S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN THE DIFFERENT REGIONS OF THE POLISH CARPATHIANS

Abstract. The Flysch Carpathians are mountains particularly susceptible to landslides. The type of land relief (deep incised valleys, slope inclinations), geological settings (complex of flysch rocks) and tectonics (tectonic dislocation, fault zones) are decisive (R ą c z k o w s k i, M r o z e k 2002). One of the methods used to prevent the adverse effects of mass movement is to make accurate maps of terrain that are predisposed to such processes. In this study, the author used the weight of evidence statistical method, which in the adopted scale (1 : 10,000) gives relatively good results. The importance of individual passive factors (predictors) in making a landslide susceptibility map varies in different parts of the Carpathians. In the foothills, where shallow landslides of weathered material are common, the relief, surface water, and land use are very significant. In the Beskids, lithology and tectonics are more significant. Landslide susceptibility maps should be a regular part of local development plans in Carpathian communities.

Keywords: the Polish Carpathians, landslide, susceptibility, flysch

INTRODUCTION

The large number of landslides in the Polish Carpathians, result in property damage and financial losses. Dealing with the consequences of landslides involves seeking low-cost solutions for preventing the damage from mass wasting. One effective and inexpensive method to reduce the adverse effects of landslides is to construct landslide susceptibility maps. This is a way to prevent or minimize losses associated with development on these slopes. Mapping areas threatened by potential mass movement may facilitate informed decisions about investment and permits for construction of residential homes on such terrain, reducing future losses. An equally important factor that can significantly reduce losses resulting from landslides is the awareness of people living in threatened areas. The public should be well informed about the danger as they are in other European Union (EU) countries, where the *Living With Natural Hazards* programme has been introduced (P o p r a w a, R ą c z k o w s k i 2003). This aspect is particularly important because local population, lacking detailed knowledge about landslides, can erase past disaster events from their memory.

In Poland, landslide susceptibility maps are still very rare. Despite huge material losses, the problem seems to be ignored in the Polish Carpathians. This situation lasted for decades until the extreme events of 1997 with precipitation-induced floods and landslide movements, increased the interest in this problem.

This paper focuses on the construction of landslide susceptibility maps for selected areas in the Polish Flysch Carpathians. The maps were based on a single research method and the same passive factors (predicates). The applicability of the chosen method in the Polish Carpathians was verified, followed by determining the most important predictors that influence landslide formation in particular areas.

LANDSLIDE SUSCEPTIBILITY IN THE POLISH CARPATHIANS

Most relevant techniques for determining landslide risk and indicating zones of landslide susceptibility involve geographic information system (GIS). GIS allows for a rapid analysis of cartographic materials and as well choosing methods adjusted to the goal, scale, and available data. The large number of studies conducted by many authors worldwide confirms that these methods can be applied in practice (C l e r i c i et al. 2002, R.J. P i k e et al. 2003, V a n W e s t e n et al. 2003, A y a l e w et al. 2004).

Landslide susceptibility has not been often studied in Poland. T. M r o z e k et al. (2004) used the analysis of the data from a few thematic layers to assess landslide susceptibility with the spatial prediction model. The method was applied to data collected in the research area of Bystrzanka–Biczyska, located in the Beskid Niski Mountains in the Polish Carpathians. The chosen area is characterized by a large number of landslides (29% of the examined area). Landslide susceptibility was assessed with the weight of evidence statistical method (B o n h a m-C a r t e r et al. 1989) in which the prediction of a new event (landslide) is deduced from already known passive factors controlling mass movements. The subsequently prepared landslide susceptibility map is the result of the influence of the analyzed factors (landslides, lithology, tectonics, relief, and land use).

T. M r o z e k (2008) conducted a wider research on risk assessment and the risk of landslide occurrence in the Bystrzanka catchment area. Apart from the aforementioned analysis of landslide susceptibility, the author assessed landslide hazard and the associated risks that occur in the examined area of the flysch Carpathians, using statistical methods and GIS techniques. To make the maps, two statistical methods belonging to two-dimensional and multidimensional groups were used; the obtained results were used to make a cross-verification. The applied methods showed the connection between the occurrence of a landslide and factors such as distance from a tectonic dislocation line, slope aspect, slope inclination, and land use. The obtained results confirm the usefulness of the statistical methods and GIS techniques for determining landslide susceptibility and landslide risk analysis in small catchments In addition, the applied research procedure allows the results to be used in planning processes.

M. Kamiński (2007) applied a different method to make a landslide susceptibility map for a chosen area in the Jodłówka region of the Dynów Foothills. The index method was used for estimating landslide classes thematic maps. The analysis was based on the maps of active landslides in the examined area, a geological map, and a map of terrain inclination and slope aspect. Increased landslide susceptibility was associated with slopes with a northern aspect and inclinations of 7–15° and 15–22°, covered with diluvium deposits.

M. Długosz (2009) made an assessment of landslide susceptibility in the Polish flysch Carpathians. The analysis for structural landslides was based on two passive factors: lithology and terrain inclination. The applied method was a simple index method assigning a landslide susceptibility factor to the particular passive factor classes. The valuation, was based on the literature (Bober 1984, Zabuski et al. 1999), showed that landslide susceptible- or or very susceptible areas, occupy more than 7000 km^2, that is, 36% of the entire area of the Polish Carpathians. This includes regions underlain by flysch rocks, susceptible to sliding and with a sandstone, shale-sandstone or shale lithological structure; and slope gradient ranging between 9° and 14° and between 15° and 25°. Because of the scope of the research, the final landslide susceptibility map should be regarded only as illustrative material.

STUDY AREA

The research was carried out in four selected areas (Figs. 1, 2): A. the Beskid Niski Mountains, Szymbark area; B. the Dynów Foothills, south of Sędziszów Małopolski; C. western part of Podhale region; D. the Beskid Żywiecki Mountains, within the Żabnica catchment.

These areas, subject to the detailed landslide mapping, GIS analysis, were chosen so as to represent the diversity of the passive factors controlling landslides in the Polish Carpathians. The diversity directly results from the varied relief and complex geological structure of the Carpathian range. These factors condition development of landslides in different parts of the Carpathians, and influencing distribution, type and morphometric parameters of the mass movements (Tab. 1).

THE BESKID NISKI MTS.

The study area in the Beskid Niski Mts. covers 22.8 km^2 is located in the region of Szymbark, in the marginal part of the Beskidy Mts. and the Carpathian Foothills (Fig. 1 — area A, Fig. A). Its western and northern boundary is the Ropa River, and the eastern boundary is the Bielanka Stream. The area is located within the

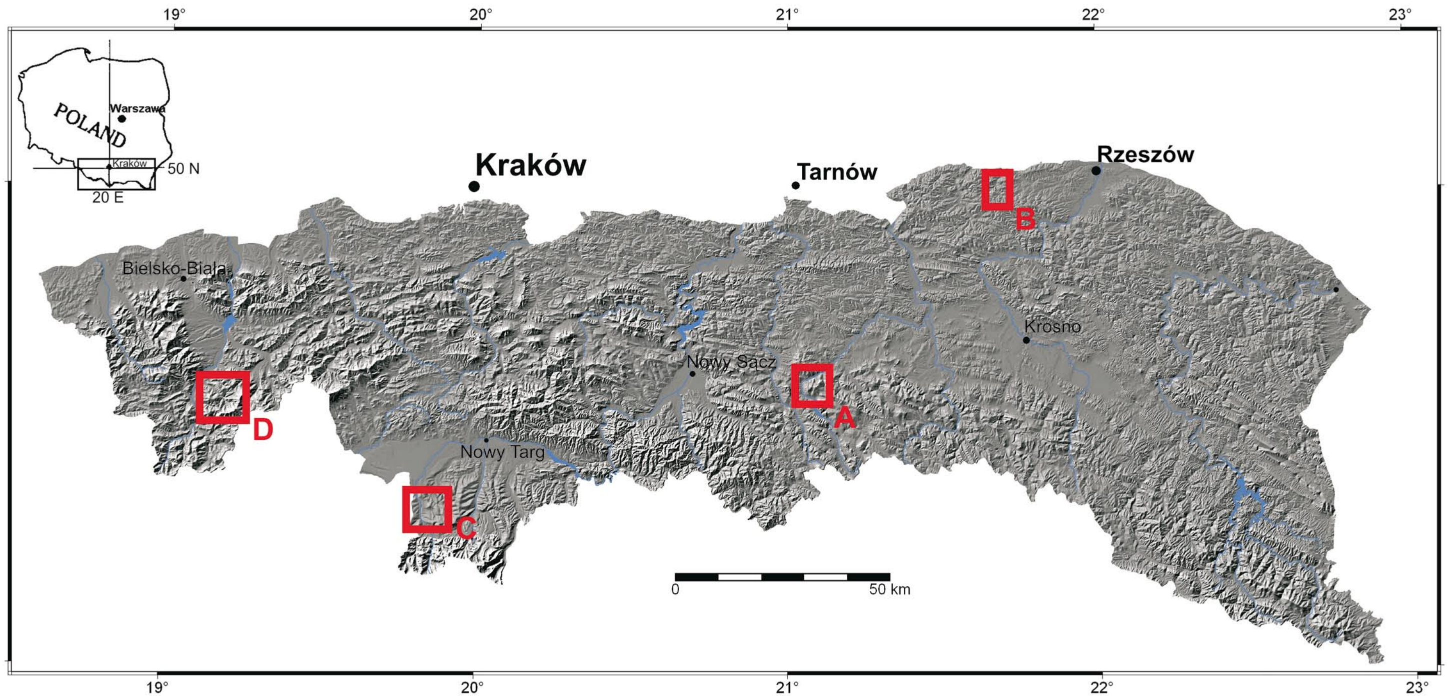

Fig. 1. Localization of study area in the Polish flysh Carpthians. A — Beskid Niski Mts. (Szymbark village area), B — Dynów Foothills (south of Sędziszów Małopolski), C — western Podhale, D — Beskid Żywiecki Mts. (Żabnica catchment)

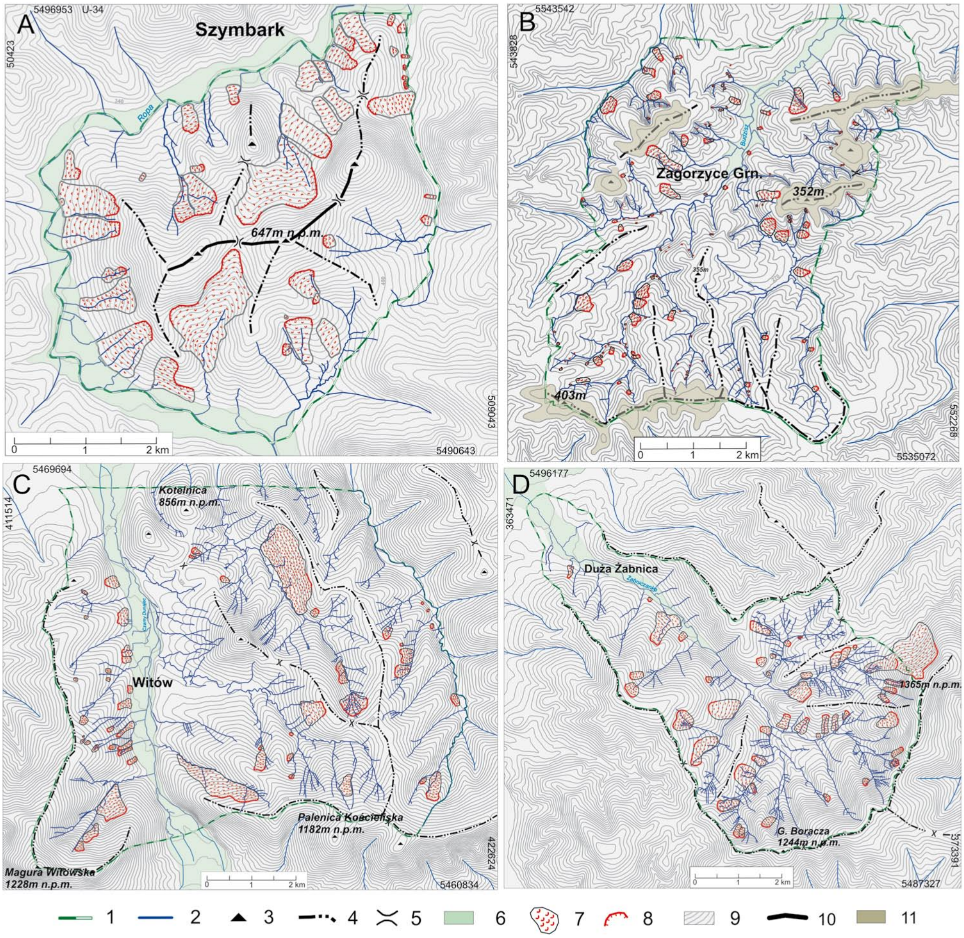

Fig. 2. Main elements of relief of the study areas (A — Beskid Niski Mts., Dynów Foothills, C — western Podhale, Beskid Żywiecki Mts.) 1 — border of the study area, 2 — river, 3 — peak, 4 — side ridge, 5 — pass, 6 — flood plane, 7 — colluvium, 8 — scarps of landslide, 9 — slope, 10 — main ridge, 11 — flat ridge

Magura Nappe. Resistant sandstones build the top of the Miejska Góra, the Łysa Góra, and the Suchy Wierch, under which there are Eocene variegated shales and inoceramic beds forming topographic lows with more gentle relief. These formations occupy nearly 90% of the examined area. Krosno beds and Grybów shales occur in the southeastern part and Ciężkowice sandstone in the north. The rock masses in the study area were re-folded, relocated along the fault on the Ropa River axis, and cut into blocks by smaller faults (Ś w i d z i ń s k i 1953, S i k o r a 1970).

The study area of the Beskid Niski Mts., has low mountain and foothill relief with the maximum altitudes reaching 647 m (Suchy Wierch). Dominating slopes are those with inclination of 6°–10° and 11°–16° (over 37% and 36% of the examined area, respectively). Larger slope inclinations occur within the ridges formed on resistant Magura sandstones and within landslide scarps where they exceed 30°.

Forty-three landslides with the total area of 515 ha occur on an area of 22.8 km^2. The most common forms in this area are deep rocky-weathered material landslides or rocky landslides. In certain cases, only weathered material was the dislocated. According to the classification by D. J. V a r n e s, rotational slides are dominant in this area, with clearly formed scarps and clearly visible slopes and colluvial swells. The main morphometric parameters of landslides that occur in the four examined areas can be found in Table 1.

Table 1

Morphometric parameters of the research areas and of the rotational landslides investigated during the field work

Study area		Beskid Niski Mts.	Dynów Foothills	Podhale	Beskid Żywiecki Mts.
Area [km^2]		22,8	37,3	64,0	36,4
Altitude [m a.s.l.]		647	420	1228	1365
Denivelation [m]		450	200	530	900
Slope inclination [°]	max	45	52	40	68
	mean	6–10, 11–16	3–8, 9–14	3–8, 9–14	15–25
Slope directions [main]		N, E, S, W	N, E, S, W	N, E	N, W
Landslides	rotational	42	99	35	44
	translational	1	8	17	1
Lenght of landslides [m]	max.	800	450	660	800
	min.	40	4	40	20
	mean	370	96	248	300
Width of landslides [m]	max.	400	300	640	600
	min.	30	4	30	25
	mean	255	67	212	215
Height of main scarp [m]	max.	35	15	15	40
	min.	0	0	0	0
	mean	15	2,6	2,7	13
Area of landslides [ha]	max.	313	13	120	45
	min.	0,2	0,2	0,3	0,03
	mean	12	1,2	8	7,2

THE DYNÓW FOOTHILLS

The research was carried out in an area of 37.3 km^2 situated in the southern part of the Sędziszów Małopolski municipality and in a part of the Ropczyce municipality (Figs. 1 — area B, 2B). The geology is dominated by sandstone and shales of inoceramic beds, developed in two broad zones that occupy 70% of the examined area. In the northern part there occurs local, thick-bedded sandstone and shales of inoceramic beds (20% of the area). The older inoceramic beds, situated in the region of the Szkodna and Zagorzyce villlages, are separated by a narrow line of younger rock formations, including Eocene variegated shales and menilite beds (J a s i o n o w i c z et al. 1964; J a s i o n o w i c z, K u c i ń s k i 1965). Older formations are covered with Quaternary deposits. These are mainly covers of weathered bedrock which occur mainly in the southern part of the region. In the north, there are loesses from the Vistulian glaciation (S t a r k e l 1957).

The study area is situated in the Dynów Foothills, between the Wisłoka River to the San River, and to the Sandomierz Basin (S t a r k e l 1972). The foothill relief contains flat prominences at a height of 350–400 m a.s.l. In the northern part, the foothill descends with a rocky step toward the Sandomierz Basin at relative heights of 50–100 m. This rock step is cut both by valleys of the Wielopolka drainage basin and by numerous small valley formations. The flat-topped ridges are separated by 100-150 m deep with valleys with wide terraced floors in the lower sections and narrow floors bottoms in the headwater sections (S t a r k e l 1957, K l i m e k et al. 1969). The slopes, with inclinations of 3–8° and 9–14° are the most common; larger inclinations are typical of the V-shaped valley sides particularly in the southern part of the region.

158 forms with the total area of 127.3 ha and representing different types of mass movements were mapped in this area. The most numerous are rotational slides (99 forms) they are also the most varied in size. There are also undercut slopes (24 forms), debris flows (20 forms), translational slides (8 forms), and rocky debris flows (4 forms). The wide variation of size of each form occurs mainly within the rotational slides, the most common form in the area (Tab. 1).

PODHALE

The study was carried out in the western part of Podhale with a total area of 64 km^2. Its western border is the ridge of Krowiarki (906 m a.s.l.) and the Magura Witowska (1228 m a.s.l.). In the south, the border runs along the Gubałówka (1120 m a.s.l.) ridge and along the Bystry Stream to the east (Figs. 1 — area C, 2C).

The research area is dominated by sandstone-shale and sandstone Lower Chochołów Beds, occupying 64% of the area, as well as sandstones and bentonite Upper Chochołów Beds, occupying 28% of the area. The remaining 8% of the area is underlain by shales and sandstones of Ostrysz Beds (4%) and Lower and

Upper Zakopane Beds (4%) with shales and thin-bedded sandstones (B a d a k 1964).

The Gubałówka Foothills is a broad, flattened plateau sloping to the north, with heights slightly exceeding 1200 m a.s.l. The valleys, 200 to 300 m deep, and their width, as in the example of the Czarny Dunajec Valley, reaches 500 m. The length of the convex and convex-concaves slopes reaches up to 2 km. Hillside inclinations differ depending on the bedrock: on the resistant Toryska Beds and Zakopane Beds, slope gradients locally exceed 37°. Slopes with inclinations between 3–8° (45%) and 9–14° (37%) are the most common.

Fifty-one landslide forms with the total area of 411 ha were recognized.. The forms can be classified as (cf. D. J. V a r n e s 1978), rotational slides (35 forms) and translational slides (17 forms). Weathered material landslides (22) and rocky-weathered material landslides (22) dominate. Landslides in the western part of Podhale significantly differ in terms of morphometry (Tab. 1). They are mainly old and inactive forms which are only locally reactivated. The average inclination of a landslide slope is 10° and ranges from 7° to 15°.

BESKID ŻYWIECKI MOUNTAINS

With a total area of 36.4 km^2, the Żabinca catchmentis located within the Magura Nappe (Figs. 1 — area D, 2D). In the examined area, the Magura sandstones dominate, and they occur along two lines in the north and in the south. They represent 51% of the rocks forming the bedrock. Eocene rocks in the middle part of the catchment are separated by older rock formations, particularly by Ciężkowice Sandstones and Pasierbiec Sandstones, as well as inoceramic shales and Hieroglyphic Beds (27%). Within the line of the older rocks, ordinary inoceramic beds (9%), sandstones from Szczawnica (4%), and thick-bedded sandstones and conglomerates of inoceramic beds (4%) also occur. The remaining 5% of the research area consists of Sub-Magura Beds and Krosno Beds (B u r t a n et al. 1956). The border zone of the Magura Nappe creates favorable conditions for the existence of tectonic faults. Within the research area their direction is NW–SE.

The relief of the Żabnica catchment consists of the homoclinal ridge of Romanka (1365 m a.s.l.) and the Lipowska ridge (1323 m a.s.l.) placed in the SE wing of the Sopotnia–Mała Rajcza anticline. In its centre, the Żabnica valley was formed. The convex and concave-convex valley sides have varied slope gradients, most commonly ranging from 15° to 25° (54%) and from 9° to 14° (24%). In the southern part of the research area, in the headwaters of the V-shaped valleys, the slope inclinations exceed 40°, whereas within the landslide scarps inclinations exceed 45°. The elevations reach 1365 m a.s.l. (Romanka).

Fourty-five landslides with a total area of 325 ha were mapped in this area. With one exception, all forms were classified as rotational slides. Rocky-weathered material forms dominate (35), followed by rock slides (7) and weathered material forms (2) (Table 1).

METHODS

Weight of evidence method was used to make the landslide susceptibility maps and to determine the role of each passive factor in landslide development. This method is a logarithmic-linear version of the Bayes' Theorem. It was first used to identify potential mineral deposits (Bonham-Carter et al. 1989). Later, the method was successfully used to determine landslide-prone areas (van Westen 1993, van Westen et al. 2003, Mrozek et al. 2004, Mrozek 2008, Barbieri, Cambuli 2009).

The *weight of evidence* method is based on the statement that "the past and the present are the keys to the future". With a map of landslide, data on the regularity of landslide development in a particular area, and maps of passive factors influencing landslides, areas with environmental conditions favourable for the occurrence of landslides can be determined we can make calculations that will allow us to identify those areas having particular environmental conditions favorable for development of such forms.

The analysis was prepared on the basis of a script by C. J. van Westen (2002), which allowed the weight of evidence method to be adapted to the ILWIS program.

The calculations are based on the detailed landslide map of the research area. For the four study areas, such maps were constructed based on field mapping at a scale of 1 : 10,000. The detailed landslide map is used to calculate the a priori probability and determine the likelihood of the occurrence of a landslide in a given area, without considering any controlling factors. The probability is calculated as a ratio of the area occupied by landslides to the entire research area.

$$P_{prior} = P\{S\} = \frac{N_{pix}\,(\text{Slide})}{N_{pix}\,(\text{Total})}$$

where:
$P_{prior} = P\{S\}$ — Conditional probability for having a landslide S;
N_{pix} (Slide) — Number of pixels with landslides in the study area;
N_{pix} (Total) — Total number of pixels in the map.

The next step is to consider the relation between conditioning factor and occurrence of landslides. This relation is called conditional probabilistic, and can be expressed by the formula:

$$P\{S/B\} = \frac{P\{S \cap B\}}{P\{B\}} = \frac{Npix\{S \cap B\}}{Npix\{B\}}$$

$P\{S/B\}$ — the conditional probability of having a landslide while you are in unit B.

In other words, the conditional probability is the density of landslides within a unit (lithological unit in the lithological map), calculated as the number of pixels within landslides in the unit, divided by the total number of pixels in the unit.

As mentioned above, in this study the weights of evidence method (Bonham-Carter 1994) was selected for indirect landslide susceptibility assessment. In this method, positive and negative weights (W^+ and W^-) are assigned to each pixel of the factor maps, which are defined as (van Westen 2002):

Eq. 1

$$W_i^+ = \log_e \frac{P\{B_i/S\}}{P\{B_i/S\hat{}\}}$$

and

Eq. 2

$$W_i^- = \log_e \frac{P\{B_i\hat{}/S\}}{P\{B_i\hat{}/S\hat{}\}}$$

where:
B_i — presence of a potential landslide conditioning factor,
$B_i\hat{}$ — absence of a potential landslide conditioning factor,
S — presence of a landslide, and
$S\hat{}$ — absence of a landslide.

The method can be performed using individual factor maps that only contain two classes representing the presence or absence of a factor. For each factor W_i^+ is used for those pixels of a factor to indicate the importance of the presence of the factor for the occurrence of landslides. If W_i^+ is positive, the presence of the factor is favourable for the occurrence of landslides; if W_i^+ is negative, it is not favourable.

W_i^- is used to evaluate the importance of the absence of the factor for the occurrence of landslides. When W_i^- is positive, the absence of the factor is favourable for the occurrence of landslides; if W_i^- is negative, it is not favourable. Weights with extreme values indicate that the factor is useful for susceptibility mapping, while factors with a weight around zero have no relation with the occurrence of landslides (van Westen 2002).

For each factor there are four possible combinations, of which the frequency, expressed as number of pixels, can be calculated with GIS (Tab. 2).

Table 2

Four possible combinations of a potential landslide conditioning factor and a landslide inventory map. *N*pix = number of pixels

		B_i: Potential landslide conditioning factor	
		(Present)	(Absent)
S: Landslides	Present	$N\text{pix}_1$	$N\text{pix}_2$
	Absent	$N\text{pix}_3$	$N\text{pix}_4$

Based on equations 1 and 2, the weight of evidence can be expressed in numbers of pixels as follows:

Eq. 3

$$W_i^+ = \log_e \frac{\dfrac{\text{Npix}_1}{\text{Npix}_1 + \text{Npix}_2}}{\dfrac{\text{Npix}_3}{\text{Npix}_3 + \text{Npix}_4}}$$

and

Eq. 4

$$W_i^- = \log_e \frac{\dfrac{\text{Npix}_2}{\text{Npix}_1 + \text{Npix}_2}}{\dfrac{\text{Npix}_4}{\text{Npix}_3 + \text{Npix}_4}}$$

where:
npix_1 — nslclass (number of pixels with landslide in the class)
npix_2 — nslide (number of pixels with landslide in the map) – nslclass
npix_3 — nclass (number of pixels in the class) – nslclass
npix_4 — nmap(total number of pixels in the map) – nslide – nclass + nslclass

The last stage of the analysis is the calculation of the final weights and the contrast factor. To obtain the total weights of each factor, the positive weight of the factor itself should be added to the negative weight of the other factors in the same map. This is done by first adding up all negative weights of the classes of one map. The final weight is calculated as:

*W*map = *W*plus + *W*mintotal – *W*min

In which *W*mintotal = the total of all negative weights in a multiclass map.

To quantify the spatial association between a map class and the occurrence of landslides, the contrast factor as mentioned in G. F. Bonham-Carter (1994) is defined:

$$C_w = W^+ - W^-$$

The contrast factor is 0 when the landslide pattern and map class pattern overlap only by the expected amount due to chance; positive when there is a positive association between the two patterns; and negative when there is a negative association between the two patterns (van Westen 2002).

DATA COLLECTION

The analysis is based on a detailed map of landslides within the study area. GIS analysis takes into consideration the whole range of the examined landslides. Two different approaches can be found in the literature. The first one is based on the selection of a series of points representing a particular landslide. There are different ways of selecting such points. The most common way is to randomly generate the pixels representing a particular form (Chung 2006). The second method proposed in the literature is based on choosing one point that represents the landslide. This method is often practised when the input data used for the analysis differs in scale or resolution (Mrozek 2008). However, both methods of the analysis of the available information are incomplete. When using single or randomly selected data points representing a particular landslide, we may overlook important information concerning the regularity of landslide development within the research area. If the entire area is considered, more information can be introduced into the model, thus reducing researcher interference in the process of modelling. The vector maps of landslides from the four regions were brought to raster images with a raster size of 10 × 10 m.

Apart from the map of landslides, a few thematic layers with passive factors influencing landslide development were used in the making of the model (Fig. 3). The six most important factors were chosen: geological settings, terrain inclination, slope aspect, land use, distance from the geological bed contact zone, and distance from surface watercourse (Fig. 3). Those factors were selected on the basis of the literature when considering (a) the diversity of environmental conditions in all research regions and (b) the diversity of landslides in those areas. To make the selection, the availability of the spatial date that could be included in the analysis was considered important. The chosen data were possible to obtain equally and with the same level of accuracy.

An important element of the analysis was to use a digital elevation model of the research area. Such a model was constructed on the basis of the same methods and reference materials for each research area. The source of the data were topographical maps at a scale of 1 : 10,000. The constructed elevation models were used to visualize the results and to construct maps of slope gradient maps, aspect and distance from watercourses map.The slope gradient maps were generated by the tools in the Ilwis softtware using filters and a calculating formula.

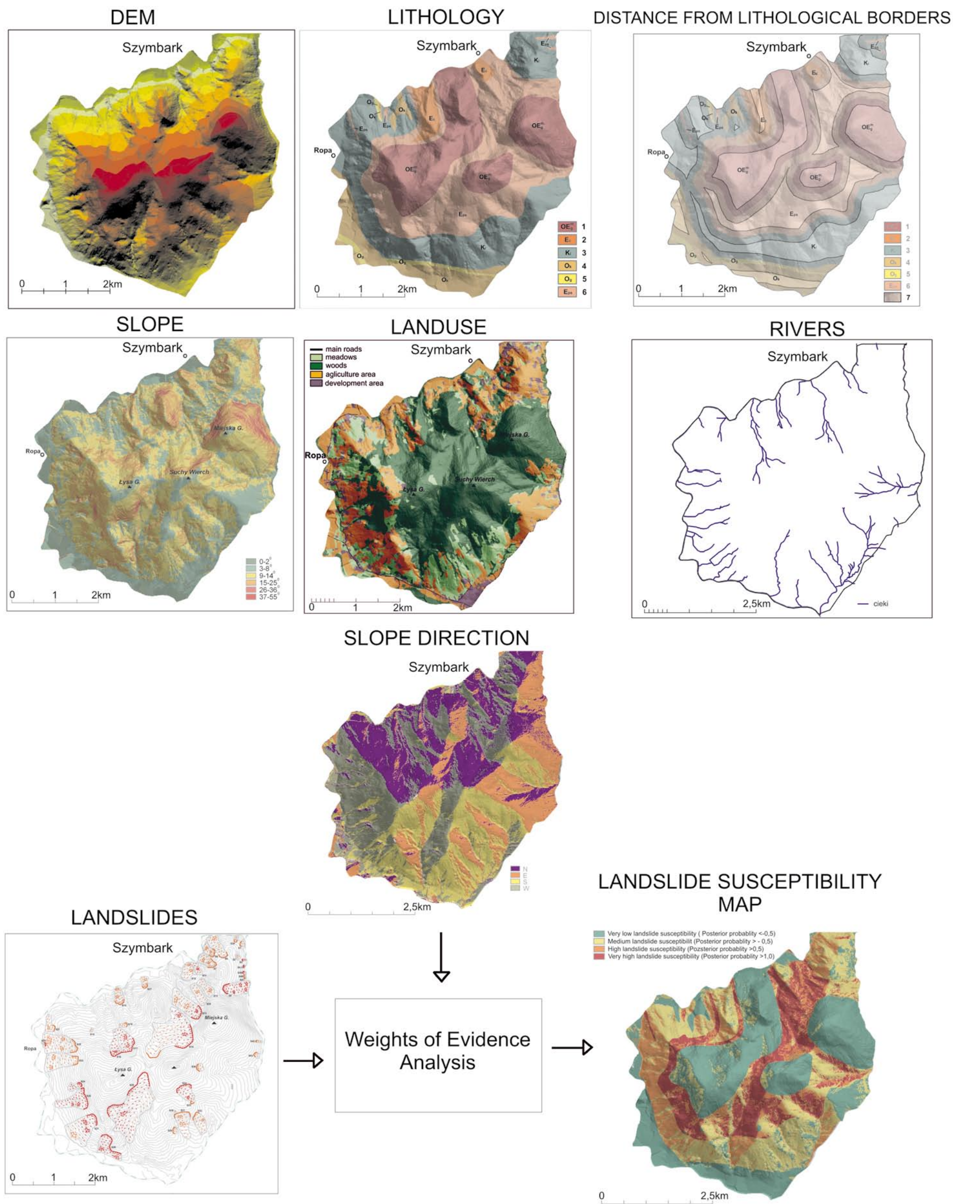

Fig. 3. Simplified flow chart for WofE modeling. Main components of analysis (Beskid Niski Mts.)

Geological maps used in the analysis were obtained by digitalization of detailed geological maps of Poland at a scale of 1 : 50,000. For different research regions following sheets were used: for the Beskid Niski Mts. — sheet Gorlice (S i k o r a 1964); for the Dynów Foothills — sheets Frysztak (J a s i o n o w i c z et al. 1964) and Ropczyce (J a s i o n o w i c z, K u c i ń s k i 1965); for the Podhale — sheet Czarny Dunajec (B a d a k 1964) and for the Beskid Żywiecki Mts. — sheet Milówka (B u r t a n et al. 1956).

Based on the geological maps, the maps of the geological beds contact zones were made. Field observations and data from the literature indicated that the contact zones are more susceptible to landslides (K o t a r b a 1986, W ó j c i k 1997, 2002). To conduct GIS analysis, the maps were made with a separate buffer zone on the geological beds contact zones with a width of 200 m.

Land use is the last of the passive factors included in the analysis, which may influence landslide formation. Maps for such research areas were made on the basis of topographical maps at a scale of 1 : 10,000, and orthotophotomaps in the same scale.

All the subject maps constructed for the analysis were changed into raster images with one raster size 10 × 10 m.

DATA PROCESSING AND CONSTRUCTION OF THE LANDSLIDE SUSCEPTIBILITY MAPS

Preparation and processing of the input materials suitable for the model, as well as the whole process of modelling and verification of the results, were conducted with the ILWIS software (Integrated Land and Water Information System).

The modelling was carried out in accordance with the principles described above. Weight values W^+, W^- and C_w were calculated. Predictors between 0.1 and 0.5 have low predictive significance, between 0.5 and 1.0 — have medium significance, between 1 and 2 have great significance, and above 2 — have extremely great significance. On this basis, predictors of landslide susceptibility were chosen. The predictors with absolute value exceeding 0.5 were considered the values of predicative importance (K e m p, B o n h a m-C a r t e r 1999 vide M r o z e k 2008). The values of weights of the predictors for the Beskid Niski Mts. and the Dynów Foothills, relevant for the modelling, are shown in Table 3.

After calculating the weight values and their selection, the selected predictors were added in order to make the final map of landslide susceptibility (Fig. 4).

The next step was a two-step verification of the model First, the “success rate” was established as a percentage of the pixels of the landslide area in each class of landslide susceptibility. Such data are obtained by combining the final map of landslide susceptibility with the initial map of landslides existing in a given study area. The obtained results confirmed the correctness of the modelling conducted for all four study areas. Of the total area of landslides, 68% to 85%

Table 3

Positive, negative and total weights, contrast for each class used for building the model. Example from Beskid Niski Mts. and Dynów Foothills

Area	Theme	Classes	W^+	W^-	C_w	*W*map
Beskid Niski Mts.	Slope direction	E	– 0. 5	0. 12	– 0. 62	– 0. 67
		W	0. 43	– 0. 19	0. 62	0. 57
	Lithology	Magura sandstones	– 0.8	0.22	– 1.02	– 1.1
		Krosno beds	– 1.7	0.09	– 1.8	– 1.8
		Grybów slates	– 0.72	0.009	– 0.73	– 0.81
		Variegated shales	0.57	– 0.3	0.88	0.80
	Slope	0–20	– 2.20	0.07	– 2.28	– 2.34
		9–140	0.39	– 0.36	0.45	0.48
		26–360	– 0.49	0.009	– 0.50	– 0.56
Dynów Foothills	Slope direction	E	– 1. 00	0. 20	– 1. 2	– 1. 25
		W	0. 61	– 0. 27	0. 88	0. 83
	Lithology	Babice loams	0.69	– 0.02	0.71	0.77
		High thickness sandstones and slates — Inoceramian beds	– 0.47	0.06	– 0.54	– 0.48
		Cherts and slates	1.6133	– 0.02	1.63	1.69
		Slates and sandstones	2.35	– 0.04	2.39	2.45
		Variegated shales	1.44	– 0.01	1.45	1.51
	Distance to rivers	Buffer 0–100 m	0.3	– 0.2	0.31	0.54
		Buffer 201–300 m	– 0.46	0.01	– 0.52	– 0.59
		Buffer 301–400 m	– 0.74	0.01	– 0.76	– 0.83
	Slope	0–20	– 3.01	0.06	– 3.08	– 3.06
		3–80	– 0.57	0.33	– 0.90	– 0.89
		9–140	0.48	– 0.26	0.74	0.75
		15–250	0.48	– 0.11	0.60	0.61
	Distance from lithological borders	Buffer < 100 m	0.32	– 0.1	0.42	0.64
		Buffer > 100 m	– 0.1	0.32	– 0.42	– 0.51
	Landuse	Meadows	0.95	– 0.11	1.07	1.22
		Agriculture area	– 0.23	0.30	– 0.53	– 0.38

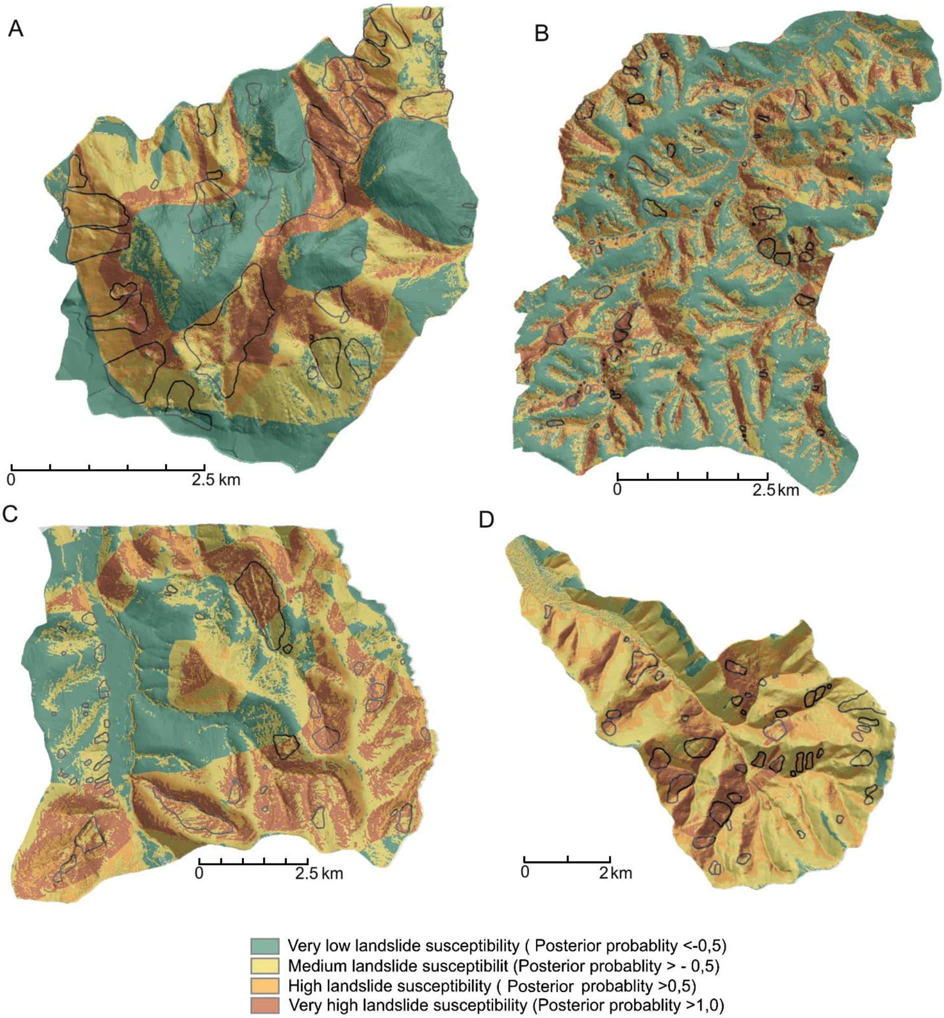

Fig. 4. Landslide susceptibility maps for the study areas (A — Beskid Niski Mts., Dynów Foothills, C — western Podhale, Beskid Żywiecki Mts.)

(depending on the study area) occurred on slopes considered landslide susceptible or very susceptible if the weight value of predictors exceeded 0.5 (Fig. 5).

The second stage of model verification involved similar calculations with only active landslides considered. The results obtained from this kind of verification also confirm the correctness of the modelling conducted for particular areas. The obtained percentage compliance of the active landslides ranges from 71% to 87%. This compliance is particularly important in analysis based on the total area of landslides.

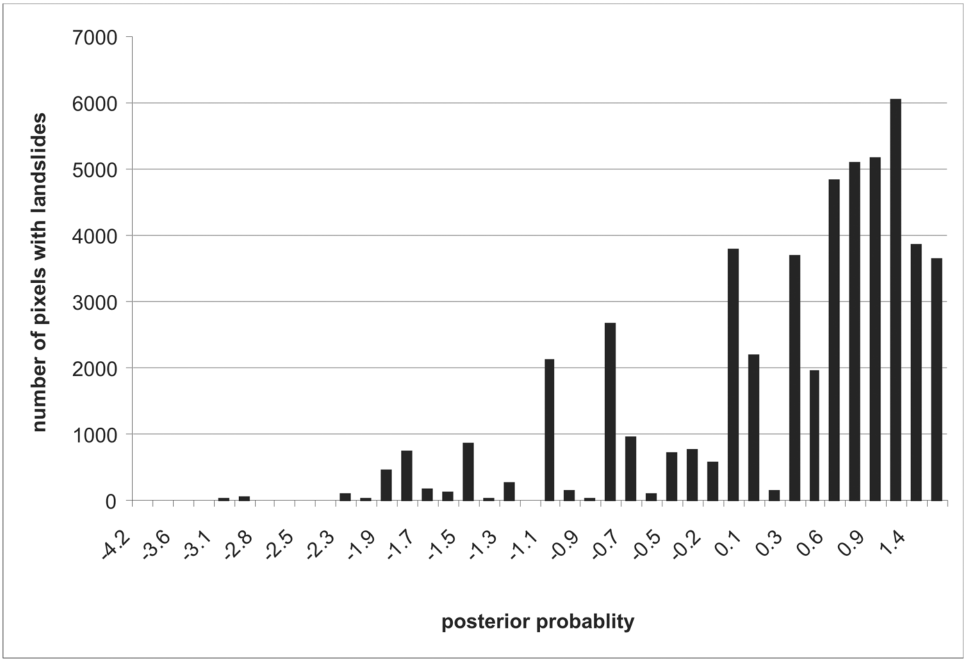

Fig. 5. Correlation between distribution of pixels, representing landslides and value of posterior probability. Example from study area in the Beskid Niski Mts.

DISCUSSION

The analysis and modelling showed which of the particular passive factors are significant for landslide formation and are important for mapping landslide susceptibility.

The question is, which of the predictors is important for this type of analysis conducted in different parts of the Polish Carpathians.

SLOPE ASPECT MAP

The analysis showed increased landslide susceptibility on the slopes with western aspect and reduced on slopes with eastern aspect. This pattern, typical of the Beskid Niski Mts.,the Foothills, and Podhale region, may be explained with the greater amount of precipitation on the slopes with western orientation. The opposite situation in the Żabnica catchment in the Beskid Żywiecki Mts., where annual precipitation is the highest in the Polish flysch Carpathians, is difficult to explain.

MAP OF THE DISTANCE FROM THE LITHOLOGICAL UNITS BOUNDARY

Landslide occurrence on the boundaries of lithological forms was previously described in the Polish flysch Carpathians (K o t a r b a 1986, W ó j c i k 1997, 2002). The analysis confirmed the existence of such determinants in the Dynów

Foothills and in the Beskid Żywiecki Mts. They are also true in the Beskid Niski, despite negative results obtained for the locations where the landslides were formed on the contact of non-permeable shales and the aquifer in Magura Sandstones (K o t a r b a 1986). This is probably related the extent of the landslides which may occupy entire slopes. If the modelling had been conducted on the basis of the separation zones instead of the entire slope areas, the result would have probably been positive.

LITHOLOGY

The impact of lithology on landslide development in the flysch Carpathians seems to be indisputable. The relation of the landslides development within the areas where particular rocks, especially shales, occur, was repeatedly described (B o b e r 1984, K o t a r b a 1986, Z a b u s k i et al 1999). However, using this factor in the analysis of landslide susceptibility poses some difficulties. The problem occurs when in the particular area only one or two lithological forms dominate, while other forms occupy only a small percentage of the area. Such situation may lead to overestimating or reducing the weight value of individual rock series. Among the four study areas, only the analysis conducted in the Beskid Niski Mts. yielded reliable data which confirmed the increased landslide susceptibility within the Variegated Shales. In the other areas such relations are also noticeable; however, because of the small percentage of shale layers in the study areas, the results are difficult to interpret. Within these areas, one or two rock series occupy up to 90% of the total area.

GRADIENT MAP

The results of the analysis confirmed results of the previous studies (B o b e r 1984, Z a b u s k i et al. 1999). Increased landslide susceptibility occurs on the slopes with the inclination between 9° and 14°; the slopes with inclination between 15–25° (shallow weathered slides on the Dynów Foothills) are less susceptible to landslides. The probability of a landslide occurring on the slope with an inclination below 8° and above 25° significantly decreases. This rule applies to all research areas, regardless of landslide type.

MAP OF THE DISTANCES FROM WATERCOURSES

This factor is particularly important in the case of the delapsive landslides, which are induced by an impulse at the lower part of the slope. Slope instability is often caused by undercutting by a watercourse. It is particularly common in the case of younger weathered material landslides. This study suggests the undercutting of slopes by a swollen river is probably less important for deep structural landslides. The relation between landslide development and the distance from watercourses is best noticeable in the Dynów Foothills and in the Beskid Żywiecki Mts. In the Dynów Foothill part of the flysch Carpathians, landslides are the most frequent in the break zone between steep valley side and gentle plateau. Hence, the distances from the watercourses are significantly important in determining the zones susceptible for landslides in the Dynów Foothill areas. Such a relation also occurs in Beskid Żywiecki Mts., where erosive activity of the watercourses may have an additional triggering impact for landslide formation. This particularly applies to source areas with intense headward erosion.

MAP OF LAND USE

The last factor taken into consideration in the analysis is the land use. The fieldwork and the GIS analysis have not shown any direct relation between landslides formation and vegetation. The results only indicate a lack of landslides on agricultural areas. The only area where land use may have an impact on determining the susceptible zones is the Dynów Foothills, where the zones susceptible for landslides formation are used as meadows and wastelands. The research in the four areas has not confirmed the assumption about the role of forests in protecting the slopes from sliding. During the fieldwork in different regions of the flysch Carpathians, the author found several active slides covered with old forest. Also, a few new landslides, formed in the forest area were mapped.

This applies to both structural landslides and shallow landslides of the weathered material. For all these reasons, the maps of the land use have been omitted in making the landslide susceptibility maps.

CONCLUSIONS

The applied method yielded relatively good results in each of the study areas at the chosen scale of study. This is confirmed by the results of the analysis and previous studies. The final maps of landslide susceptibility present useful information about zones of potential landslide development.

Making of a detailed landslide susceptibility map should be preceded by a field reconnaissance and inventory of landslides. Such analysis should be performed for one type of landslide, dominatant in the particular area. It is especially important for structural landslides and shallow weathered material slides. The other important issue is to obtain reliable input data that can be used in the model. Such data should present similar levels of accuracy adapted to the scale of the study and to the types of gravity mass movements on a particular area.

The importance of individual passive factors (predicates) in making the landslides susceptibility maps is different in each region of the Polish Carpathians. This diversity results from varied relief, complex geological settings, and complicated tectonics within the flysch Carpathians. Types of landslides existing in a particular area are also very important. When making a landslide susceptibility maps in the foothill areas, where apart from weathered-rock landslides, weathered slides are very frequent, the land relief (inclinations, slope aspect), and the distance from the watercourse must be considered important. On the slopes in the Beskidy Mts., apart from relief, lithology and tectonics are also important.

The weakness of the study is that tectonics is omitted in the analysis. Maps of faults and maps of zones of tectonic dislocations should be components of such studies. It applies particularly to the deep structural landslides. However, the dimensions of the buffer zone should be considered when preparing the input materials for a model.

Landslide susceptibility maps should be used in the zoning of Carpathian municipalities. Relatively simple methods of calculations and the possibility of obtaining reliable input data for a model can be considered an additional advantage in making such maps. The only limitation is the need to obtain an accurate map of landslides in a particular area. Such maps should be made through the terrain mapping conducted by a qualified professional. The Landslide Protection System (SOPO) project, carried out by the Polish Geological Institute can serve as a solution to the above problem. This project assumes making the accurate maps of landslides and landslides hazard areas at a scale of 1 : 10,000 for all Carpathians municipalities. Such materials can be a good basis for making landslides susceptibility maps. Prepared in such a way, maps of the zones susceptible to landslides can be a valuable supplement to the SOPO project.

Within the area of the Polish Carpathians, there are municipalities where landslides occupy vast areas so the occurrence of potential new landslides is impossible. It seems pointless to make maps for such areas. Therefore, the question is whether the current material losses resulting from landslides are connected to the development of new forms or activation of landslides, which already exist. Many houses and investments are still developed on active landslides. Rejuvenation of the old landslide areas in the flysch Carpathians after long-lasting precipitation events is more significant than the creation of new forms. However, because landslides are unpredictable phenomena, it is necessary to determine new, potential zones of landslide occurrence.

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