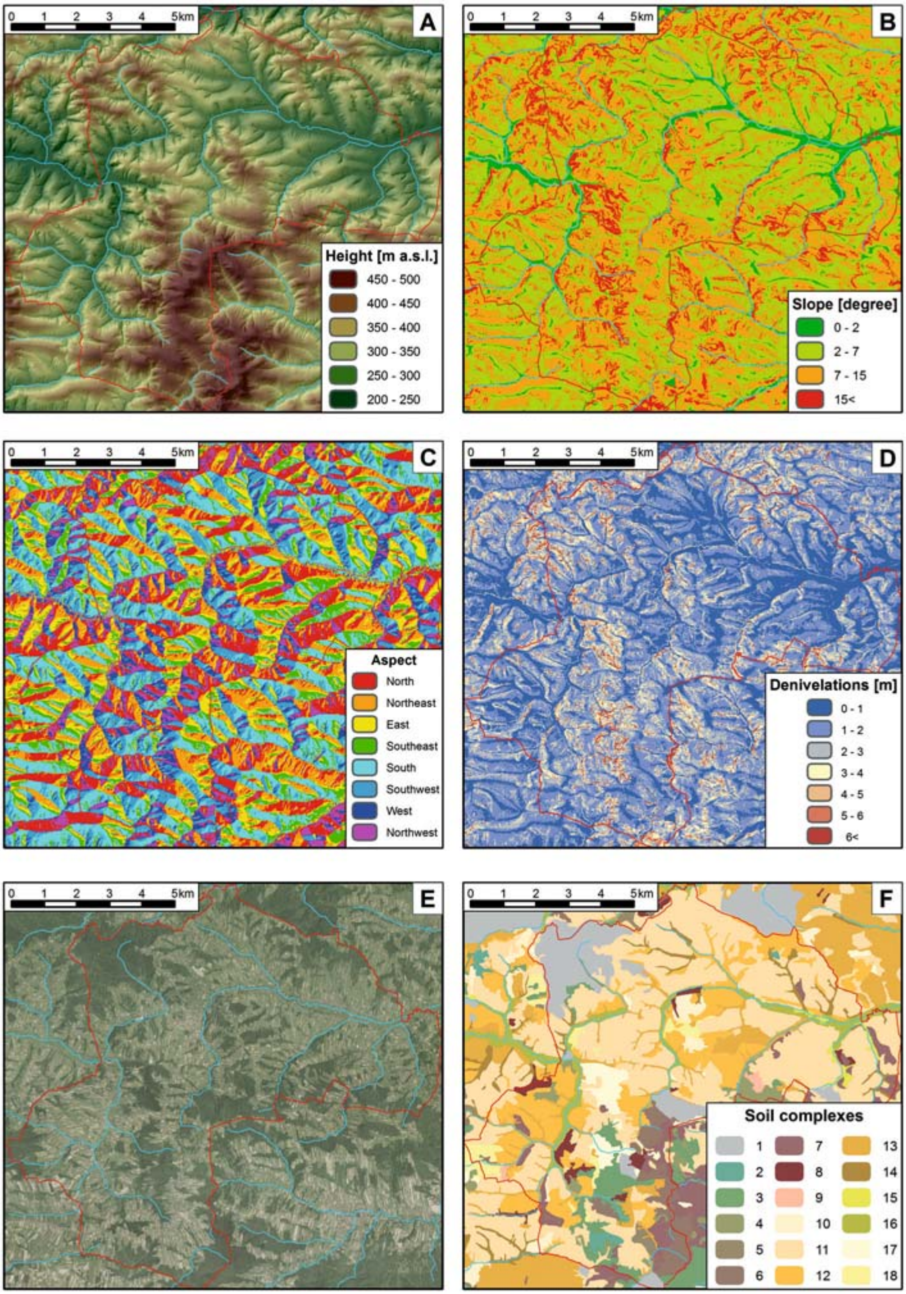

Fig. 1. Environment elements analyzed in relation to vulnerability to mass movements on the area of Nowy Wiśnicz commune: A – elevation model, B – inclination map, C – aspect map, D – height difference map, E – orthophoto (source: geoporta.gov.pl), F – soil map (based on: Soil-agricultural Map, IUNG in Puławy 1:25,000)

and integrating soil and root cohesion

$$C = \frac{c_r + c_s}{D \cdot \cos\alpha \cdot \rho \cdot g} \quad , \tag{4}$$

equation (1) reduces to the following form:

$$FS = \frac{C + \cos\alpha \cdot [1 - w \cdot r] \cdot \tan\phi'}{\sin\alpha} \tag{4}$$

During calculations the “w” parameter which shows relative wetness is very important. Stability calculations are integrated with subsurface flow calculations in SINMAP model. It is assumed that hydraulic conductivity of soil profile is:

$$T = k \cdot D \cdot \cos\alpha \tag{5}$$

where: k – permeability coefficient, D – see above,

While the lateral discharge at any point of the river basin is determined by the following equation:

$$q = R \cdot a \tag{6}$$

where: a – specific catchment area, ratio of contributing area to the unit contour length.

Comparing the potential hydraulic conductivity of soil profile (formula no. 5) with the lateral discharge (formula no. 6), the relative wetness of profile can be as follows:

$$w = \min\left(\frac{R \cdot a}{T \cdot \sin\alpha}; 1\right) \tag{7}$$

Final formula for the factor of safety in any point of river basin is obtained by incorporating the above relation into the equation (4):

$$FS = \frac{C + \cos\alpha \cdot \left[1 - \min\left(\frac{R \cdot a}{T \cdot \sin\alpha}; 1\right) \cdot r\right] \cdot \tan\phi'}{\sin\alpha} \tag{8}$$

where: C – component of root and soil cohesion, R – rainfall intensity, T – soil transmissivity, i.e. hydraulic conductivity (permeability coefficient) times soil thickness, r – water to soil density ratio, α – slope angle, ϕ’ – effective internal friction angle of the soil.

In SINMAP model it is assumed that the values of geotechnical parameters of each soil are variable and within a certain range. Therefore for each elementary area of analysis (cell) a number of stability values are determined. Final effect of stability calculations is the value of stability index (SI) for the analyzed elementary area, which determines the probability of landslide occurrence (table 1).

Table 1. Slope stability classification according to SINMAP (Pack et al. 1999)

Stability Index	Predicted state	Remarks
SI ≥ 1.5	Stable slope zone	Significant destabilizing factors are required for instability
1.5 > SI ≥ 1.25	Moderately stable zone	Moderate destabilizing factors are required for instability
1.25 > SI ≥ 1.0	Quasi-stable zone	Minor destabilizing factors could lead to instability
1.0 > SI ≥0.5	Lower threshold slope zone	Destabilizing factors are not required for instability
0.5 > SI ≥ 0.0	Upper threshold slope zone	Stabilizing factors are required
0.0 > SI	Defended slope zone	Slopes permanently unstable

In order to realize the purpose of this paper and prepare the model of slopes stability in the area of Nowy Wiśnicz commune the following were used:

– digital elevation model, made available by CODGiK, which was used to draw an inclination map (Fig. 1A), for necessary analysis of directions and duration of rainfall flow as well as for stability calculations; elevation model was made at the resolution of 10 x 10 m;

– a map of soil complexes of the area of Nowy Wiśnicz commune, it was created based on the soil-agricultural map in the scale of 1:25,000 (IUNG in Puławy); for calculations eighteen basic soil complexes and three types of land use (arable lands, grasslands, forests) were distinguished; as a result there were 54 complexes altogether (Fig. 1F), which were diverse in relation to the values of geotechnical parameters (Table 2);

– values of hydraulic conductivity of each soil complexes were determined based on literature on soil mechanics (Wiłun 2000; Pisarczyk 1999) and then differentiated in relation to the land use. Based on papers by Słupik (1981), Copin and Richards (2007) it was assumed that arable lands are characterized by higher hydraulic conductivity (by half an order of magnitude) in relation to grasslands and pastures.

Table 2. Geotechnical parameters of soil complexes

No.	Soil complexes	Threshold values of permeability coefficient [m/s]		Threshold values of angle of internal friction [°]		Threshold values of cohesion [kPa]	
		Upper	Lower	Upper	Lower	Upper	Lower
1	Debris	1.00E-02	1.00E-03	36	28	1.0	0.0
2	Light sandy loams	1.00E-06	1.00E-07	28	22	3.5	0.0
3	Light loams 0.5 m thick	5.00E-07	5.00E-08	27	21	5.0	0.0
4	Light loams 1.0 m thick	5.00E-07	5.00E-08	27	21	5.0	0.0
5	Medium sandy loam	1.00E-07	1.00E-08	29	23	4.0	0.0
6	Medium loams 0.5 m thick	5.00E-08	5.00E-09	29	23	5.0	0.0
7	Medium loams 1.0 m thick	5.00E-08	5.00E-09	29	23	5.0	0.0
8	Heavy loams and heavy sandy loams	5.00E-09	5.00E-10	25	18	5.0	0.0
9	Clays and sandy clays	1.00E-09	1.00E-10	24	17	9.0	3.0
10	Loess and loess-like formations 0.5 m thick on a low permeable ground	1.00E-05	1.00E-06	31	24	2.5	0.0
11	Loess and loess-like formations 1.5 m thick on a low permeable ground	1.00E-05	1.00E-06	31	24	2.5	0.0
12	Loess and loess-like formations 0.5 m thick	1.00E-05	1.00E-06	31	24	2.5	0.0
13	Loess and loess-like formations 1.5 m thick	1.00E-05	1.00E-06	31	24	2.5	0.0
14	Clayey loess and loess-like formations	1.00E-06	1.00E-07	30	24	3.0	0.0
15	Clayey silts	5.00E-07	5.00E-08	29	22	2.5	0.0
16	Common silts	5.00E-06	5.00E-07	30	23	1.5	0.0
17	Light loamy sands	1.00E-05	1.00E-06	32	24	1.0	0.0
18	Heavy loamy sands	1.00E-06	1.00E-07	31	24	1.5	0.0

Knowledge about the values of effective strength parameters of soils in our country is greatly limited, it is often because a direct shear test is mainly used to determine strength parameters, which are then considered as total parameters. Thus the strength parameters of distinguished soil complexes were assumed arbitrarily, mainly basing on the foreign literature (Iverson 2000; Cornforth 2005; Brandon et al. 2006; Rahardjo et al. 2010) at the same time assuming that these soils are mostly unconsolidated and their cohesion can be close to zero. In case of soils in located in forests and bushy areas the values of cohesion were increased up to 3 kPa. This range corresponds with minimal values of cohesion of roots systems presented in Schmidt et al. publication (2001).

A significant influence on the slopes equilibrium conditions has the rainfall, which infiltrates and causes changes in stress state and as a result contributes to decrease in stability. For purposes of this analysis it was assumed that rainfall intensity is 50 mm per day ($5.8 \cdot 10^{-7}$ m/s).

Information from SOPO base concerning the localization of landslides from weathered material at the area of Nowy Wiśnicz commune was used to verify the results.

MODELING RESULTS AND THEIR ANALYSIS

The results of stability modeling using SINMAP are presented in Figure 2, which shows areas with different probability of mass movements occurring at the rainfall of 50 mm/d. Over half of the area of Nowy Wiśnicz commune (57.5%) was classified as stable, where Stability Index was higher than 1.5. About 80% of the commune was classified as the area with low or very low probability of landslide occurring. Stable areas are valley bottoms, ridges and slopes of inclination up to 7°. The most resistant to stability loss were the following soil complexes: common silts, clayey silts, clays and sandy clays, used as grasslands.

The creators of SINMAP model assumed that the value of Stability Index below 1.0 is for unstable areas with high or very high probability of mass movements. In relation to the Nowy Wiśnicz commune, areas with very high or high vulnerability to landslides formation are about 20% (2% and 18.3% of the analyzed area respectively). The most vulnerable to stability loss are slopes of inclination above 15° (4.4% of the whole area) and from 7° to 15° (14% of the commune area). In this context the most hazardous are the areas where the height differences are 4 m and more (6.3% of the commune area). The most vulnerable to stability loss are the following soil complexes: light loam, debris, loess and loess-like formations of different thickness.

Because of the exposure the highest probability of landslide formation is on the south and south-east slopes, which are considered to be potentially the most dry. Only 10% of these slopes is in danger of landslide occurring. About 25% of

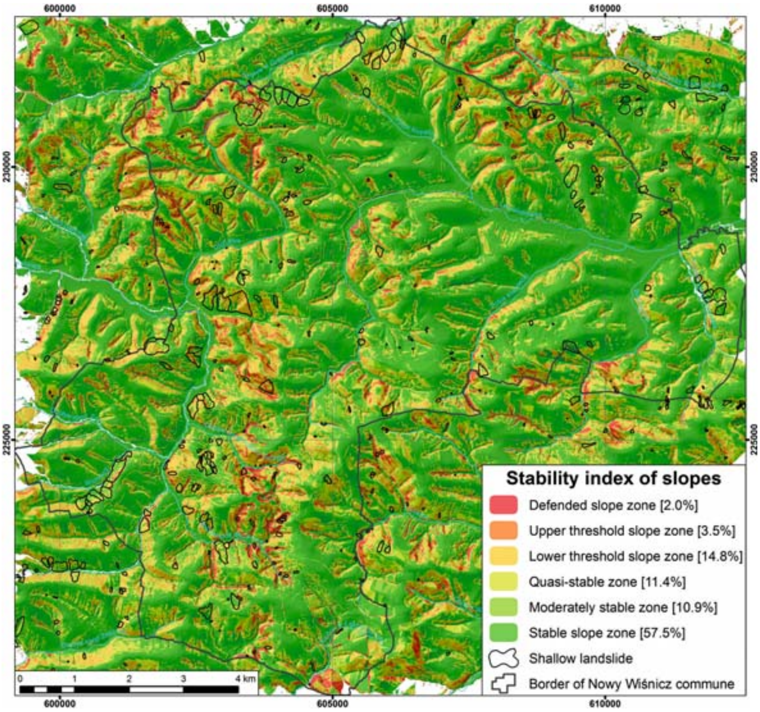

Fig. 2. Values of Stability Indexes for the area of Nowy Wiśnicz commune at the rainfall of 50 mm/d

north and north-west slopes has high or very high probability of landslide formation.

A detailed analysis of relations between chosen geomorphologic factors and vulnerability to mass movements was presented in Table 3 and Figure 3.

Based on SINMAP model assumptions and input data it can be stated that slope stability conditions in this model are the result of strength and hydraulic parameters of slope covers and slopes angle. In stability analysis the hydraulic conductivity is expressed by the value of soil saturation. Modeling results of the level and spatial image of full saturation of soils in Nowy Wiśnicz commune at the rainfall of 50 mm/d and 5 mm/d were practically the same. It means that the influence of soils hydraulic conductivity on slope stability is very similar in the whole area, thus it can be omitted in further analysis. Thereby the values of angle of internal friction and cohesion of each soil complex have the biggest influence on stability index. The highest probability of stability loss concerns the light loam complexes located in forests and bushy areas. Geotechnical parameters of this soil in comparison to the others have intermediate values and a negative influence of land inclination (above 15º) additionally had some influence here.

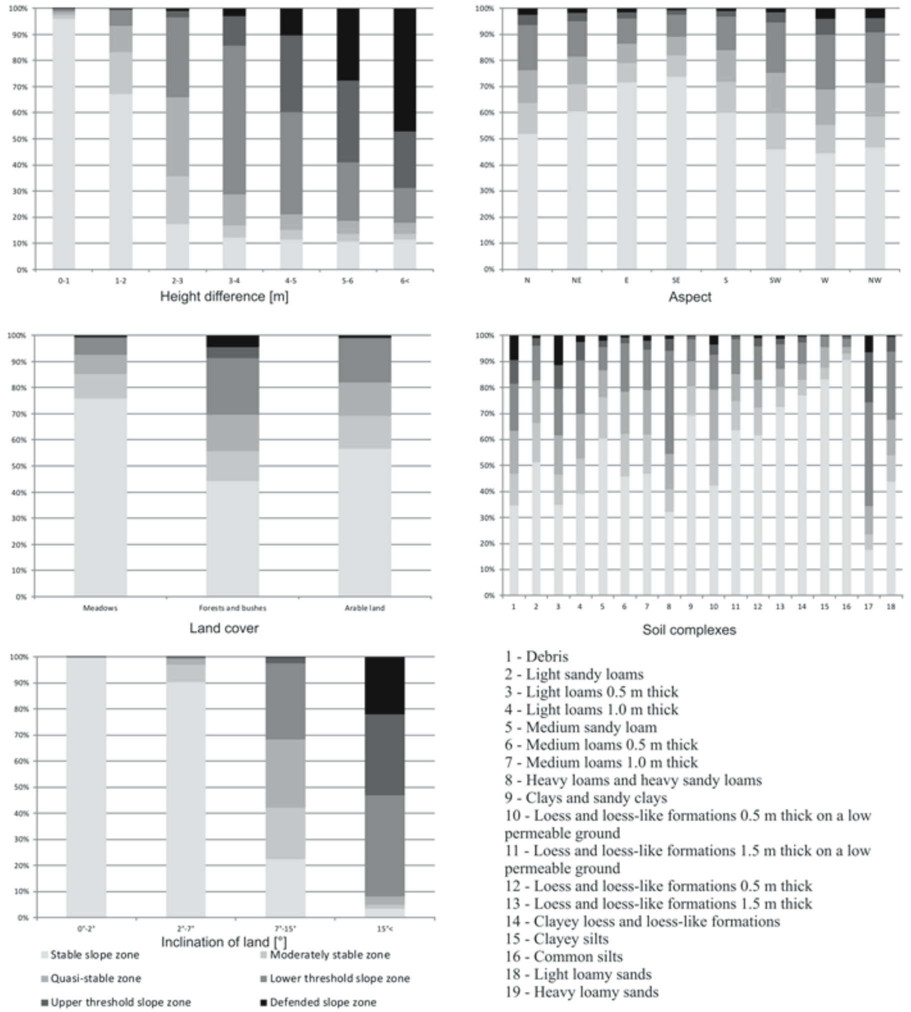

Fig. 3. Percentage variation of classes of vulnerability to mass movements in relation to: height difference, exposure, land use, inclination (supplement to Table 3)

A significant influence on the value of stability index had also land inclination, what can be noticed by comparing data showed on Figure 1B and 2. The diversity of stability index values in relation to inclination was presented collectively in Table 3. These data show that the areas with inclination above 15° are the most threatened with mass movements, areas with inclination of 7–15° are threatened to a small extent and areas with inclination below 7° can be considered as safe (SI>1.0).

Comparing the modeling results with information from SOPO base and with field observations of landslides, the authors stated that they are to a great extent convergent, what proves good accuracy of the physical model for the process of stability loss used in SINMAP. In case of landslide processes in Nowy Wiśnicz commune the efficiency of the model was evaluated at 90%. Among 262 landslides formed within the slope covers in the commune, 88 are in defended slope zone, 87 in the upper threshold slope zone, 67 in the lower threshold slope zone, 9 in the quasi-stable area, 7 are in the moderately stable zone and only 4 in stable slope zone.

While comparing observation and modeling results, it can be noticed that they are different. These divergences concern mostly landslides located in the vicinity of river beds, where side erosion is a significant factor conducive to mass movements activation. According to Thiel (1989), this process is one of the most important factor inducing earth movements in the area. Another factor that has the influence on modeling results is also limited information concerning lithology of the surface layers. Data obtained from IUNG in Puławy concern basically soil formations to the depth of 1.5 m. They are difficult to interpret for specialists of geotechnics or engineering geology and, as showed the results of research on a number of landslides which were carried out by the authors, these data are not always consistent with the reality. The results of calculation of a degree of wetness of a soil profile were interesting, they showed that at the rainfall of 50 mm/d a significant part of the profile is saturated. These results might seem controversial, but observations of Carpathian slopes during heavy rainfall show that seepages are relatively common.

CONCLUSIONS

Results of modeling of slopes equilibrium using SINMAP model at the area of Nowy Wiśnicz commune showed that a significant part of the area is not threatened with surface mass movements. In general the areas that are vulnerable to mass movements are slopes which are 4 m or higher, at inclination above 7°. Calculations also showed that a significant factor directly influencing vulnerability to mass movements is in general low hydraulic conductivity of formations occurring in this area, what is conducive to saturation of soil profile. Calculations results showed that there is a relatively good conformity in indicating the areas threatened with mass movements with the localization of existing landslides, registered in SOPO base. Although, the results analysis and comparison of spatial data with field observations of chosen objects at the area of Nowy Wiśnicz commune showed that further field and laboratory tests in order to properly identify lithology and geotechnical characteristics of soils in slope covers are necessary to improve the description of the analyzed area.

Tab. 3. Percentage register of types of stability in relation to qualities of the area of Nowy Wiśnicz

Types of stability		**Stable slope zone**	**Moderately stable zone**	**Quasi-stable zone**	**Lower threshold slope zone**	**Upper threshold slope zone**	**Defended slope zone**	**Sum**
Soil complexes	Soils with strong skeleton (debris)	2.68	0.94	1.27	1.42	0.70	0.74	**7.7**
	Light sandy loams	0.25	0.07	0.08	0.07	0.02	0.00	**0.5**
	Light loams 0.5 m thick	1.36	0.45	0.59	0.69	0.36	0.45	**3.9**
	Light loams 1.0 m thick	0.83	0.29	0.36	0.43	0.15	0.05	**2.1**
	Medium sandy loam	0.24	0.06	0.04	0.04	0.01	0.01	**0.4**
	Medium loams 0.5 m thick	1.71	0.61	0.61	0.69	0.08	0.03	**3.7**
	Medium loams 1.0 m thick	1.69	0.55	0.62	0.57	0.12	0.07	**3.6**
	Heavy loams and heavy sandy loams	0.50	0.13	0.21	0.61	0.07	0.02	**1.5**
	Clays and sandy clays	0.26	0.04	0.04	0.03	0.00	0.00	**0.4**
	Loess and loess-like formations 0.5 m thick on a low permeable ground	0.54	0.22	0.25	0.17	0.05	0.04	**1.3**
	Loess and loess-like formations 1.5 m thick on a low permeable ground	27.63	4.87	4.54	5.77	0.59	0.08	**43.5**
	Loess and loess-like formations 0.5 m thick	9.37	1.62	1.61	1.96	0.47	0.17	**15.2**
	Loess and loess-like formations 1.5 m thick	3.95	0.42	0.38	0.51	0.13	0.07	**5.5**
	Clayey loess and loess-like formations	1.44	0.11	0.12	0.15	0.04	0.01	**1.9**
	Clayey silts	0.59	0.03	0.05	0.03	0.00	0.00	**0.7**
	Common silts	3.16	0.09	0.09	0.11	0.03	0.01	**3.5**
	Light loamy sands	0.49	0.17	0.31	1.13	0.54	0.18	**2.8**
	Heavy loamy sands	0.76	0.17	0.24	0.46	0.10	0.01	**1.7**

Table 3. cont.

Inclination of land [°]	0°-2°	6.99	0.01	0.01	0.00	0.00	0.00	**7.0**
	2°-7°	41.46	3.09	1.07	0.31	0.01	0.00	**45.9**
	7°-15°	8.74	7.65	10.07	11.30	0.88	0.14	**38.8**
	15°<	0.28	0.13	0.26	3.22	2.57	1.82	**8.3**
Aspect	N	8.37	1.90	2.03	2.78	0.65	0.40	**16.1**
	NE	8.96	1.56	1.55	2.02	0.49	0.27	**14.8**
	E	7.78	0.81	0.81	1.07	0.27	0.16	**10.9**
	SE	9.06	1.01	0.89	1.03	0.20	0.11	**12.3**
	S	9.55	1.92	1.91	2.05	0.35	0.16	**15.9**
	SW	5.75	1.71	1.96	2.39	0.49	0.19	**12.5**
	W	3.44	0.84	1.03	1.62	0.48	0.31	**7.7**
	NW	4.53	1.13	1.25	1.89	0.53	0.36	**9.7**
Land cover	Meadows	24.83	3.09	2.47	2.12	0.41	0.15	**33.1**
	Forests and bushes	16.22	4.13	5.19	7.89	2.42	1.60	**37.5**
	Arable lands	16.40	3.65	3.76	4.83	0.63	0.20	**29.5**
Height difference [m]	0-1	25.36	0.40	0.29	0.29	0.05	0.03	**26.4**
	1-2	27.17	6.51	4.14	2.32	0.25	0.10	**40.5**
	2-3	3.24	3.41	5.70	5.75	0.47	0.18	**18.7**
	3-4	0.98	0.36	0.94	4.58	0.89	0.25	**8.0**
	4-5	0.41	0.12	0.22	1.38	1.04	0.37	**3.5**
	5-6	0.16	0.04	0.07	0.34	0.48	0.42	**1.5**
	6<	0.15	0.03	0.05	0.17	0.28	0.61	**1.3**
SUM		**57.5**	**10.9**	**11.4**	**14.8**	**3.5**	**2.0**	**100**
Probability of landslide formation		**Low**			**High**		**Very high**	

The applied model allows to determine of the rainfall intensity influence on the equilibrium conditions of slopes, taking geotechnical parameters of soil and topography into account. However, it does not allow to simulate changes in stability conditions in real time. Despite this disadvantage the model can be considered as a preliminary tool for indicating areas predisposed to surface mass movements.

While analyzing the simulation results, keep in mind that SINMAP model applies only to surface mass movements, occurring mainly as mud flows, debris-mud flows or shallow landslides within slope covers. This model cannot be used for stability analysis of deeper slope layers, where geological and engineering conditions are more complicated.

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STRESZCZENIE

W pracy przestawiono wyniki modelowania podatności powierzchniowych warstw zboczy na ruchy masowe na terenie gminy Nowy Wiśnicz znajdującej się w obszarze Pogórza Wiśnickiego. Do analiz wykorzystano model SINMAP, który integruje obliczenia hydrologiczne przepływu śródglebowego oraz obliczenia stateczności. Modelowanie przeprowadzono, wykorzystując numeryczny model terenu w postaci rysunku rastrowego o rozdzielczości 10x10 m oraz mapę kompleksów glebowych wydzielonych na podstawie map glebowo-rolniczych w skali 1:25 000.

Modelowanie stateczności zboczy obszaru gminy Nowy Wiśnicz przeprowadzono przy opadach 50 mm w ciągu doby. Przy tych warunkach opadowych ponad połowa obszaru gminy Nowy Wiśnicz (57,5%) zaklasyfikowana została jako stabilna, gdzie wartość współczynnika stateczności (SI) jest wyższa od 1,5. Około 80% terenu gminy zostało ocenione jako obszar o małym lub bardzo małym prawdopodobieństwie powstania osuwisk.

W skali całego obszaru badań obszary o bardzo dużej i dużej podatności na powstawanie osuwisk stanowią około 20% obszaru gminy (odpowiednio 2% i 18,3% obszaru poddanego analizie). Są to stoki o nachyleniu powyżej 15° , pokryte glinami lekkimi, grunty mocno szkieletowe, lessy i utwory lessowate o różnej miąższości. Skuteczność modelu w przypadku badań procesów osuwiskowych gminy Nowy Wiśnicz oceniono na poziomie 90%.