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APPLICATION OF SINMAP TERRAIN STABILITY MODEL TO GRODARZ STREAM WATERSHED

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ABSTRACT

The article presents research results on slope stability mapping using SINMAP model on loess upland area of Nałęczów Plateau in eastern Poland.
The SINMAP approach applies to shallow transitional landsliding phenomena controlled by shallow groundwater flow convergence. The SINMAP theory does not require numerically precise input and accepts ranges of values representing their uncertainty.
Output stability indices, presented in the analysis should not be interpreted as numerically precise but most appropriately in terms of relative hazard. SINMAP can be used for forest planning and management, forest engineering, and other geohazard studies.

Key words: SINMAP model, slope stability, upland watershed, loess terrain.

INTRODUCTION

Processes of terrain surface destruction, so-called mass movements, caused by a disturbance in equilibrium between slope stabilizing and destabilizing forces, are not only the most destructive erosion processes but also the most difficult to control. The Polish classification system distinguishes six types of mass movements [2]: peel-off, sliding, creep, soil-fluxion, out-dropping and settlement.

The most frequently observed types of mass movements in Poland are forms of landslides of different depth and range, as well as forms accompanying soil-fluxion processes (so-called soil-fluxion tongues) [2]. A country-wide reconnaissance revealed about 2000 landslides and numerous soil-fluxion forms. Due to economical losses and a threat to population posed by this type of erosion, a great necessity and urgency to work out risk assessment and treatment methods is registered.

Many approaches to assess slope stability and landslide hazards [4, 5] can be adopted. They usually rely on studies or surveys such as qualitative field inspections and future instability patterns forecasts for similar conditions, multivariate analysis of factors characterizing observed sites of slope instability, classification related stability according to criteria such as slope, geologic structure, and failure probability analysis supported by slope stability models with stochastic hydrologic simulations. None of those methods, however, employs to full extend the fact that the occurrence of debris flow source areas is strongly dependent on surface topography through accumulation of shallow subsurface flow, increased soil saturation, increased pore pressure and shear strength reduction [4, 5].

Recently, growing availability of GIS (Geographic Information System) systems and popularity of data in form of Digital Elevation Models (DEM), along with tools for their processing and analysing, collecting terrain topography data that are essential for slope stability analysis purposes, has became considerably easier and less time-consuming. Possibility of integrating spatial data into GIS systems and their subsequent universal analyses allows to extent analysis to practically unlimited range of considered variables.

A SINMAP model is one of digital models which describe terrain stability implemented GIS environment. Its application is limited to shallow transitional debris slides. Theoretical basis of the model is the relation between an infinite slope stability and a steady-state hydrological model represented by a parameter of topographical wetness index [4, 5]

CHARACTERISTICS OF SINMAP MODEL

Software

The SINMAP model is distributed as a free extension of ESRI ArcView© GIS (version 3.0a or later) with a Spatial Analyst© extension installed (version 1.0 or later). Installation files can be downloaded at no cost from www.engineering.usu.edu/dtarb/. SINMAP extension installation procedure is similar to others ArcView© extensions, and requires a user to copy sinmap.avx and sinmap.dll files to EXT32 and BIN32 directories in ArcView© home directory, respectively. After loading the extension to ArcView© project through ArcView© File/Extensions menu, SINMAP adds a new menu element to the ArcView© GUI named SinMap as well as two other tool buttons. The model includes also additional tools for spatial operations on raster data.

Input data

The model requires three groups of input data:

1. terrain topography in a DEM grid format;
2. soil mechanical and hydraulic properties in a grid or polygon vector format;
3. landslide source areas inventory in a point vector format.

Topographic data in DEM format are preprocessed by a built-in pit-filling module. The next step is to compute the required topographic parameters, such as slope and specific catchment area.

The model requires the following soil properties data:

- range of cohesion values;
- soil density value;
- range of internal friction angle values;
- range of R/T ratio.

For calibration purposes the landslides inventory map is needed, obtained from aerial or satellite orthophotos.

Output data

The modelling results are presented in a form of the following maps:

- stability probability expressed as stability index divided into six classes;
- topographic wetness index divided into five classes;
- graph of landslide occurrence in fields of slope and specific catchment area;
- summary table.

By adopting suitable ranges for variables it is possible to calibrate and group the majority of observed landslides into the smallest SI classes (tab. 1).

Table 1. The definition of slope stability index SI classes.

SI value	Predicted state	Possible influence of factors not modeled
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 slope zone	Minor destabilizing 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 may be responsible for stability
0.0>SI	Defended slope zone	Stabilizing factors are required for stability

Limitations of the model [4, 5]

1. The model is designed to simulate only shallow transitional landslides initiation zones controlled by shallow subsurface flow;
2. It is not applicable to deep-seated instability zones;
3. It simulates landslides potential initiation zones, not hazard areas;
4. Spatial accuracy is strongly dependent on DEM resolution.

CHARACTERISTICS OF THE STUDIED AREA

All the spatial information on the area of Grodarz watershed was collected by various digitalisation and data analysis methods and integrated into the Digital Watershed Model stored in GIS database in UTM projection. The Digital Watershed Model structure is designed for erosion assessment purposes and land use structure analysis. Some of the statistical data and analytical results are presented below.

Physiography

Grodarz stream watershed (28.6 km^2) is located at the convergence of three physiographical regions: the Nałęczów Plateau, the Bełżycka Plain and the Małopolska Vistula Gorge [3]. Geographical diversity of the region is reflected in the topography and lithology of the watershed area. Its central part, located on the Bełżycka

Plain, is characterized by a relatively flat relief and sandy-loamy soil mantle, while northern and southern edges, situated on deep loess soils exhibit very reach relief with a very dense (up to 11 km/km^2) net of valley- and road-gullies.

Lithology

The soils in the studied area are predominantly deep (15-30 m) fine granular eoglacial silts and moderately deep clayey sands, both overlaying calcareous bedrock (fig. 2) [3].

Land use

The land use information was obtained through supervised classification in the ERDAS Imagine© v. 8.4. using 1:25000 aerial orthophotos with spatial resolution of 1m (Fig.3). The land use structure of the studied area is strongly dependent on the terrain topography. The majority of gullies, especially valley-gullies, and steep slope areas are covered by anti-erosion land use types: forests, orchards and grasslands, but some part of the area is still used as an arable land, characterized by an unfavourable arrangement of plots and rural roads. Such a defective arrangement shapes the overland flow, causing erosion rates to increase and potential terrain stability failures to occur, especially in the snow-melting season.

Appearance of mass movements

The soil mantle with majority of strong cohesive soils that overlay steep slopes keeps the terrain of the study area relatively stable. Only one relatively shallow (5 m) landslide (Photo.1) has been found. In the recent years, no soil-fluxion accompanying forms have been observed, though, soil-fluxion can be activated in thaw seasons.

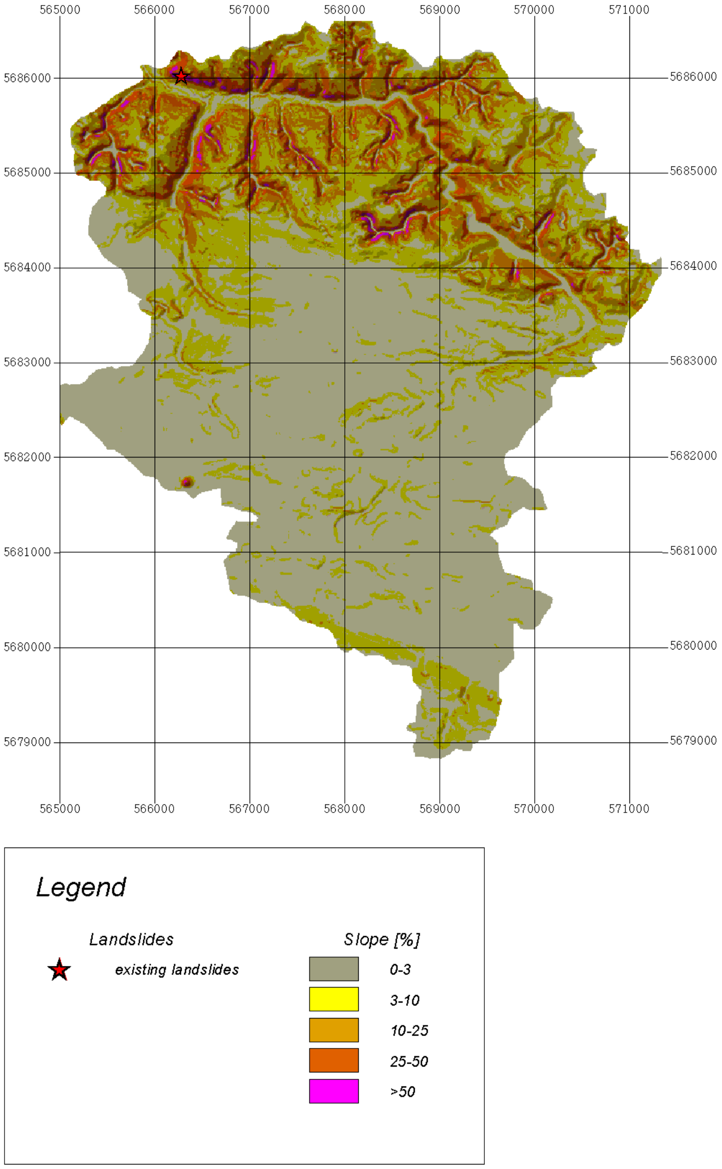
Photograph 1. The existing landslide in the Grodarz stream watershed

MODEL INPUT PARAMETERS

DEM

The DEM grid, used as an input relief data, has a spatial resolution of 10 m. It was obtained by interpolating the contours from a topographic map (scale 1:10000) by means of the TOPOGRID method in ESRI ARC/INFO© v. 7.2.1 [1]. The map of the terrain slope, obtained from DEM, is shown in figure 1.

Figure 1. The map of terrain slope in Grodarz stream watershed



Soil properties

The soil information layer, stored in a vector format (Fig.2), was digitalized from a 1:25000 scale soil map obtained from the Institute of Soil Science and Plant Cultivation in Puławy and based on the literature [6, 7]. The soil C (dimensionless cohesion) parameter was dedifferentiated to two cases: the case of landsliding modelling, where the soil depth was assumed to 5 m, and the case of soil-fluxion with the soil depth equal to freezing depth of 1.1 m, characteristic for the area of Lublin Upland. In the second case C_{min} was assumed to $C_{min}=0$, which considers cohesionless conditions representing a liquid state of the soil.

Detailed soil input parameters are shown in table 2.

Figure 2. The map of soil cover in Grodarz stream watershed

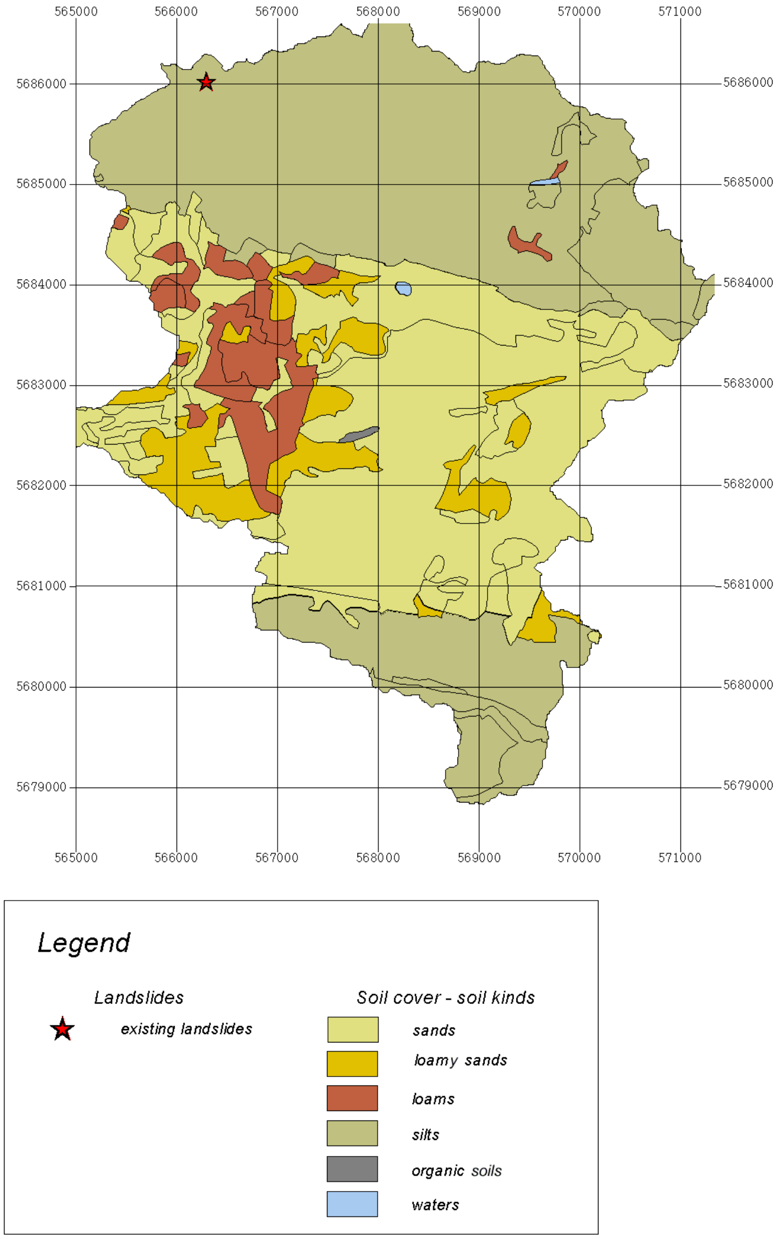


Figure 3. The map of land use structure in Grodarz stream watershed

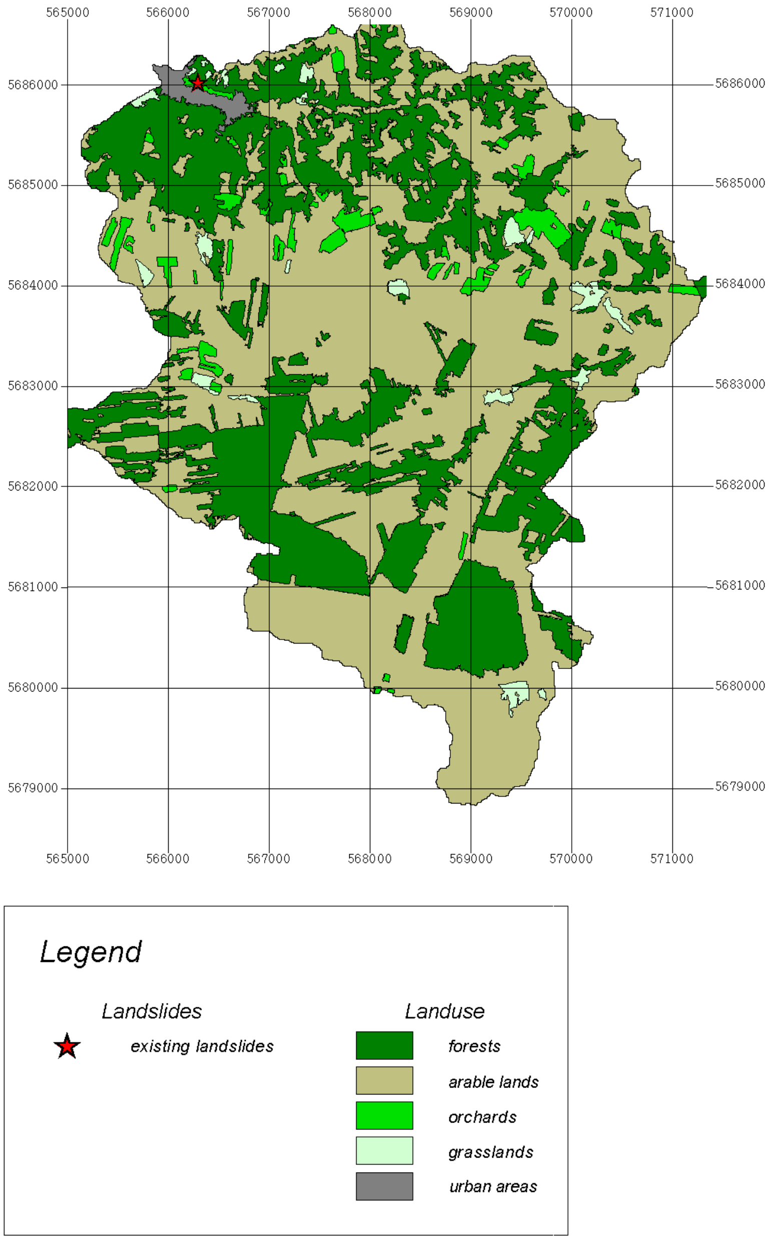


Table 2. The input parameter values for Sinmap simulation in Grodarz watershed for the landsliding case

Soil class	Land use	Bulk density	Combined soil and root cohesion[*]		Soil friction angle[#]		Hydraulic conductivity[##]		Hydraulic transmissivity		Effective recharge rate		T/R	
			Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
		rho_s	C		phi		H		T		R			
		$kg*m^{-3}$	Pa	Pa	deg	deg	$m*h^{-1}$	$m*h^{-1}$	m^2*h^{-1}	m^2*h^{-1}	$m*h^{-1}$	$m*h^{-1}$	m	m
Loam	Forests	1570	30	35	30	35	0.000	0.417	0.000	2.085	0.028	0.0400	0.00	74.46
Loam	Orchards	1570	20	25	30	35	0.000	0.417	0.000	2.085	0.032	0.0400	0.00	65.16
Loam	Grass lands	1570	30	35	30	35	0.000	0.417	0.000	2.085	0.032	0.0400	0.00	65.16
Loam	Farm lands	1570	20	25	30	35	0.000	0.417	0.000	2.085	0.036	0.0400	0.00	57.92
Organic	Forests	1200	18	22	18	22	0.000	0.833	0.000	4.165	0.028	0.0400	0.00	148.75
Organic	Farm lands	1200	18	22	18	22	0.000	0.833	0.000	4.165	0.036	0.0400	0.00	115.69
Fine sand	Forests	1350	0	0	32	39	0.833	4.170	4.165	20.85	0.028	0.0400	103.75	744.64
Fine sand	Orchards	1430	15	19	25	30	0.833	4.170	4.165	20.85	0.032	0.0400	103.75	651.56
Fine sand	Grass lands	1430	8	15	30	45	0.833	4.170	4.165	20.85	0.032	0.0400	103.75	651.56
Fine sand	Farm lands	1350	0	0	32	39	0.833	4.170	4.165	20.85	0.036	0.0400	103.75	579.17
Loamy sand	Forests	1350	0	10	20	25	0.083	0.833	0.417	4.165	0.028	0.0400	10.43	148.75
Loamy sand	Orchards	1430	17	22	20	25	0.083	0.833	0.417	4.165	0.032	0.0400	10.43	130.16
Loamy sand	Grass lands	1430	17	22	20	25	0.083	0.833	0.417	4.165	0.032	0.0400	10.43	130.16
Loamy sand	Farm lands	1350	0	10	20	25	0.083	0.833	0.417	4.165	0.036	0.0400	10.43	115.69
Silt	Forests	1470	15	22	20	28	0.083	0.833	0.417	4.165	0.028	0.0400	10.43	148.75
Silt	Orchards	1220	15	15	18	23	0.083	0.833	0.417	4.165	0.032	0.0400	10.43	130.16
Silt	Grass lands	1470	15	22	20	28	0.083	0.833	0.417	4.165	0.032	0.0400	10.43	130.16
Silt	Farm lands	1470	15	22	20	28	0.083	0.833	0.417	4.165	0.036	0.0400	10.43	115.69
Silt	Close buildings	1470	15	22	20	28	0.083	0.833	0.417	4.165	0.001	0.0400	10.43	4165.00

[#] - Wiłun. 1987; [##] - Zawadzki. 1995.

Climate characteristics

The characteristics of climatic conditions represented by an effective recharge parameter (R) for precipitation and a corresponding snow-melting scenario for an average intensity of 40mm/h and 1h duration time, reduced to the effective precipitation with reference to specific land use types [2] are shown in table 2.

Inventory of mass movement forms

The landslide inventory data were collected from 1:25000 scale, 1 m resolution aerial orthophoto maps and the terrain inventory data. Field inspections revealed only one moderately deep (4-5 m) landslide form. Many forms of small-scale mass movements located in gullies were found, but the resolution of the DEM (10 m) was not good enough for simulations. There are historical records describing occurrence of soil-fluxion forms in Grodarz watershed, but none of those forms has been observed in recent decades, possibly due to the land use changes leading to afforestation of steep slopes.

MODELLING RESULTS

The results of landsliding modelling confirmed the interpretation of the existing phenomena under assumed recharge conditions. It is located between the saturated and lower threshold wetness index saturation zone (Fig.4, Fig.5) and lies completely within the defended slope zone (Fig.6, Fig.7). The slope-contributing area plot (Fig.8, Fig.9) confirms such an interpretation: few points are located in similar slope conditions, although the point representing the existing landslide has the largest contributing area. Similar stability conditions cover another 2 ha, whereas 2 654 ha (93%) of the watershed area remains absolutely stable (tab. 3).

Figure 4. Wetness index for the case of landsliding modeling

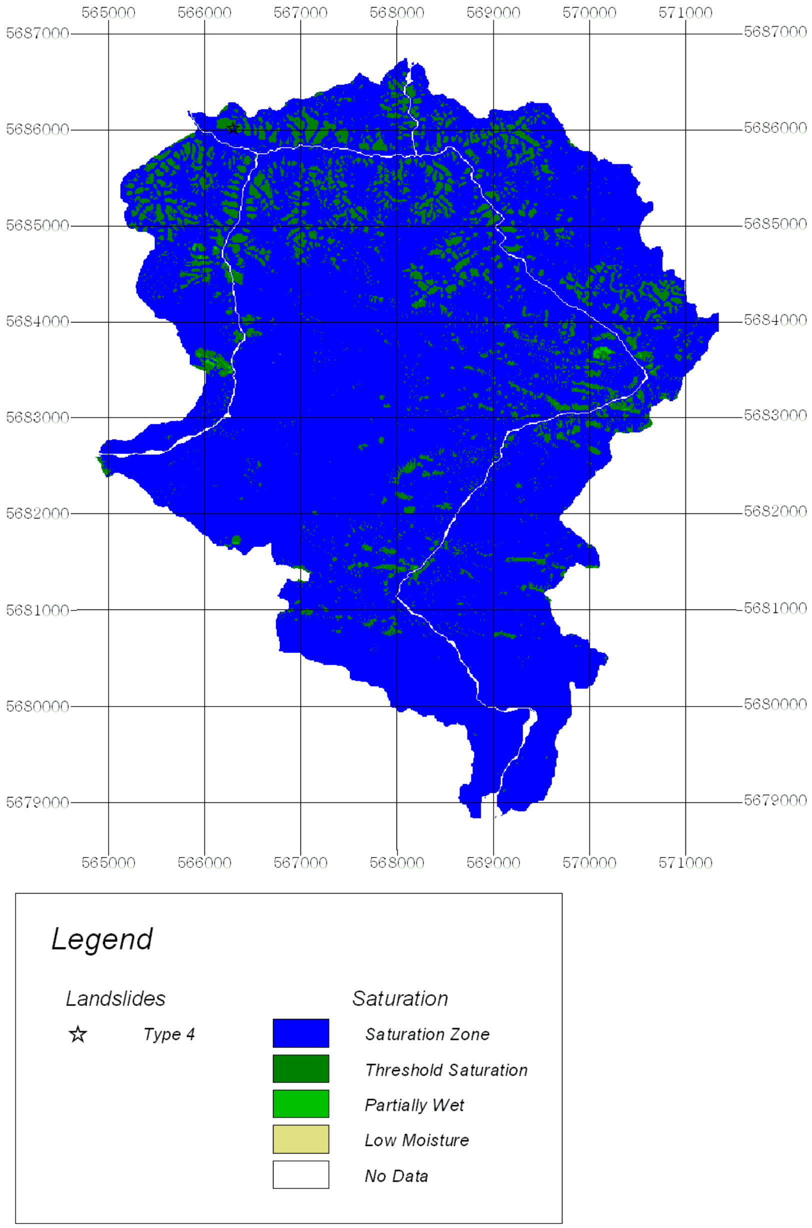


Figure 5. Detailed view on location of existing landslide within wetness index zones

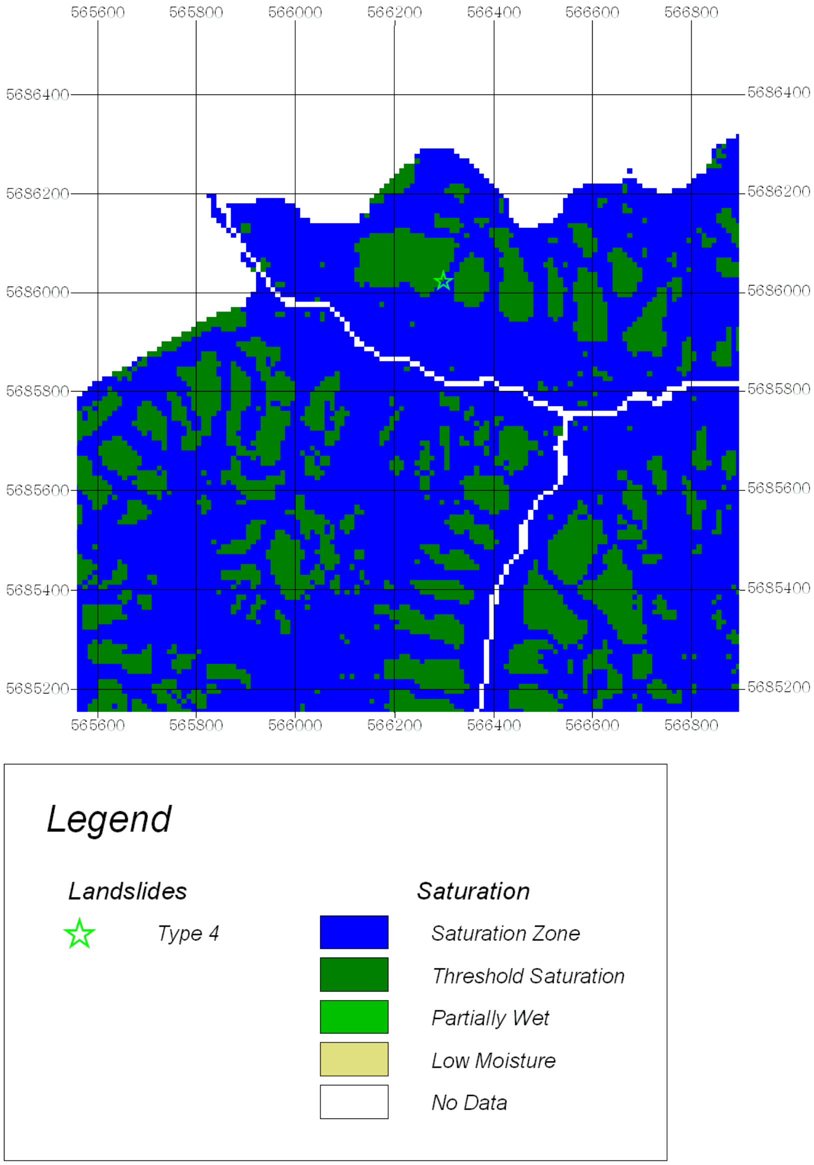


Figure 6. Stability index in the case of landsliding modeling

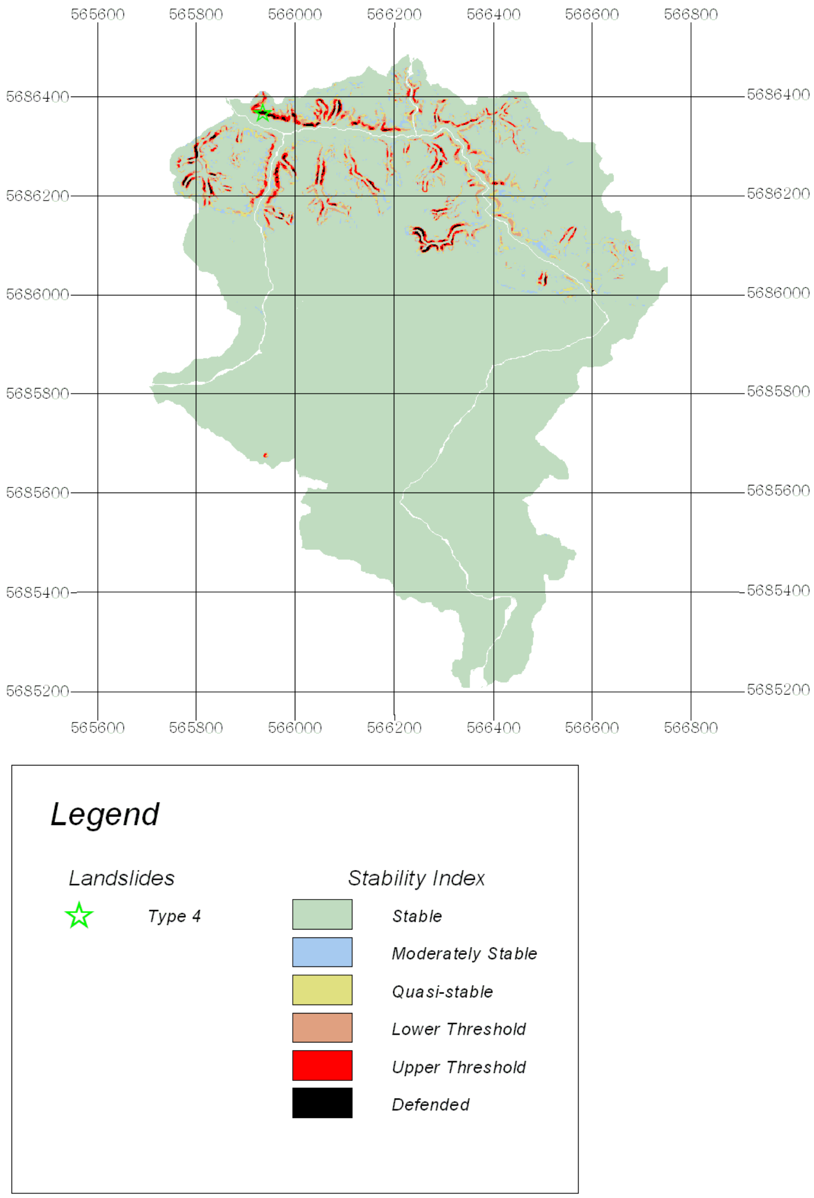


Figure 7. Detailed view on the location of existing landslide within stability index zones

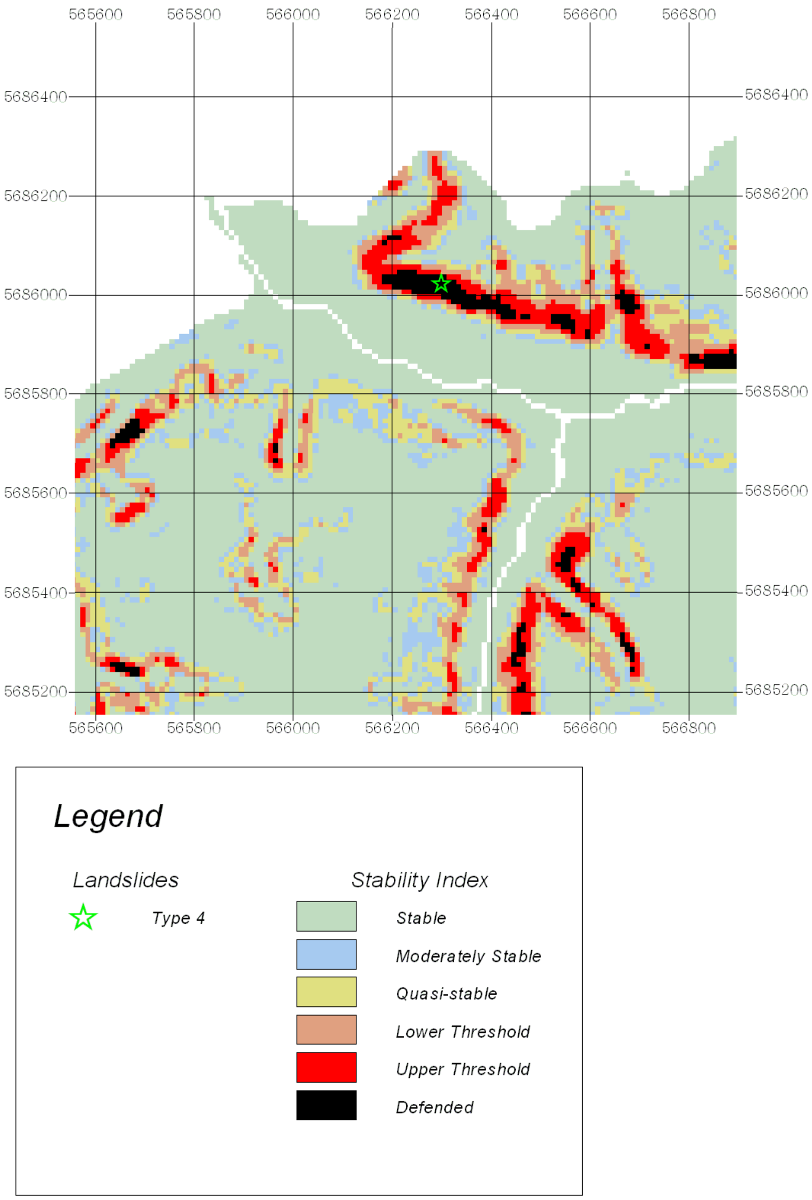


Figure 8. Slope-contributing area plot for the case of lansliding modeling (all calibration regions)

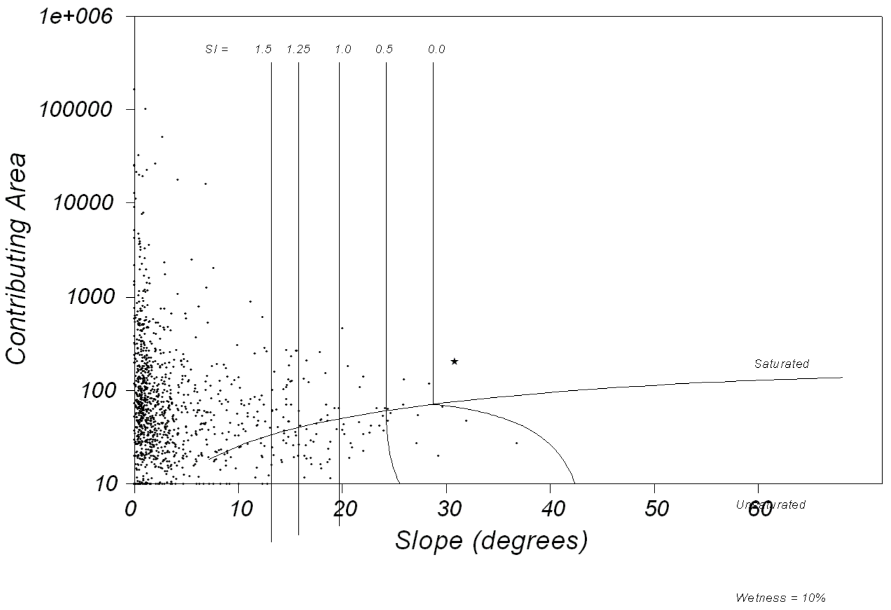


Figure 9. Detailed slope-contributinf area plot for the case of lansliding modeling (calibration region with existing landslide)

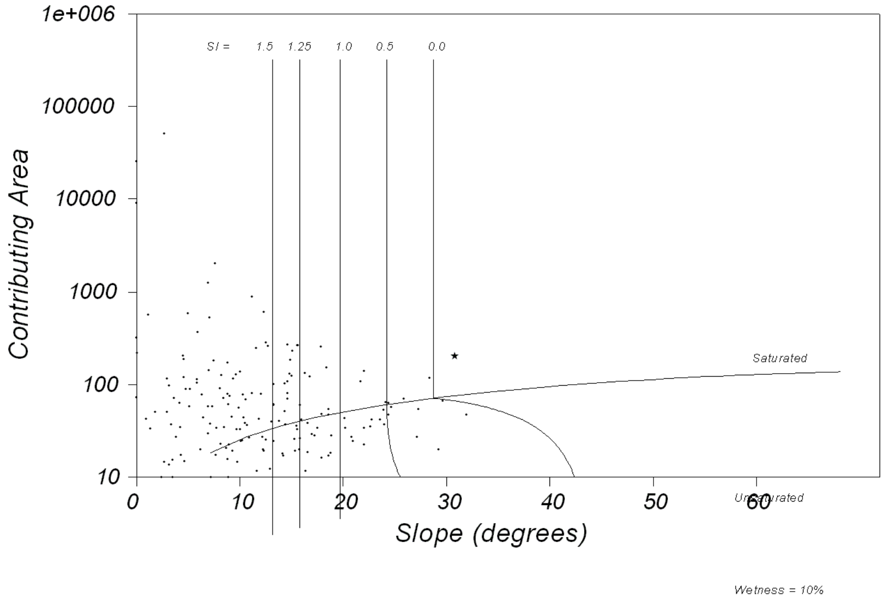


Table 3. Modeling results

The case of landsliding modeling						The case of soil fluxion modeling								
normal modeling procedure												additional afforestation analysis		
wetness index			stability index			wetness index			stability index			stability index		
range	area		range	area		range	area		range	area		range	area	
	ha	%					ha	%		ha	%		ha	%
0-0.1	0	0	<0	2	0	0-0.1	0	0	<0	0	0	<0	0	0
0.1-1.1	4	0	0-0.5	5	0	0.1-1.1	4	0	0-0.5	0	0	0-0.5	0	0
1.1-2.1	315	11	0.5-1	41	1	1.1-2.1	315	11	0.5-1	484	17	0.5-1	179	6
2.1-3.1	2541	89	1-1.25	69	2	2.1-3.1	2541	89	1-1.25	107	4	1-1.25	68	2
			1.25-1.5	89	3				1.25-1.5	83	3	1.25-1.5	57	2
			>1.5	2654	93				>1.5	2186	76	>1.5	2556	89

The modelling of soil fluxion, adjusted to specific conditions of snow melting (minimum cohesion equal to 0, unfrozen soil depth equal to 1.1 m), revealed the same spatial structure of wetness index zones, when compared to the landsliding modelling. Stability index values (Fig.10, Fig.11) are in this case much higher (Table 3). No zones were detected below 'lower threshold', although the share of SI classes below SI=1.25 is 5 times greater.

Figure 10. Stability index for the case of soil fluxion modeling

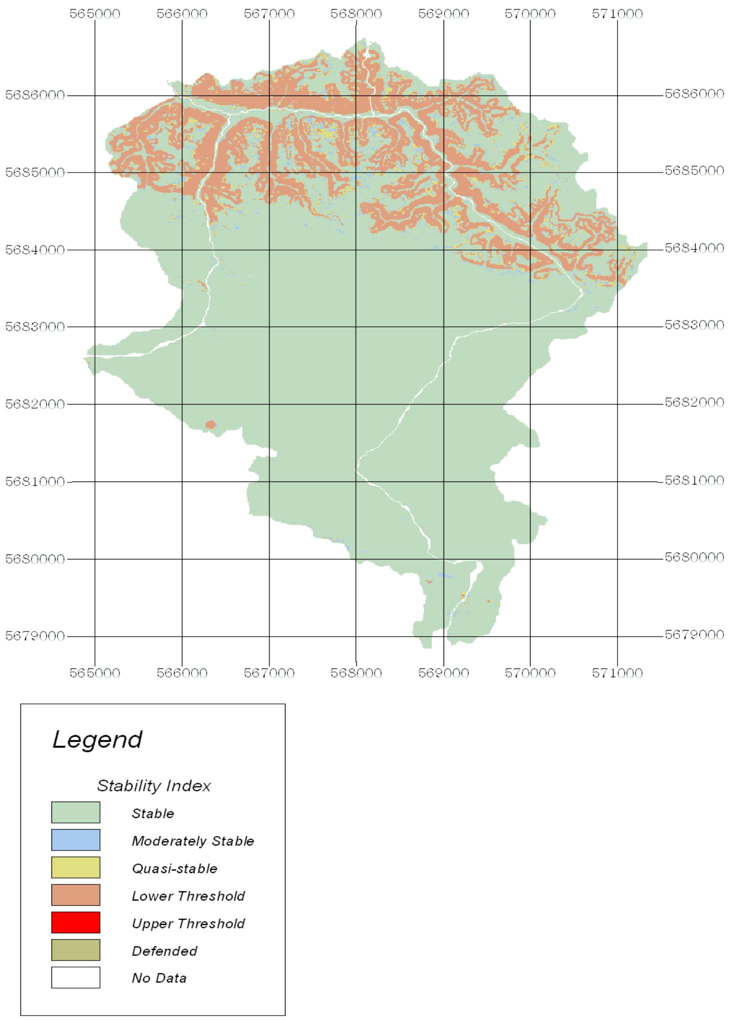


Figure 11. Slope-contributing area plot for the case of soil fluxion modeling

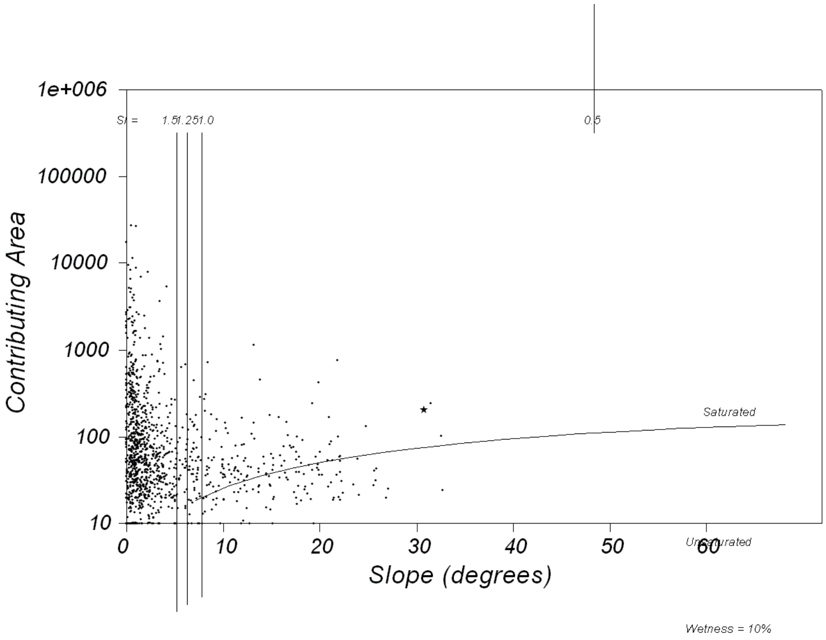


Figure 12. Stability index for the case of soil fluxion modeling transformed through the land use overlay analysis

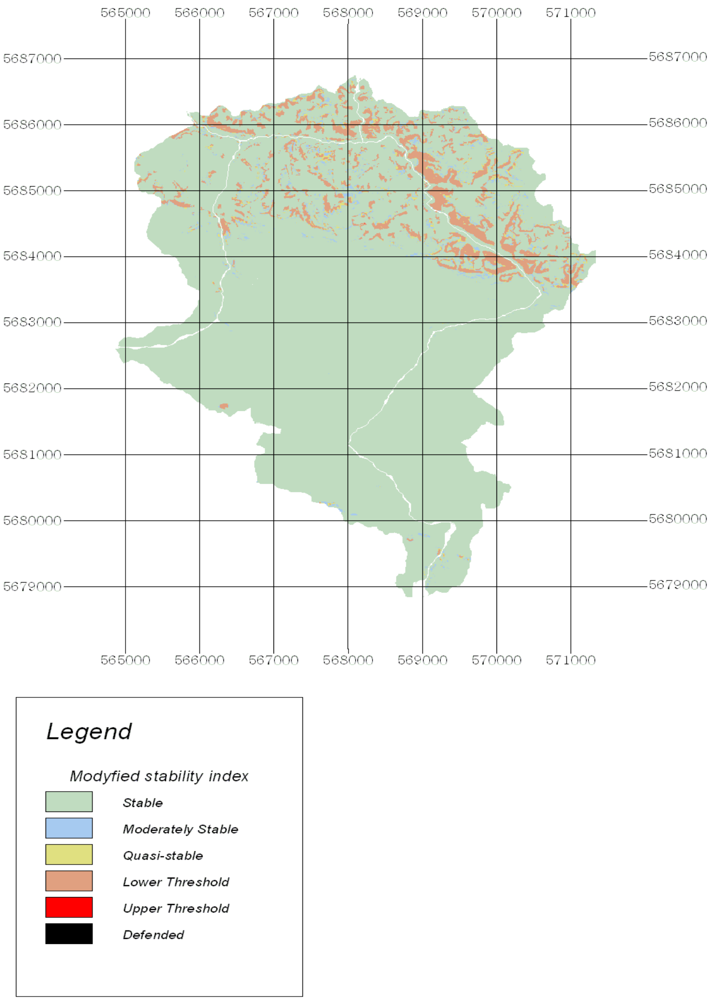
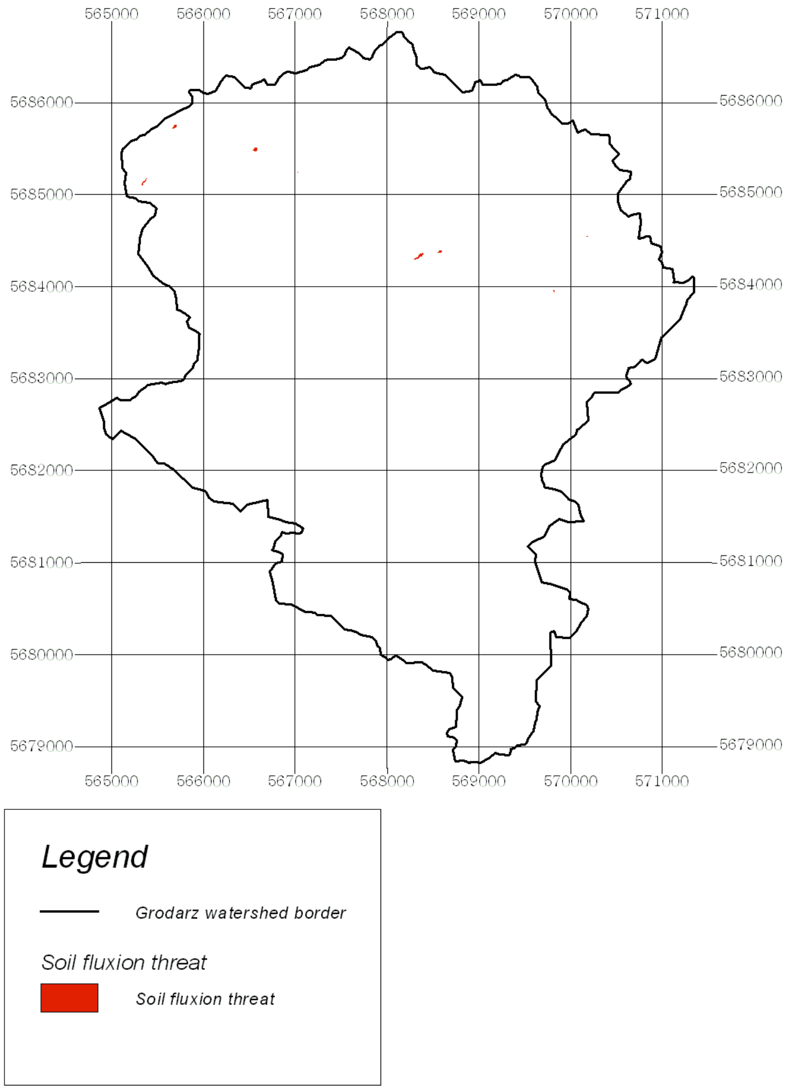


Figure 13. Descriptive analysis of soil fluxion threat



The resulting map of slope stability index in the adjusted snow-melting conditions was then improved by an additional analysis that considered a protective effect of forests and orchards (Fig.12). All slopes, covered by this land use types, were assumed stable [3]. It led to about 6% decrease in the area prone to soil fluxion.

Further descriptive analysis, based on terrain aspect and slope overlay [3] was made for comparison. The analysis assumes that the most soil fluxion susceptive terrains are characterized by a slope >30° and northern aspect. The results revealed only seven very small areas (maximum 1.2 ha) susceptive to soil fluxion (Fig.13).

DISCUSSION

The SINMAP model tested for two case scenarios, namely a moderately shallow (<5 m) landsliding and soil fluxion, within the area of Grodarz stream watershed proved to be useful in both scenarios.

The existing landslide was modelled correctly and no further model calibration was necessary. The modelled landslide phenomena is located within the most unstable slope-contributing area zone, characterized by the highest pore pressure while other areas, classified as ‘defended’ slope zones are afforested and probably therefore stable. The modelling results should be therefore treated as potential landsliding.

In case of modelling the soil fluxion phenomena, primarily not taken into consideration by the authors of SINMAP, the model revealed similar output quality, and again the modelling results should be treated as a potential reality, if the additional analysis of protective land use types is excluded from investigation. In case of soil fluxion phenomena, under assumed cohesionless soil conditions, such a stabilizing influence was of much greater importance when compared to landsliding. Therefore, it seems reasonable to conclude that modelling with SINMAP should be followed by an additional transformation that subtracts the areas of protective land use types from lower stability zones.

The SINMAP model provides more spatial and qualitative information about soil fluxion threats than any other descriptive method and unlike many it has firm physical bases.

REFERENCES

4. Hutchinson M. F., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. Journal of Hydrology: 106, 211-232
5. Józefaciuk Cz., Józefaciuk A., 1996. Mechanizm i wskazówki metodyczne badania procesów erozji. [Mechanism and methodology guidance for erosion processes research]. Biblioteka Monitoringu Środowiska, Warsaw, p: 150 [in Polish].
6. Józefaciuk Cz., Józefaciuk A., Nowocień E., Wawer R., Podolski B., 2002. Struktura przestrzenna i ilościowa zagrożenia użytków rolnych erozją wodną powierzchniową w zlewni potoku Grodarz na Płaskowyżu Nałęczowskim. [Spatial and quantitative structure of surface water erosion threat to arable lands in Grodarz stream catchment area located on Nałęczów Plateau]. Fragmenta Agronomica, 1 (73): 95-111 [in Polish].
7. Pack R. T., Tarboton D. G., Goodwin C. N., 1998a. Terrain Stability Mapping with SINMAP, technical description and users guide for version 1.00. Report Number 4114-0, Terratech Consulting Ltd., Salmon Arm, B.C., Canada, p: 75.
8. Pack R. T., Tarboton D. G., Goodwin C. N., 1998b. The SINMAP Approach to Terrain Stability Mapping. 8th Congress of the International Association of Engineering Geology, Vancouver, British Columbia, Canada 21-25 September 1998, p:7.
9. Wiłun Z., 1987. Zarys geotechniki [Geotechnics outlines]. Zarys geotechniki. Wyd. Kom. i Łącz., Warsaw, p: 723 [in Polish].
10. Zawadzki S., 1995. Gleboznawstwo [Pedology]. PWRiL, Warsaw, p:562 [in Polish]. s

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