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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S
Recent geomorphological hazards in Carpatho-Balcan-Dinaric region

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EXTREME GEOMORPHIC PROCESSES IN THE EASTERN CARPATHIANS: SPECTRUM, CAUSES, DEVELOPMENT, ACTIVIZATION AND INTENSITY

Abstract. Mass activization of landslides, mudflows and other dangerous geomorphic processes in the Eastern Carpathians after extreme flood events in the years 1969, 1971, 1998, 2001 have been observed. These processes caused millions of financial losses as well as numerous human victims. The paper deals with analysis of present-day extreme geomorphic processes distribution and development in the Eastern Carpathians (Western Ukraine). The main attention is paid to determination of present-day processes spectrum, assessment of the floods, river bed deformations, landslides, mudflows and avalanches. Data about distribution, intensity, and activization causes of extreme processes play important role in implementation of preventive measures in the region.

Key words: extreme geomorphic processes, processes spectrum, floods, river bed deformations, landslides, mudflows, avalanches, Eastern Carpathians

INTRODUCTION

In spite of noticeable success in research of dangerous hydrological and geomorphic processes in the Eastern Carpathians in the recent decades (Rud'ko 1991; Adamenko et al. 2000; Kravchuk and Rud'ko 2002; Paliyenko 1999; Romashchenko and Savchuk 2002; Kovalchuk 1997, 2003; Kovalchuk et al. 2005; Steidl et al. 2005), some questions and problems are still urgent to be studied from the geomorphological point of view: determination of the spectrum of actual relief-forming processes in the mountain, pre-mountain and flat regions as well as the assessment of the role of each type process in the relief-forming and ecological situation; analysis of actual geomorphic processes within the river catchments of different rank; morphological typification of the river beds and river-bed processes, as well as creation of their distribution and intensity maps; forecasting of the trends and intensity of the development of erosion-accumulation processes within river beds and flood plains in the different-rank catchments; ascertaining of the main causes of activization of dangerous geomorphic processes, and so on.

AIM AND METHODS OF INVESTIGATIONS

The aim of our research is the consideration of the present-day extreme geomorphic processes in the Eastern Carpathians as genetic complexes in the river basin system. Their existence and functioning are caused by the integrated mineral-substance and water circulation in the different-rank catchment systems.

We analysed spatial distribution, tendencies and intensity of development, causes, geomorphic effects and activization risk of these processes. To reach this goal the following tasks were implemented:

— Determination of the spectrum of actual geomorphic processes in the Eastern Carpathians;
— Analysis of water runoff, flood and sediment transport regimes, as well as their long-term changes;
— Flood modelling and determination of the potential flooded zones in the Upper Dnister river valley (between Sambir and Rozdil towns, Precarpathian plain) during various flood events;
— Assessment of information procurement concerning the factors and parameters of the extreme geomorphic processes, as well as evaluation of availability (accessibility), reliability and applicability of this information to GIS modelling and research;
— Creation of the data bases on parameters and distributions, as well as about the factors of geomorphic processes;
— Modelling of flood events, landslides, mudflows, fluvial erosion and accumulation in the Eastern Carpathians;
— Assessment of dike breaking and overflooding risk in the river valleys, determination of the potential flooded zones, evaluation of mudflow and landslide activization risk;
— Analysis of horizontal and vertical river-bed deformations.

The processes spectrum is the combination (complex) of exogenous and endogenous processes within the definite territory (river catchment for example), which is characteristic in the definite time moment. The processes spectrum is defined on the base of field investigations and analysis of geomorphological maps.

The geomorphic risk is the probability of rising or extreme activization of the natural or man-made relief-forming processes in the definite place and time, and also threat of their effects upon natural and economical objects with negative consequences for human health and life (Kovalchuk and Petrovs'ka 2003).

Integrative evaluation of the geoecological role of the processes spectrum has been based on the system approach and includes the complex analysis of the main endogenous and exogenous processes and energetic potential of the relief (morphometric parameters, evaluation of lithologic composition and so on).

In this research, the following methods were used: field investigations, cartometric analysis, historic-geomorphic analysis and synthesis, semi-stationary observations, aerial and satellite images analysis, GIS-modelling, and others.

Basic information has been provided by large-scale topographic maps, medium-scale thematic maps illustrating the factors of process development and activization, long-term hydrological data, and information about distribution and development of geomorphic processes. For flood modelling, the river beds and valleys morphometric data (river bed depth and width, river bank height, width and height of the dikes, distance between the dike and river bank, etc.) and hydrological data have been used. The different-time topographical maps, river bed cross-sections and longitudinal profiles, and correlations between water level and discharge ($Q = f(H)$) have been used for the analysis of river bed vertical deformations. This type of deformation has been evaluated by comparing different-time cross-sections. The obtained results were compared with different-time $Q = f(H)$ curves and other results of long-term semi-stationary observations in the region (Holoyad et al. 1995; Kovalchuk 1997). The ascertained long-term changes of water level in the river bed pointed to either erosion or sedimentation trend in the river bed. For the investigated gauging stations the tendencies, scales and mean intensity (for the period 8–32 years) of the river bed deformations have been evaluated.

GIS was also the main instrument for the mapping and modelling of actual geomorphic processes. GIS techniques were elaborated on the basis of ArcView and ARC/INFO software. For flood modelling, the GIS-compatible hydrological modelling software HEC-RAS (provided by our colleagues from ZALF, Germany) was used.

Based on the results of our field investigations and information collected by the Transcarpathian Geological Expedition, the geomorphic processes database has been created (Habchak 2005). The GIS maps (with the basic scale 1 : 200,000) of the landslide distribution and density in the Transcarpathian region for three periods (before 1998, 1998–2002, after 2002) have been prepared. These periods have been chosen to evaluate the role of extreme floods causing landslide activization.

SPECTRUM OF PRESENT-DAY GEOMORPHIC PROCESSES

In the geomorphic process spectrum in the Eastern Carpathians we can determine two groups by their relief-forming effects: major (dominating) and secondary ones. The first group includes weathering, erosion (slope and river bed), landslides, mudflows, avalanches, karst, man-caused processes as well as rain-floods and snowmelt-floods. The second group includes aeolian processes, chemical denudation, biogenic denudation and accumulation, and others.

Depending on the tectonic position, topography, and rock properties, i.e. depending on the type of geomorphic system and climatic conditions, the spectrum of geomorphic processes is formed (Table 1).

The table shows that the spectrum and relief-forming role of the leading process change depending on the following criteria: distribution area or removed material volume, and the relief characteristics. In the mountains, the main relief-forming processes include erosion, landslides and mudflows. Due to human activity the effects of processes have been increased hundreds times (Kovalchuk 2003).

Table 1

The actual relief-forming processes spectrum in the Eastern Carpathians (Kovalchuk 2003)

Type of process	% of area	Type of process	% of removed material
Slope wash	38	Land-slides	41
Land-slides	23	Slope wash	30
River bed erosion and accumulation	12	River bed erosion and accumulation	11
Mud-flows	9	Mud-flows	7
Avalanches	6	Man-caused	6
Man-caused	6	Landslips	2
Karstic processes	3	Avalanches	1
Landslips	2	Karstic processes	1
Biogenic	1	Biogenic	1
Total	100	Total	100

DISTRIBUTION AND DEVELOPMENT OF MAIN GEOMORPHIC PROCESSES

FLOODS

The most flood-dangerous territories in the Eastern Carpathian region are valleys of the Upper Dnister River and its pre-mountain tributaries, as well as river valleys of the Tisza and Teresva rivers. Mountain part of the region is characterized by the maximum totals and intensity of precipitation — main precondition for rain-flood development. Intensive economical activity in the Tisza River basin during the last decades has noticeably enhanced the effects of natural factors.

The analysis of hydrometeorological data sets and recent publications show that during the last 100–120 years the highest floods in the Upper Dnister River basin were observed in July 1911, June 1927, September 1941, August 1955, June 1969, May 1970, July 1980, July 1984, May 1989, July–August 1997, July 1998, and July 2001 (Aizenberg 1962; Shvets 1972; Romashchenko and Savchuk 2002). At the time of extreme flood events, the water level rose up to 10 m above

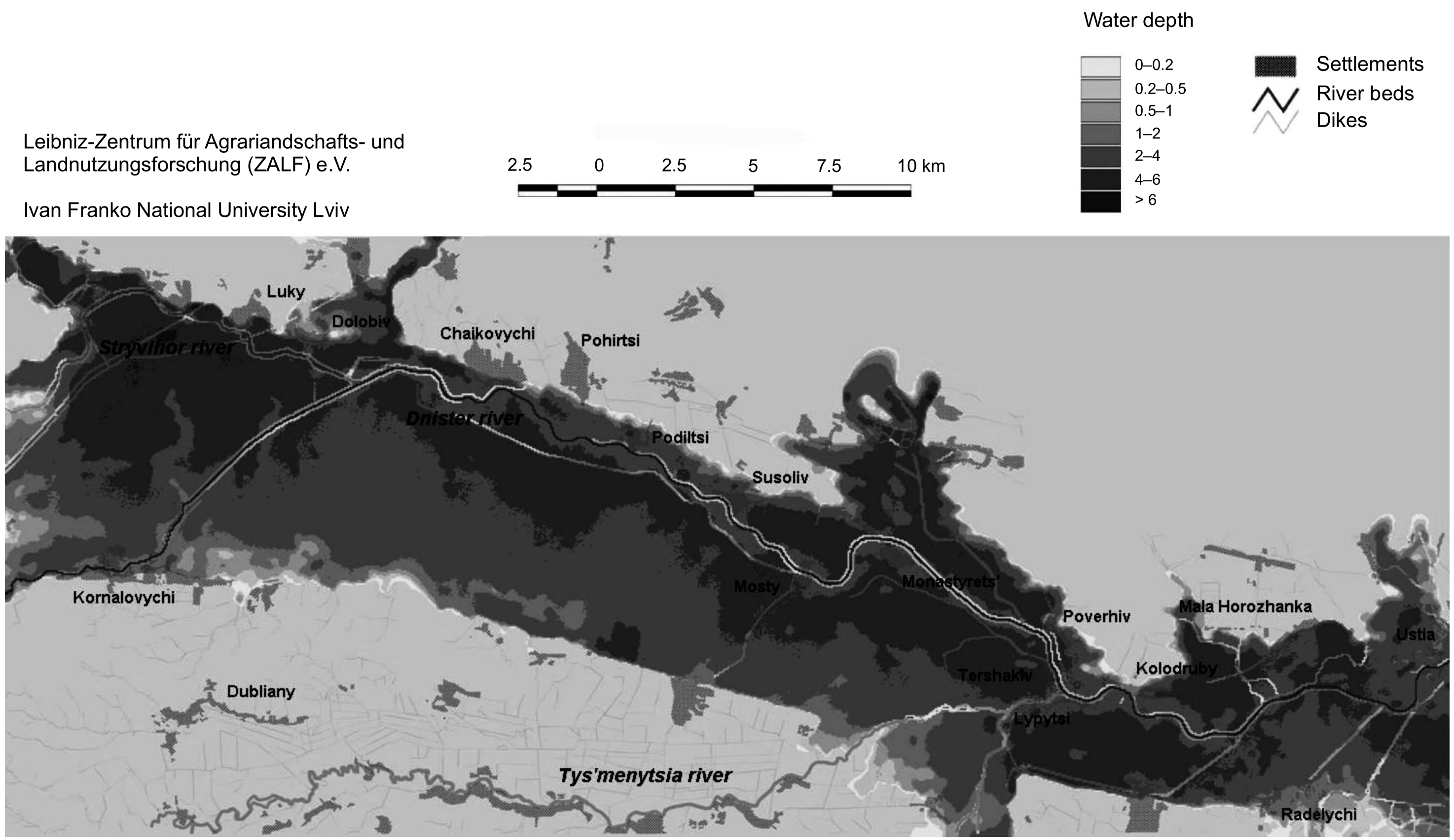

Fig. 1. The Upper Dnister River valley areas characterized by the highest risk of flooding by 100-years flood (after Kovalchuk et al. 2005)

normal, flooded zones are extended up to tens of square kilometres. As a result of such floods hundreds people perished, and thousands of buildings and tens of kilometres of roads were destroyed. Mostly the Upper Dnister, Tisza and Teresva river valleys are affected by floods.

In the Eastern Carpathian river basins, the duration of floods fluctuates from hours to a few days. The maximal water levels and discharge are observed in summer–autumn period (usually May–October). In the mountain part the annual precipitation changes from 1,000 to 1,300 mm. Usually, duration of water rise is 4 days and recession — about 8 days. The most intensive water level rise is observed in the transition zone between the mountains and submontane plains (Shvets 1972; Kovalchuk 1997). Due to intensive precipitation (120–250 mm/day), the specific runoff in the mountain watersheds amounts to 2.5–3.1 $m^3 \cdot s^{-1}$ from 1 km^2 (Kovalchuk 1997).

The flood protection systems in the Ukrainian Carpathians include dikes, drainage channels, sluices, pumping stations, etc. Unfortunately, most of the dikes (built between 1950 and 1970) are characterized by imperfections, like: small distance between the dike and river channel, technical imperfections, or deformed tops of dikes due to the present-day geomorphicc processes. Low flood protection affectivity is also caused by unsatisfactory exploitation state of engineering objects, like drainage channels, sluices and pumping stations, as well as by the accumulations of natural and man-made garbage in the river beds.

As a result of GIS modelling of the extreme floods (Kovalchuk et al. 2005), the areas characterized by high flood risk have been determined. Such areas in the Upper Dnister River valley are illustrated in Figure 1.

On the basis of the generated digital elevation model, and the maps of risk of dike breaking and overflooding, as well as of water levels during different water procurement flood events, the effectiveness of the existing dike protection in the Upper Dnister River valley has been analysed (Kovalchuk et al. 2005; Steidl et al. 2005).

About 70% of the dikes in the river valley are characterized by high risk of dike overflooding in case of 100-years-flood event. The 25-years-flood events may cause breaking and overflooding of about 20–30% of the dikes. Therefore, it is strongly necessary to make reconstruction of the existing flood-protection system in the Eastern Carpathians river basins. With a view to this purpose, specialists of the Lviv Regional Water Resources Authority have worked out the project of polders building on the Upper Dnister River floodplain.

LANDSLIDES

The Eastern Carpathians are characterized by active development of gravitational processes, like: landslides, mudflows, avalanches, and others (Table 1). These processes become especially active after the flood events. Landslides are often formed on steep slopes with stratified and differently dipping strata (Habchak 2005; *Assessment...* 2000; *Regional...* 2003).

Landslide formation is caused by saturation of the weathered rocks by water, cutting of slope bases by the engineering works, and undermining of slopes by rivers during the flood events. The landslides in the Eastern Carpathians are in different phases of development. Most of the landslides are in the stage of stabilization. Within the Transcarpathian region (S-slope of the Carpathians), 746 active landslides, 154 mudflows, and 143 zones of active erosion were mapped in the year 2003 (Habchak 2005; *Report...* 2003; *Regional...* 2003). Activization of these processes was observed after the floods in autumn–winter 1998, spring 1999 and spring 2001.

Complete deforestation of slopes and felled trees transportation in every season (only winter is accepted) are the main cause of landslide development (Herasymchuk 2000), especially in narrow river valleys with high and steep slopes (30–50°).

Landslide distribution in the Transcarpathian region is very irregular (Fig. 2) (Habchak 2005). The big portion of landslides are confined to the Solotvyno depression (or Molasse Carpathians), showing characteristic relief inversion. In this region, before the year 1998 sixteen landslides had been mapped in three settlements. After the flood events in 1998, 1999 and 2001, additional 33 activated landslides were mapped.

The highest flood and landslide risk in the Eastern Carpathians is characteristic for the Teresva River basin (38% of the landslides in the Transcarpathian region). The density of landslide distribution changes from 0.3–0.4 unit/km^2 (near Lopukhiv and Ust' Chorna villages) to 0.7 – 0.9 units/km^2 and locally can reach up to 1.9 units/km^2. The high density of landslide distribution in this region is caused by suitable lithological conditions and high seismic activity. The overall area damaged by landslides in the Teresva River basin amounts to 130.15 km^2, in the Uzh River basin — 41.44 km^2, in the Rika River basin — 32.66 km^2, and in the Latorytsia River basin — 30.63 km^2.

Many areas of the Carpathian foothills are deforested and modelled by landslides that developed in the period of intensive snow melting and rainfall. The groundwater level rises up very quickly and processes are activated. Among landslides which have been activated after the extreme flood events we can separate two groups: 1) landslides formed in horizontally lying Neogene clays alternating with siltstones, sandstones, and limestones, 2) landslides formed within clayey flysch strata. These landslides are most hazardous for the automobile roads of the region.

MUDFLOWS

The floods in the Eastern Carpathians quite often cause mudflow processes. The geological structure and relief determine the potential mudflow hazards (Fig. 3). The regime of mudflow activization depends on the amount and intensity of precipitation.

In the Tisza River basin, the most hazardous regions are White-Tisza–Apshyts'kyi and Black-Tisza–Teresvyns'kyi, representing the zones of high risk.

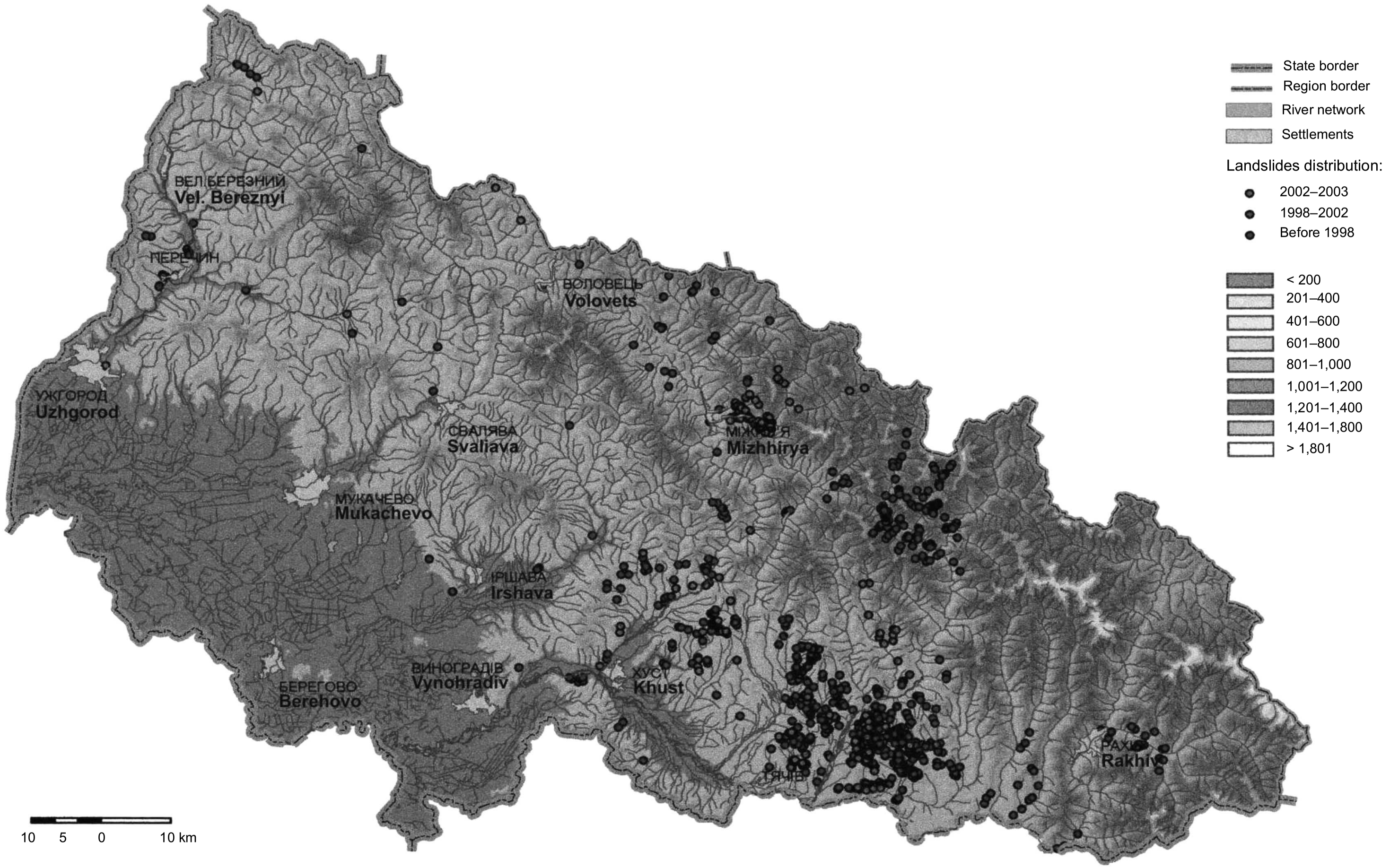

Fig. 2. Distribution of landslides in the Transcarpathian region (after Habchak 2005)

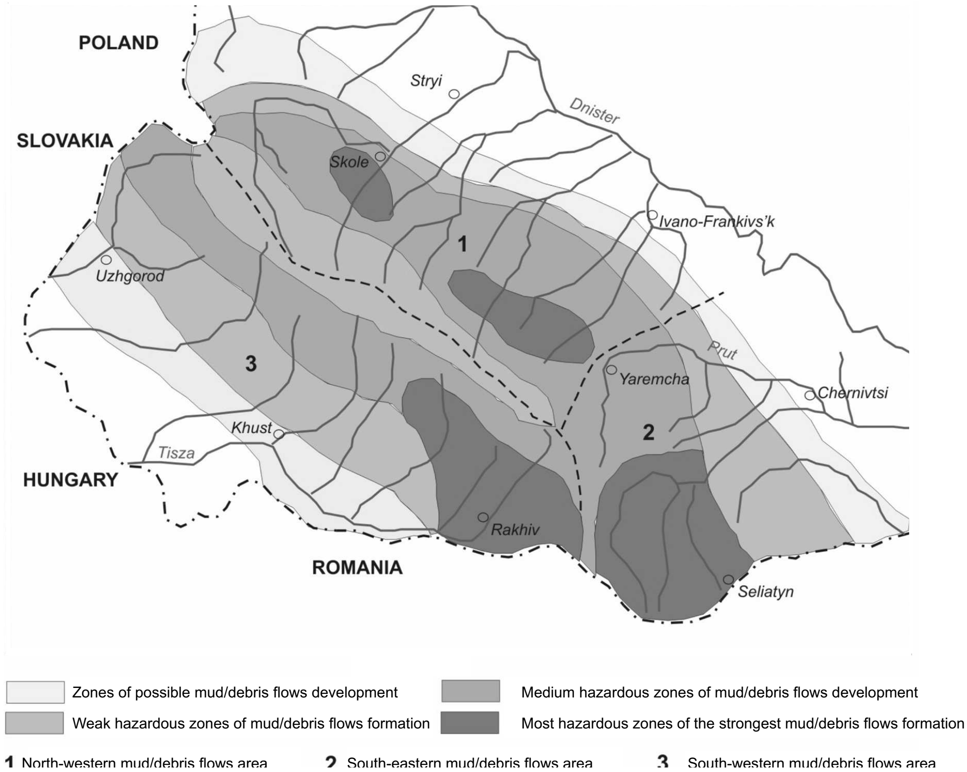

Fig. 3. Distribution of mudflows in the Eastern Carpathians

More than 160 mudflows have been mapped in the first and second areas (the average mudflow catchment area is 0.24–63.00 km^2, the average area of mudflows is 0.1–2.2 km^2).

The mudflow susceptibility of a catchment depends on the amount of rock material which is brought off outside the catchment from an area of 1 km^2. The Transcarpathian region is characterized by small mudflows (about 500,000 m$^3 \cdot$ km^{-2}) (*Substantiation*... 2001). The floods in 1998 and 1999 have shown that critical parameters for mudflow activization is precipitation of 100–200 mm/day and 0.1–0.2 mm $\cdot$ min^{-1} intensity. The impact of natural factors impact is redoubled by the complete deforestation of steep slopes and transportation of fallen trees, together with destruction of vegetation cover.

In the Krosno zone, two main types of mudflows have been determined. The first type is typical in the catchments with slope steepness about 40–50°, usually deforested. The mudflow thalwegs gradient changes from 35–50° in the headwaters to 25–30° in the transit zones (*Substantiation*… 2001). The water-debris and water-mud-debris flows are formed here. The second type of mudflows is characteristic for the Teresva River basin, dominated by bedrock composed of clayey flysch strata. Here water-mud and mud-debris types of mudflows are developed.

Somewhere we can also observe mudflows of the "dam-type" which are formed due to the blocking of river beds by landslides.

Other mudflow hazardous regions on the northern slope of the Carpathians are the Prut, White Cheremosh, Bystrytsia Nadvirnians'ka, Limnytsia, Chechva, and Svicha river basins (Holoyad et al. 1995). The mudflow catchments have usually cirque-like form, and the percentage of sediments fluctuates from 10–35 to 70%. The flows move with a speed of 3–4 $m \cdot s^{-1}$, and the duration of each event is 1.5–2.0 hours (Holoyad et al. 1995).

VERTICAL DEFORMATIONS OF THE RIVER BEDS

The strongest river bed deformations are confined to the mountain and pre-mountain parts of river valleys. The average suspended load in the upper Dnister River catchment varies between 10.0 (Shchyrka River; Shchyrets) and 634.5 (Rybnyk River; Maidan) tons per year from one square kilometre. The maximum values of suspended load are between 28.8 (Shchyrka; Shchyrets) and 4,400.0 (Rybnyk; Maidan) tons per year from one square kilometre. The sediments load changes, evaluated for the period of 1950–2000, are characterized by different trends. Decreasing tendencies were determined for the Dnister (Strilky; 300%), Dnister (Rozdil; 250%), Shchyrka (Shchyrets; 200%), and Holovchanka (Tuchlia; 50%) rivers, whereas increasing tendencies were recorded for the rivers of Bystrytsia (Ozymyna; about 300%), Opir (Skole; 200%), Stryi (Verkhnie Syniovydne; 80%) and Dnister (Halych; 50%). No apparent changes at Sambir (Dnister River) and Yamnitsia (Bystrytsia River) were detected.

The river bed deformations were calculated for same time period. Erosion dominates within the larger part of the Dnister River catchment. The highest intensity of erosion is confined to the river beds of Stryvihor (Luky; 62.5 mm/year), Ruzhanka (Ruzhanka; 45.0 mm/year), Slavs'ka (Slavs'ke; 35.0 mm/year), and Stryi (Verkhnie Syniovydne; 31.25 mm/year) (Table 2). Accumulation prevails in the Dnister (Sambir; 20.0 mm/year), Tysmenytsia (Drohobych; 20.0 mm/year), Shchyrka (Shchyrets; 7.8 mm/year), and Bystrytsia (Ozymyna; 6.25 mm/year) rivers. The Dnister (Rozdil), Stryvihor (Khyriv), and Stryi (Matkiv) rivers are characterized by relative stability of their channels.

Table 2

Intensity of vertical deformations of river beds in the upper Dnister River catchment

River	Settlement	Period [years]	Deformation [cm]	Average intensity [mm/year]
Dnister	Strilky	29	–40	–13.79
Dnister	Sambir	32	+64	20.00
Dnister	Rozdil	29	–8	–2.76
Dnister	Zhuravno	29	–10	–3.45
Stryvihor	Khyriv	7	–1	–1.43

River	Settlement	Period [years]	Deformation [cm]	Average intensity [mm/year]
Stryvihor	Luky	32	–200	–62.50
Vereshchytsia	Komarno	10	–16	–16.00
Shchyrka	Shchyrets	32	+25	7.81
Bystrytsia	Ozymyna	32	+20	6.25
Tysmenytsia	Drohobych	10	+20	20.00
Stryi	Matkiv	10	–1	–1.00
Stryi	Zavadivka	10	–5	–5.00
Stryi	Yasenytsia	10	–5.5	–5.50
Stryi	V. Syniovydne	32	–100	–31.25
Zavadka	Rykiv	7	–10	–14.29
Yablunka	Turka	32	–32	–10.00
Rybnyk	Maidan	7	–10	–14.29
Opir	Skole	10	–7	–7.00
Slavska	Slavske	10	–35	–35.00
Holovchanka	Tukhlia	32	–60	–18.75
Oriava	Sviatoslav	10	–5	–5.00
Ruzhanka	Ruzhanka	8	–36	–45.00

The main reasons for sediment load transformation are changes in land use structure, and exploitation of channel and floodplain carriers. Such features are caused by different level and duration of human impact.

The conducted analysis revealed that water runoff and sediment load changes were caused by intensive deforestation at the end of the 1950s–beginning of the 1960s, tilling of slope lands using hard agricultural machines and some increase of precipitation in the period of 1960–1975. Hence, human activity was the main cause of runoff transformation. This conclusion is confirmed by the created and analysed cumulative curves for water runoff, sediment load and precipitation, as well as by analysis of the map of sediment load changes which was constructed for the period of 1950–2000. The results of river bed vertical deformations are closely correlated with sediment runoff changes. For example, an increase in sediment load is observed in the Dnister River upstream of Sambir. For this part of the river, activization of fluvial processes due to gravel carriers functioning upstream of Sambir was ascertained. River bed vertical deformations of different trends and intensity are caused by both gravel exploitation and increasing water runoff. It is confirmed by different time cross-sections and characters of vertical deformations observed in other river systems of the Eastern Carpathians (Holoyad et al. 1995; Kovalchuk 1997).

AVALANCHES

The avalanches developed on steep mountain slopes (> 20°) are caused by a number of factors (relief morphology, depth of snow cover and its growing intensity, temperature and wind regimes, etc.; Maslova et al. 1999). In high mountain groups of the Eastern Carpathians, the avalanches are formed in February or March on slopes inclined at 20°–45°, with altitude 300–2,000 m. The longest avalanche pathways are more than 3 km long, averaging at 100–500 m. The avalanche core areas change from 1–5 to 40–50 hectares. The average avalanche recurrence is one per year (in the headwater catchments of the Tisza, Teresva, Shopurka, Tereblia, Latorytsia, Borzhava, and Rika rivers), sometimes — one per 2–3 years (Verkhovyna ridge, Uzh, Latorytsia and Borzhava headwaters; Maslova et al. 1999).

In February 1999, the snow procurement was 3–4 times higher than the many-year normal. It led to development of mass avalanches, the volume of snow amounting to 300–500 thousands cubic metres. Many avalanches blocked the roads and small river beds. Locally, debris cones were up to 20 m high.

CONCLUSIONS

1. The geographic features of water runoff and sediment load runoff distribution determine the potential, type, and space distribution of hydro-geomorphic processes. The dynamics of runoff regime determines the intensity of the latter.
2. Analysis of flood formation and development point to landscape-climatic and man-made causes of these processes in the Eastern Carpathians. Among the first factors, the most important are the totals (1,000–1,600 mm), intensity (1.3–7.4 mm · min^{-1}), and duration of precipitation, as well as the area affected by rainfall (up to 10–20 thousands km^2), slope inclination, state of vegetation cover, soil and bedrock characteristics, etc. Among man-made factors, the most considerable are the changes of vegetation cover, deforestation, slope tillage, intensive pasturing, channel state, changes of soils characteristics, and so on.
3. Analysis of landslides formed in the period of 1998–2004 shows that landslide types are determined by geological structure; big landslides are usually tectonically-controlled.
4. The trends of river bed deformations, their scale and intensity are correlated with long-term water runoff and sediment load changes, as well as with human impact upon river beds and their catchments.
5. Rainfalls with intensity of 100–200 mm/day and 0.1–0.2 mm · min^{-1} lead to activization of mudflows in the region. This factor is redoubled by complete deforestation of steep slopes and transportation of fallen trees, with the destruction of vegetation cover.

6. The main types of avalanches in the region are soggy-snow based and dry-snow based. The avalanche intensity is very irregular and changes from year to year, depending on snow procurement.
7. Data obtained from field studies, calculations, and GIS-modelling are crucial for ascertaining the potential hazards and risk posed by actual geomorphic processes.

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STRESZCZENIE

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EKSTREMALNE PROCESY GEOMORFOLOGICZNE W KARPATACH WSCHODNICH: ZAKRES, PRZYCZYNY, ROZWÓJ, AKTYWIZACJA I INTENSYWNOŚĆ

Ruchy masowe typu osuwania, spływy błotne i inne procesy geomorfologiczne wystąpiły w ukraińskich Karpatach Wschodnich po wielkich powodziach w latach 1969, 1971, 1998 oraz 2001. Spowodowały wielkie szkody materialne oraz ofiary w ludziach. Analizy przebiegu powodzi, transportu materiału w rzekach oraz rejestracje zmian w rzeźbie dolin wykonano w dorzeczu dolnego Dniestru podczas tych zdarzeń ekstremalnych. Wyróżniono rzeźbotwórcze procesy dominujące i towarzyszące (drugorzędne). Do grupy pierwszej włączono erozję, osuwanie, spływy ziemne, lawiny, krasowienie oraz działalność człowieka. Do grupy drugiej włączono procesy eoliczne, denudację chemiczną i biochemiczną. Określono wskaźniki intensywności procesów oraz oszacowano wielkość niektórych zmian w rzeźbie Karpat Wschodnich.