Chapter 8
Recent Landform Evolution in the Ukrainian Carpathians

Ivan Kovalchuk, Yaroslav Kravchuk, Andriy Mykhnovych, and Olha Pylypovych

Abstract In the Ukrainian Carpathians the boundary between the forest and subalpine belts (at about 1,400–1,500 m) divides different systems of geomorphic processes. In the subalpine belt mass movements, gully erosion and nivation dominate and affect the slopes of extensive erosional surfaces. Avalanches occur on slopes with inclinations of 20–45° at elevations of 300–2,000 m. Neotectonic uplift and denudation rates are in approximate equilibrium (both 1.5–2.5 mm $year^{-1}$). Gullies and ravines are the most widespread form of erosion at lower elevations. There are three types of karst in the Ukrainian Carpathians: carbonate, sulfate, and salt karsts. In recent decades human impact on geomorphic processes has intensified and landslides, debris flows, and extreme floods have become more frequent. The alterations in the water and sediment discharges and channel morphology of rivers are good indicators of environmental changes.

Keywords Water erosion • Debris flows • Avalanches • Sheet erosion • Gully erosion • Floods • Channel evolution • Nivation • Karst • Human impact • Ukrainian Carpathians

---

I. Kovalchuk (✉)
Department of Geodesy and Cartography, Faculty of Land Use, National University of Nature Use and Life Sciences of Ukraine, Vasylkivs'ka Str. 17/114, 03040 Kyiv, Ukraine
e-mail: kovalchukip@ukr.net

Y. Kravchuk
Department of Geomorphology, Faculty of Geography, Ivan Franko National University of Lviv, Doroshenko Str. 41, 79000, Lviv, Ukraine
e-mail: 2andira@ukr.net

A. Mykhnovych • O. Pylypovych
Department of Applied Geography and Cartography, Faculty of Geography, Ivan Franko National University of Lviv, Doroshenko Str. 41, 79000 Lviv, Ukraine
e-mail: 2andira@ukr.net; olha@tdb.com.ua

D. Lóczy et al. (eds.), *Recent Landform Evolution: The Carpatho–Balkan–Dinaric Region*, Springer Geography, DOI 10.1007/978-94-007-2448-8_8,

8.1 The History of Geomorphological Investigations in the Ukrainian Carpathians

The history of research into recent geomorphological processes in the Ukrainian Carpathians is summarized in a range of papers (Krawczuk 1999, 2003; Kovalchuk 1997; Kovalchuk and Kravchuk 2001; Shushniak 2004). One of the first scientific papers dedicated to the Ukrainian Carpathians was written by the Polish geographer W. Pol (1807–1872) on the Tatra, Beskyds, Petros (Horhany), Polonynas, Chornohora, Pokuttia, and Bukovyna regions (Pol 1851). In the subsequent period research was conducted by the State Geological Institute of Austro-Hungary, established in Vienna in 1849.

The *Department of Geography at Lviv University* was founded in 1882. Its first head, A. Reman, was the author of a regional physico-geographical atlas of Poland and the Carpathians. H. Velychko (1863–1932) published the monograph "Relief of Polish–Ukrainian lands with special attention to the Carpathians" (1889) and was the first to regionalize the Carpathian Mountains. E. Romer (1871–1954) and S. Rudnyts'kyi (1877–1937) studied the origins and geomorphic development of mountains ridges, river valleys, and mountain glacial features (Shushniak 2004; Romer 1909). Rudnyts'kyi ascertained the existence of denudation surfaces in the Beskids and their absence in the Horhany, and revealed the different character of river valleys formed in different regions of the Carpathians. Based on expeditions, E. Romer carried out detailed morphostructural analyses of the Eastern Carpathians and elaborated a genetical-chronological approach to the Dnister river valley. After World War I experts of the Polish State Geological Institute and the Warsaw University were also involved in research. B. Sviders'kyi (1892–1943) is known for his monograph "Geomorphology of Czarnogora (Chornohora)" (1937), supplemented with a pioneering large-scale geomorphological map of Chornohora at a scale of 1:25,000. In 1922, during the 13th International Geological Congress in Bruxelles, the Carpathian Geological Association was founded. Its meetings promoted the study of Carpathian geomorphology (Shushniak 2004).

After World War II the government of the *Soviet* Union launched several scientific *expeditions* to the region. The best-known researchers were H. Alferyev and I. Hofstein from the State Carpathian Scientific Research Institute in Boryslav. Morphotectonical and geomorphological investigations were carried out by collaborators at the Lviv (P. Tsys', S. Subbotin), Chernivtsi (B. Ivanov, K. Herenchuk) and Moscow (A. Spiridonov) universities, the Moscow Geological Survey (A. Bogdanov, M. Muratov, G. Raskatov), the Lviv Branch of Ukrainian Geological Survey (M. Yermakov, M. Zhukov), the Leningrad Oil Institute (O. Vyalov) (Shushniak 2004; Professor… 2004).

In 1950 the *Department of Geomorphology* was founded at the Lviv University by Petro Tsys', a representative of regional geomorphological analysis. His achievements were the first detailed geomorphological regionalization and morphostructural analysis of the Ukrainian Carpathians (1956), the study of neotectonic (Tsys' 1956) movements, and the determination of the main phases of the geomorphic evolution of the Carpathians with special attention to the development of river valleys and denudational-accumulational surfaces. During next 20 years a set of papers were published on the problems of morphotectonics (P. Tsys', K. Herenchuk), river valleys development (M. Kozhurina), and denudation surfaces (Ya. Kravchuk) (Kravchuk 2001; Professor… 2004).

The Department of Geomorphology was engaged in regional geomorphology (initiated by P. Tsys'), engineering geomorphology (Ya. Kravchuk), experimental and environmental geomorphology (I. Kovalchuk), and paleogeography of the Pleistocene (A. Bohuts'kyi). Experimental and field investigations of recent geomorphologic processes of the Ukrainian Carpathians were carried out by O. Boliukh, Ya. Kravchuk, M. Kit, D. Stadnyts'kyi, I. Kovalchuk, M. Aizenberg, A. Oliferov, Ya. Khomyn, R. Slyvka, and V. Shushniak. The formation of denudational surfaces, the problems of geomorphologic regionalization and the morphosculpture of the Ukrainian Carpathians have been studied by Yaroslav Kravchuk. Engineering geomorphology and nature conservation planning appear in Ya. Kravchuk's, Yu. Zin'ko's, V. Brusak's, and N. Karpenko's works. Geomorphologic mapping projects have been carried out by Ya. Kravchuk, R. Hnatiuk, and V. Shushniak. Problems of paleogeography are studied by A. Bohuts'kyi and his students A. Yatsyshyn and R. Dmytruk. Relief genesis and the history of river valley development in Bukovyna at that period were also studied by geographers of Chernivtsi University (B. Ivanov, M. Kozhurina, M. Kunytsia, V. Lebediev, N. Krasuts'ka). In the 1980s and 1990s a new direction of geomorphological research, regional environmental-geomorphological analyses emerged (encouraged by Ivan Kovalchuk) and practiced by M. Symonovs'ka, L. Dubis, A. Mykhnovych, O. Pylypovych, N. Yedynak, S. Volos, and others.

An increased interest of the Lviv geomorphologists in the investigation of *recent exogenic processes* is observed since the mid-1960s (Tsys' 1964; Tsys' et al. 1968). In addition to field surveys and experiments, recently remote sensing methods are also used in geomorphological mapping, dynamic geomorphology, planning of landform protection and monitoring. In 1966–1969 a working group on recent exogenic processes in Carpathians was formed at the Lviv University under the coordination of Oleh Boliukh. In 1972 on the initiative of O. Boliukh and O. Skvarchevs'ka stationary and semistationary investigations of erosional processes began in the Precarpathians. The results were published in numerous monographs, dissertations, and papers (Skvarchevs'ka 1962; Boliukh et al. 1976; Holoyad et al. 1995; Kovalchuk 1997; Kravchuk 1999, 2005; Slyvka 2001). The results of observations on erosional and accumulative processes at *research stations* (runoff experiments, rainfall simulations) were presented in numerous papers (Boliukh et al. 1976; Tsys' et al. 1968; Kovalchuk et al. 1978; Professor… 2004; Problems… 2008; Relief… 2010). Karst processes, mudflows, and landslides have been investigated at stations over the past 30–40 years under the coordination of G. Rud'ko.

Since the 1990s, on the initiative and under coordination of I. Kovalchuk, river systems and their changes due to the *impact of* natural and *human factors* have been intensively studied (Kovalchuk 1997; Mykhnovych 1998; Kovalchuk et al. 2000, 2008; Bogacki et al. 2000; Kowalczuk and Mychnowicz 2009). Hydrogeomorphological hazards (Kovalchuk et al. 2008; Romashchenko and Savchuk 2002; Lymans'ka 2001) and various types of exogenous geomorphic processes are further investigated (Kovalchuk 1997; Slyvka 1994; Holoyad et al. 1995; Kravchuk 1999, 2005; Rud'ko and Kravchuk 2002; Kovalchuk and Mykhnovych 2004; Dubis et al. 2006), also at the Kyiv (Rud'ko et al. 1997; Obodovs'kyi 2001), Chernivtsi (Yushchenko 2009), Tavrian (Oliferov 2007), Rivne (Budz and Kovalchuk 2008), and Transcarpathian universities (Habchak 2010).

8.2 Geomorphological Regions

Most of the scientists mention the marked *vertical and horizontal zonation* of the Ukrainian Carpathians. Typical geomorphological surfaces (Tsys' 1968) are the denudation surfaces of summit levels, gently denuded upper terraced slopes at medium levels, and clearly discernible terraces at lower elevations of the mountains. The geomorphologic regions distinguished are the Precarpathian and Transcarpathian plains, Lump (Skybovi in Ukrainian), the Dividing Verkhovyna, Polonyna-Chornohora, Volcanic Carpathians, and Marmarosh Massif (Fig. 8.1, Table 8.1).

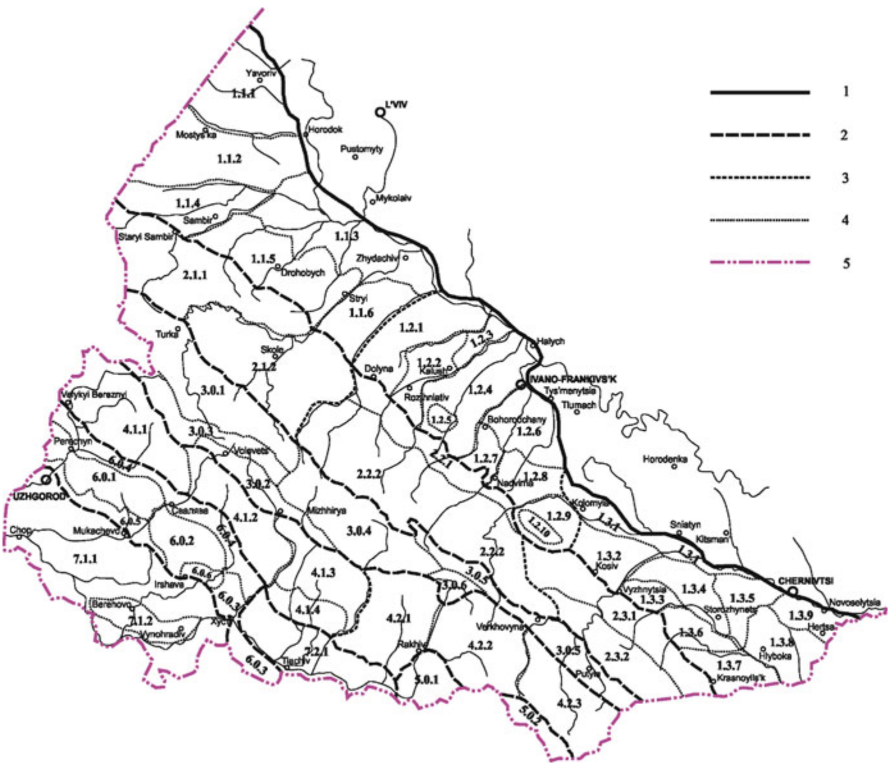

Fig. 8.1 Geomorphological units of the Ukrainian Carpathians

Table 8.1 Geomorphological units, their genetic types, and main geomorphic processes in the Ukrainian Carpathians

Geomorph. province	Geomorph. region	Geomorph. subregion	Geomorphological district	Genetic type of relief	Exogenic geomorphic processes
Eastern Carpathians (subprovince Forested or Ukrainian Carpathians)	Precarpathian premountain highland (1)	Pre-Beskid (Northwestern) Precarpathians (1.1)	Sian Plain (1.1.1)	Moraine-outwash-alluvial plain	Relict landslides, karst, activation due to human activity
			Sian-Dnister Highland (1.1.2)	Hills with glacial and fluvioglacial landforms	Erosion and landslides
			Upper Dnister Plain (1.1.3)	Alluvial	Bank erosion, floods
			Stryvihor Highland (1.1.4)	Erosional-accumulational with glacial landforms	Sheet and bank erosion
			Drohobych Highland (1.1.5)	Erosional-accumulational	Sheet and gully erosion
			Morshyn Highland (1.1.6)	Erosional-accumulational	Sheet and gully erosion
		Pre-Horhany (Central) Precarpathians (1.2)	Zalissia (Svicha) Highland (1.2.1)	Erosional-accumulational	Sheet and gully erosion
			Kalush Valley (1.2.2)	Accumulational plain	Bank erosion, karst
			Voinyliv Highland (1.2.3)	Erosional-accumulational	Sheet and gully erosion
			Lukva Highland (1.2.4)	Erosional-accumulational	Sheet and gully erosion
			Maidan Low Mountains (1.2.5)	Structural-erosional	Erosion
			Bystrytsia Valley (1.2.6)	Accumulational plain	Bank erosion
			Bystrytsia Highland (1.2.7)	Denudational	Sheet and gully erosion, landslides, debris flows
			Prut–Bystrytsia Highland (1.2.8)	Erosional-accumulational	Sheet and gully erosion, landslides.

(continued)

Table 8.1 (continued)

Geomorph. province	Geomorph. region	Geomorph. subregion	Geomorphological district	Genetic type of relief	Exogenic geomorphic processes
			Prut–Liuts'ka Highland (1.2.9)	Erosional-accumulational	Erosion, landslides
			Sloboda–Runhur Low Mountains (1.2.10)	Structural-erosional	Sheet and gully erosion, landslides, defluction
		Pokuttia-Bukovyna (Southeastern) Precarpathians (1.3)	Kolomyia–Chernivtsi Plain (1.3.1)	Alluvial plain	Bank erosion
			Pokuttia Highland (1.3.2)	Sculptural	Erosion, landslides
			Bahnens'ka Plain (1.3.3)	Alluvial plain	Sheet and gully erosion, bog processes
			Brusnyts'ka Highland (1.3.4)	Structural-erosional	Erosion, landslides
			Chernivtsi Highland (1.3.5)	Structural-sculptural	Erosion, landslides
			Siret Highland (1.3.6)	Erosional-accumulational	Sheet and gully erosion, landslides
			Krasnoil highland (1.3.7)	Erosional-accumulational	Sheet and gully erosion, landslides
			Tarashan Highland (1.3.8)	Structural-erosional	Erosion, landslides
			Hertsaiv Highland (1.3.9)	Structural-erosional-accumulational	Erosion, landslides

Lump Carpathians (2)	Beskids (2.1)	Upper Dnister Beskids (2.1.1)	Anticlinal low mountains	Erosion, mudflows, landslides
		Skole Beskids (2.1.2)	Monoclinal-lump low mountains	Erosion, mudflows, debris flows, landslides
	Horhany Mountains (2.2)	Low mountains of the Lump Horhany (2.2.1)	Monoclinal-lump low mountains	Erosion, mudflows, landslides, debris flows
		Middle mountains of the Lump Horhany (2.2.2)	Monoclinal-lump middle mountains	Erosion, mudflows, landslides, debris flows
	Pokuttia–Bukovyna Carpathians (2.3)	Pokuttia–Bukovyna Low Mountains (2.3.1)	Structural-denudational low mountains	Erosion, landslides
		Pokuttia–Bukovyna Middle Mountains (2.3.2)	Anticlinal denudational middle mountains	Erosion, landslides, debris flows
Dividing-Verkhovyna Carpathians (3)		Stryi–Sian Verkhovyna (3.0.1)	Structural-denudational low mountains	Mudflows, landslides, structural-tectonic landslides
		Volovets'-Mizhhirya Verkhovyna (3.0.2)	Structural-denudational low mountains	Mudflows, landslides, structural-tectonic landslides
		Dividing Verkhovyna (3.0.3)	Structural-denudational low mountains	Mudflows, landslides
		Deviding Horhany (3.0.4)	Anticlinal-lump middle mountains	Stone fields, debris flows, mudflows
		Vorokhta–Putyla Low Mountains (3.0.5)	Relict longitudinal valley	Erosion, landslides
		Yasinia Valley (3.0.6)	Terraced erosional low mountains	Erosion, landslides

(continued)

Table 8.1 (continued)

Geomorph. province	Geomorph. region	Geomorph. subregion	Geomorphological district	Genetic type of relief	Exogenic geomorphic processes
	Polonyna-Chornohora Carpathians (4)	Polonyna Ridge (4.1)	Polonyna Rivna (4.1.1)	Lump middle mountains with denudational surfaces	Erosion, landslides, mudflows, debris flows
			Polonyna Borzhava (4.1.2)	Lump middle mountains with denudational surfaces	Erosion, debris flows, landslides, mudflows
			Polonyna Krasna (4.1.3)	Lump middle mountains with denudational surfaces	Erosion, debris flows, landslides, mudflows
		Svydivets'–Chornohora massif (4.2)	Svydivets' Massif (4.2.1)	Lump Alpine and middle mountains	Erosion, debris flows, avalanches
			Chornohora Massif (4.2.2)	Lump Alpine and middle mountains	Mudflows, avalanches
			Hryniava and Losova (4.2.3)	Lump middle mountains with denudational surfaces	Erosion, gravitational, mudflows
	Marmarosh Crystalline Massif (5)		Rakhiv Mountains (5.0.1)	Vaulted lump Alpine and middle mountains	Gravitational, mudflows, avalanches
			Chyvchyny (5.0.2)	Vaulted lump Alpine and middle mountains	Gravitational, mudflows, avalanches
	Volcanic Carpathians (6)		Makovytsia–Syniak Massif (6.0.1)	Volcanic-erosional	Erosion, debris flows
			Velykyi Dil Massif (6.0.2)	Volcanic-erosional	Erosion, debris-flows
			Tupyi-Oash Massif (6.0.3)	Volcanic-erosional	Erosion, debris-flows

			Berezne–Lipchans'ka (Turyans'ka) Valley (6.0.4)	Volcanic-erosional	Erosion, landslides
			Transcarpathian Hills (6.0.5)	Pliocene-Pleistocene denudational-accumulational	Erosion, landslides
			Irshava Valley (6.0.6)	Intermountains denuda-tional-alluvial valley	Bank erosion, floods
	Trans-carpathian Plain (7)	Chop-Mukachevo plain (7.1)	Tysa Alluvial Plain (7.1.1)	Alluvial valley	Bank erosion. Floods
			Berehove Hills (7.1.2)	Denudational-accumulational plain with volcanic remains	Sheet and gully erosion
		Upper-Tysa (Solotvyno) valley (7.2)		Denudational-accumulational low mountains with terrace complex and salt hill remnants	Erosion, salt karstification, landslides

The dividing line between the *forest* and subalpine *belt*s runs at about 1,400–1,500 m elevation and separates different systems of geomorphic processes and assemblages of landforms. The summit surfaces (at 1,400–2,000 m) and their slopes are in the *subalpine belt* (the Polonyna-Chornohora Carpathians, Lump, Dividing (Internal) Horhany Mountains and in the Marmarosh Massif), where processes of slow debris movements, gravitational, nival processes, and avalanches dominate. Here debris of different fractions (1–300 cm diameter) moves slowly downslope at 2–4 mm year^{-1} average rate. Stone streams are 1–6 m wide and, tens to hundreds of meters long.

In the strongly dissected middle to high mountains mass movements are accompanied by sheet wash and gully erosion. Most intensive gravitational and erosion processes are observed on steep slopes (with inclinations over 12°) and on precipices. Between elevations from 900–1,000 m to 1,400–1,500 m, on the wide, steep (5–12°) to very steep (12–25°), strongly dissected slopes with a discontinuous vegetation cover, slow movements of water saturated soils with various amounts of debris are observed.

In terraced and non-terraced *river valleys* (at elevations from 500–600 m to 900–1,000 m) a variety of geomorphic processes are active, but intensive river channel erosion and accumulation as well as mudflow accumulation are predominant.

Neotectonic movements also influence geomorphic processes. Measurements at research stations testify that the denudation rate in the Drohobych Highland (Precarpathians) is 0.35 mm year^{-1}. If other processes (landslides, mudflows, gully erosion etc) are also taken into account, total denudation amounts to 1.5–3 mm year^{-1}. The rate of total denudation in the Ukrainian Carpathians calculated by I. Hofstein (1995), based on measured parameters of sediment delivery from Carpathian river basins, is 2.3 mm year^{-1}. According to V. Somov and I. Rakhimova (1983) tectonic uplift in the Ukrainian Carpathians and Precarpathians is 1.5–2.5 mm year^{-1}. Thus, the comparison of denudation and tectonic movements points to a self-regulating dynamic equilibrium.

8.3 Climate and Human Impact

The main *climatic characteristics* that control geomorphic processes are the following:

1. Precipitation is 1,400–1,700 mm year^{-1} in the mountains and 700–1,000 mm year^{-1} in the Precarpathian and Transcarpathian plains.
2. Frequent heavy rainfall events over extensive areas constitute ca 40% of the monthly amounts.
3. During rainfalls above 70 mm day^{-1}, which make up 48% of all heavy rains, the infiltration capacity of brown forest soils is exceeded and intensive erosion, floods, mudflows, landslides, damaging agricultural fields, roads, bridges, dykes and dams, ensue. Heavy rains of 200–300 mm day^{-1} intensity can continue for even 3 days.

4. Rainfall intensity can reach up to 7 mm min^{-1} for 10–30 min on slopes of 20–50°. The surface runoff coefficient from catchments of 100–200 km^2 area ranges from 2.5 to 3.1 m^3 s^{-1} km^{-2} (Kovalchuk 1997), and from catchments of 300–500 km^2 it is 1–2 m^3 s^{-1} km^{-2} in the mountains and 0.5–0.2 m^3 s^{-1} km^{-2} in the plains.
5. Strong winds with speed over 25 m s^{-1} as well as squalls and hurricanes with 40 m s^{-1} are observed almost every year and cause tree uprooting, snowdrift and avalanches.
6. Strong snowfalls (up to 40 cm deep snow per event) are also quite common (with 60–80% probability). Maximal snow depth is 3–4 m. Fast thawing causes extreme winter and spring floods.
7. Total yearly runoff equals 18.3 km^3, while the average specific runoff 0.008–0.038 m^3 s^{-1} km^{-2}, with maximum values observed in the Transcarpathians.

After rainfalls of at least 20 mm day^{-1} intensity floods are formed, and over 100 mm day^{-1} extremely high floods with water levels rising 2–4 m are generated. In mountains the width of the flooded zone ranges from 20–60 (for small rivers) to 120–500 m (for medium rivers), and 600 m–2.5 km (for the medium and large rivers in the foothills of the Pre- and Transcarpathians), while in the plains it is 2.5–5 km or even more. Stream current velocity is 2–3 m s^{-1} in the foothills, 4–5 m s^{-1} in the mountains, and up to 10 m s^{-1} along small rivers.

In recent decades human impact upon the environment, including topography and geomorphic processes, became so intense that there are significant disturbances even in the forested Ukrainian Carpathians. The following *consequences of human activities* significantly influence the distribution and operation of geomorphic processes:

1. Decreasing forest cover in the Carpathians from 75–90% to 40.2% (over the past 200 years), caused by intensive and large-scale clearance for the timber industry. It is generally accepted that a forest cover area below 35% is critical from a geomorphological aspect. In the 1960s and 1970s this critical threshold was already observed in many Carpathian subregions, particularly in foothills and low mountains.
2. The 200–300 m lowering of the upper timberline due to complex reasons, cattle grazing being the principal one.
3. Destroying crooked forests that can retain snow and water on the slopes and ridges and slow down the thawing process.
4. Changes in the species structure of forests. For instance, more than 100 thousands hectares are occupied by spruce trees *(Picea abies),* but this kind of forest cannot efficiently retain water on slopes (Hensiruk 1992). Also the changes of age structure (more than 70% of young and medium forests) are of significance. As it is known old forests can slow down runoff from a 70–100 mm rainfall event and conduct rainwater to the groundwater. Unfortunately, forests of 80 years are preserved only over 16–20% of the area.
5. Imperfect technologies and intensive forest clearance (800 000 m^3 wood per year) cause intensive erosion (removal of up to 300 t ha^{-1} soil). During the last 40 years 20 million m^3 of timber was extracted.

6. Arable land (>20% of total area) is expanding over steep slopes.
7. Heavy exploitation of mountain pastures (local name “polonyna”) with a total area about 100,000 ha, deteriorating their ecological state.
8. Development of transport (wood transportation, pipelines, electricity transmission lines etc). The total length of the pipelines within the Transcarpathian region is about 2,500 km.
9. Insufficient maintenance of hydroengineering structures. In the Transcarpathian region alone there are 646 dykes and 245 km of embankments, most of them in need of restoration. There are 378 km of dykes in the Upper Dnister river basin, most of them built in the 1960s and 1970s (65% of them need reconstruction).

Geomorphic processes along the Carpathian sections of the Dnister, Prut, and Tysa Rivers greatly intensified between 1947 and 1970. With the renewal of forests some stabilization followed after 1970. But since 1990s exogenic processes have intensified again due to deforestation, causing destructive floods (in 1997, 1998, 2001, 2004, 2008, and 2010).

8.4 Water Erosion

8.4.1 Sheet Erosion

Erosional processes are widespread almost in all geomorphological regions of the Ukrainian Carpathians, but the largest areas affected by them are located in the economically most developed regions of Carpathians. The main factors of sheet erosion are slope characteristics and structural-lithological features (the occurrence of loamy sediments). An intensification of sheet erosion is also typical for the river valleys with arable land and settlements.

The findings of investigations carried out at research stations of the Precarpathian plain in 1970s (Boliukh et al. 1976) and in 1980s in the Irshava Valley of the Volcanic Carpathians (Khomyn and Bilaniuk 2010) allow determination of *erosion rates under various crops*: for grassland: 0.003 mm year^{-1}; for wheat and rye: 0.03 mm year^{-1}; for weeds: 0.4 mm year^{-1} and for summer crops 1.7 mm year^{-1}. Taking into account the harvest areas of crops, the overall average intensity of surface erosion in the Precarpathians is calculated to be 0.35 mm year^{-1}. According to I. Kovalchuk (1997), the average rate of soil removal in Precarpathians ranges from 8.7 to 45.0 t ha^{-1} year^{-1}, i.e. a soil layer of 0.86–3.2 mm year^{-1} (4–16 times above the acceptable maximum value). The rate of chemical denudation was determined for spring thawing as 13.9 kg ha^{-1}. The ratio between solid material removal and chemical denudation for 1 km^2 is 6–1.

The *erosion of banks* of ravines, streams and meandering rivers is widely observed in the Ukrainian Carpathians. The highest rates are recorded during extreme floods and flash floods in flysch (argillites and siltstones) areas and alluvial and deluvial Quartenary sediments, typically at meanders of different size and shape along the rivers of the Beskids (Stryvihor, Dnister, Stryi), which have formed not later than Pliocene–Pleistocene. Most intensive erosion processes in the Lump Carpathians are observed usually downstream 'lumps' (ridges). Heavily eroded first, second, and third terraces are found in river valleys of the Beskids Mountains. In the Horhany Mountains major erosion can be observed not only within the transversal main river valleys, but also along the longitudinal tributaries (e.g., the Limnytsia) in synclinal valleys of unconsolidated sediments. In the Polonyna–Chornohora Carpathians and the Marmarosh Massif the distribution and intensity of erosion are well correlated with vertical belts: channel erosion and bank undercutting are common at lower elevations (500–900 m). The destruction of the lower terraces in narrow V-shaped valleys is observed along all the major rivers (the Tysa, Teresva, Tereblia, Rika, Latorytsa and Uzh).

8.4.2 Gully and Ravine Erosion

Gullies and ravines are the most widespread form of erosion in the Precarpathian and Transcarpathian regions. Bank, slope, top and bottom gullies are all present. *Slope ravines* (fixed and active) are spread on the slopes of the Maidan and Sloboda-Runhuns'ka low mountains, and on the Stryvihor–Dnister, Dnister–Bystrytsia Pidbuz'ka, Bystrytsia Solotvyns'ka–Bystrytsia Nadvirnians'ka, Liuchka Pistynka–Rybnytsia, and Prut–Siret interfluves. Ravines develop in loams and clays, often covered by thick layers (5 m and more) of eluvial-deluvial sediments. Their depths vary between 2 and 6 m. *Bank ravines* are much deeper (10–12 m and more) on the interfluve between the Prut and Bystrytsia Nadvirnians'ka Rivers. Within the Outer Precarpathians (near the Dnister River valley) gully networks develop in thick layers of Badenian and Sarmatian clays.

In the Transcarpathians gully and ravine erosion is observed in foothills as well as in the Solotvyno (Upper Tysa) valley. In contrast to the Precarpathians, here ravines develop in alluvial sediments of tens of meters thickness as usual. The densest gully network (0.4–0.6 km km^{-2}) is observed on the interfluves between the Tysa and Uzh Rivers in the Transcarpathian foothills and in the Solotvyno valley.

In the Lump and Dividing Verkhovyna Carpathians most of the gullies are located in the Menilitic and Krosno sediment complexes. Bank ravines are related to the margins of medium and high terraces with relatively thick layers of alluvial sediments. In the Beskids both fixed and actively developing ravines are located between the Vyrva–Stryvihor, Stryvihor–Dnister Rivers and in the Dnister and Trukhaniv valleys.

Gully and ravine erosion in the Horhany section of the Lump Carpathians is mostly located in the outer low mountain ranges: in the Vyhoda, Pniv-Nadvirna, and Deliatyn valleys, on interfluves between the rivers Bystrytsia Solotvyns'ka–Maniavka–Bystrytsia Nadvirnians'ka, on the right side of the Prut river valley.

Somewhere the slope ravines (fixed and active) can reach significant *dimensions*, particularly on interfluves, like the Bystrytsia Solotvyns'ka–Maniavka near the villages Krychka and Maniavka in clays with up to 1.5 m thickness. Gully dimensions vary between quite wide limits: for length from 70 to 150 m, for width from 5 to 15 m, and for depth from 3 to 12 m.

In the Dividing Verkhovyna Carpathians gully and ravine erosion is common in the San river valley, between the rivers Dnister and Yablun'ka, near the village Vovche on the slopes of the Boryn'ka catchment. Slope ravines are developed in the basins of the Vicha, Rika, Studenyi, Holiatunka and Pryslip Rivers. Near the village Nyzhni Vorota gullies incise into the floors of old wide, already fixed, ravines (balkas) (Slyvka 2001).

8.5 Mass Movements

8.5.1 Debris Flows

Debris flows in the Ukrainian Carpathians fall into two locally identified types: *"water-and-stone flows"* and *"debris floods."* The first type is characterized by high sediment loads (to 30% of the volume), fine debris <10%, thalweg inclination >0.10, and bulk density of 1.15–1.55 $g\,cm^{-3}$ (Rud'ko and Kravchuk 2002). This type of debris flow is rather rare, one event happens in 25–50 years. Debris floods are more frequent and contain 10–20% sediment load.

The most favorable regions for debris flows in the Ukrainian Carpathians are the Lump and the Polonyna-Chornohora Carpathians and the Marmarosh Massif. Especially intensive flows are characteristic for the boundaries between geomorphological regions: for instance, between the Lump and Dividing Verkhovyna Carpathians (Krosno Zone), between the Dividing Verkhovyna and Polonyna-Chornohora Carpathians, and between the Chornohora and Marmarosh Massif. In the Lump Carpathians they occur in almost all catchments. In the Beskids and Pokuttia–Bukovyna Carpathians debris flows are often associated with landslides and gullies. Numerous flows are observed in the Stryi and Opir catchments. Mud-and-stone flows periodically take place in the catchments of the Cheremosh and Siret Rivers as well as along the Pistynka River headwaters. Most of the debris flows occur in Horhany Mountains: in the Prut river basin along the streams on the Mahura slopes and along numerous tributaries of the Zhenets', Zhonka and Prut Rivers, induced by intensive sheet erosion and landslides. Debris flows associated with gravitational processes were described from several catchments of the Bystrytsia Solotvyns'ka basin. Large amounts of stone-loamy debris come into the main riverbed and induce debris floods as at the Limnytsia headwaters and tributaries. In the Polonyna-Chornohora Carpathians debris flows of mixed type predominate and their calculated bulk density ranges from 1,120–1,190 kg m^{-3} (along the Lems'kyi River in the Bila Tysa catchment) to 1,800–1,900 kg m^{-3} (in the Teresva and Apshytsia basins, where mean slope inclination is 0.12–0.25) (Rud'ko and Kravchuk 2002).

Debris flows in the Ukrainian Carpathians originate from the following types of source area: sliding, deluvial-debris, rockfall, mudstream, alluvial, and snow-slide centers. According to investigations at the Prutets' Chemehyvs'kyi research station, debris accumulation takes 5–7 years. During this time 10–15 thousands m^3 of the sediments accumulate in riverbeds of 3–5 km length. *Sliding centers* develop along the contact area (Krosno Zone) between the Lump and Polonyna-Chornohora Carpathians (inner flysch anticlinorium). *Deluvial-debris centers* dominate on the slopes of the Lump and Dividing Horhany, Svydivets' massifs and in the middle mountains of Pokuttia and Bukovyna. *Rockfall centers* of coarse debris and limited extension are related to high and steep slopes composed of massive sandstones, limestones or crystalline rocks. *Mudstream centers* are located in areas with shallow groundwater table and also of limited dimensions and low (0.5–0.7 m) sediment thickness. *Alluvial centers* are observed in the Mlyns'kyi catchment (Cheremosh river basin) with a total of 60 thousands m^3 of alluvium (along the 6.5 km section of the Mlyns'kyi stream, 0.94 m^3 of alluvium per 1 m of river length). *Snow-slide centers* mostly occur in the Chornohora, Marmarosh, and Svydovets' massifs. This type of mudflow is a secondary in Ukrainian Carpathians. The smallest and shortest flow centers are of sliding type, while the longest belong to the alluvial type.

The floods in 1998 and 1999 testified that critical thresholds for mudflows are 100–200 mm day^{-1} total rainfall amount and 6–12 mm h^{-1} intensity. The natural conditions are reinforced by the complete deforestation of steep slopes, log transport destroying vegetation cover and the generated soil erosion. Field investigations in the Krosno Zone allowed one to distinguish between *debris flows along thalwegs* and *blockslides* over soils due to supersaturation or man-made undercutting of footslopes. The first type is prevalent in the catchments of the Bradulovets', Sukhar, Volovets', and Ozerianka Rivers (slope angles of 40–50°, usually deforested). Debris flows along thalwegs occur at slope angles ranging from 35–50° in headwaters to 25–30° in transit zones. The second type of debris flow is characteristic for the Teresva basin on clayey flysch rocks. Dammed debris flows result from the impounding of watercourses by landslides (as in the Mokrianka and Brusturianka catchments). Recently 24 active debris flows have been mapped in Prut River basin, 15 in the Bilyi Cheremosh, and 11 in the Bystrytsia Nadvirnians'ka basins. Source basins are usually of circular form, the percentage of sediments amounts to 10–35% or even 70%, flow rate is 3–4 m s^{-1}, duration of the event is 1.5–2 h, and flow depth amounts to 2.5–3 m (Holoyad et al. 1995).

8.5.2 Landslides

Landslides are concentrated in the Precarpathians (especially the Pokuttia and Bukovyna regions), Dividing Verkhovyna Carpathians and along boundaries between the Dividing Verkhovyna with the Lump and Polonyna-Chornohora Carpathians and between the Lump Carpathians and Precarpathians. In the Pokuttia and Bukovyna sections over 60–70% of the area hazardous landslide occur. Landslides on the right side of the Prut catchment are usually of block type (Rud'ko et al. 1997). Around Chernivtsi city about 20 ha are occupied by slides. Disasters have been observed here from 1962 to present. In the foothill zone of the Pokuttia-Bukovyna most active *landslides of stream and block type* are found between the rivers Pistynka–Rybnytsia–Cheremosh as well as between the Siret and Malyi Siret. Stream landslides reactivate unexpectedly during spring thawing. Movements occur over viscous clays as slip planes. In the headwaters of Komarivtsi stream (right-bank tributary of the Siret) that landslides were stable between 1991 and 1996 was observed (Rud'ko et al. 1997) and explained by poor water saturation of Badenian clays.

In the Horhany (central) Precarpathians two zones of landslides can be defined. In the foothills landslides affect terraces margins, ravine banks, autochtonous slopes of clayey flysch, and clay molasses. On the right-side of the Dnister River basin, landslides develop in the thick layers of loess-like alluvial loams over Badenian and Sarmatian clays and Cretaceous rocks. Major landslides are also observed on the both sides of the Prut catchment. Near the mouth of the Loyovets' Stream a landslide scarp is more than 300 m long and 100 m deep. There are extensive active landslides on the right side of the Prut basin; one endangers a protected yew woodland. Between the Prut and Bystrytsia Nadvirnians'ka Rivers landslides affect ravine walls of 10–12 m height and are 25 m deep, 10–30 m wide, with failure scarps 5–20 m high. In the headwaters of all streams circular landslide headscarps 300 m across are widespread. Their walls and bottoms are often cut by small gullies with many small slips on their sides. There are also numerous man-induced landslides in the region.

The landslides in the Dnister river valley usually occur on old fixed and active ravine slopes. The scarps are 6–10 m high and 50–100 m wide. In the Pokuttia-Bukovyna section of the Lump Carpathians a continuous series of landslides follow the boundary with the Vorokhta-Putyla low mountains (the Krosno Zone). Extensive landslide tongues are mostly stabilized and grassed. In thin-bedded flysch shallow landslides can be seen along the Cheremosh River and Sukhyi Stream. The landslides developed in Eocene shales are deeper with steep scarps and large tongues and troughs (in the Rushoru and Richka valleys and on the southern slopes of the Lel'kiv and Hromova Mountains).

In the Lump Horhany stabilized landslides are widespread mostly in the contact belt with the Precarpathians. Large old fossil landslide bodies are located between the rivers Bystrytsia Nadvirnians'ka and Solotvyns'ka. On the slopes of the Mala and Velyka Hyha a fossil landslide with failure front up to 25 m high can be seen. The combination of the relict and recent landslides is typical for this area. The landslides are 15–17 m long with a failure front of up to 10 m height. Landslides in clays of the Maniavka catchment show clear step forms with many small mounds. In the headwaters of small rivers active circuses are numerous. Unstable slopes on 2 m thick deluvial loam near Krychka village show complicated landslide features.

In the western Dividing Verkhovyna large areas with fossil landslide slopes and locally active forms are characteristic (Rud'ko et al. 1997). There are two active stream-type landslides here: Tykhyi and Bystryi. Tykhyi has an area of 718,730 m^2 and 10–15 m thickness. The paradoxically slow-moving Bystryi ("quick") landslide is monitored since 1985. In the Polonyna near the Tereblia water reservoir fossil landslides have an estimated total volume between 100,000 and 200,000 m^3 and affect weathered argillites in fixed ravines. Movements are intensified by economic activities. In the western Polonyna Ridge older stabilized landslides in thick debris show rates of 5–10 cm per month.

In the Transcarpathian region landslides are very unevenly distributed. They are concentrated in the Solotvyno depression (or Molass Carpathians) with characteristic inversion morphostructure, on slopes above the Tereblia and Teresva river valleys and their tributaries. Until 1998 16 landslides had been mapped here but after the floods of 1998, 1999, and 2001 33 additional landslides activated. In the Teresva River basin the total number of registered landslides is 285 (38% of the total in the Transcarpathian region). Slope stability along the Teresva River is reduced by road constructions on the river terraces and by riverbank erosion. After the major floods block landslides of step-like topography reactivated along the Mokrianka, Yalivets', and Brusturanka Rivers. Maximum landslide density reaches 1.9 landslides per km^2 at Ternovo, an area with susceptible rocks and high seismicity. Landslides are also common in the Tereblia basin with densities locally amounting to 0.7–1.2 units per km^2. The overall area affected by the landslides is 130.15 km^2 in the Teresva River basin, 41.44 km^2 in the Uzh River basin, 32.66 km^2 in the Rika River basin, and 30.63 km^2 in the Latorytsia River basin.

The landslides reactivated after flood events fall into two groups: (1) those formed on Neogene horizontal clay layers with intercalated sandstones and limestones; (2) those formed in clay-flysch rocks. Generally landslides of lamellar and structural-lamellar types are predominant (their overall volume is 1.5–3 million m^3) and most hazardous for roads.

In the Transcarpathian foothills minor landslides with clear seasonal activity form in weathered volcanites (as around Uzhgorod city). Clearcutting on slopes, wood transportation, and construction significantly contribute to landslide generation, particularly in narrow river valleys between high walls with steep (30–50°) slopes.

8.5.3 Other Gravitational Processes

Other gravitational processes mostly affect the steep slopes of the Polonyna-Chornohora Lump Carpathians, Marmarosh Massif, and the Volcanic and Dividing Verkhovyna Carpathians. In the Precarpathians they are widespread on the left half of the Bystrytsia Nadvirnians'ka catchment on very steep slopes (35–40°) in argillite and sandstone debris of 3–15 cm diameter but larger (25 cm) blocks of sandstones also occur. Debris is accumulated on floodplains or reach the riverbed.

In the Lump Carpathians gravitational processes are active on mountain ridges of Paleocene and Eocene sandstones as well as on upper Cretaceous sandstone-argillite-siltstone sequences. On the gentler southwestern slopes of the Lump Carpathians barren summit *felsenmeers* gradually change into *block streams* and accumulation features at footslopes. On the steeper northeastern slopes rockfalls and felsenmeers often fixed by mountain pines and by firs and birches at lower elevations. In the Lump Horhany within the upper belt of the northeastern slopes *rockfalls* are widespread in the crooked forest zone of the Hrofa–Moloda–Popadia, Mahura, Koza, and Hora Massifs (Kravchuk 2005). The height of steep slopes (>45°) can locally reach 100 m. Most of them are not very active, some of them were active more than 100 years ago. The Dovbushanka rockfall on 27 December 1897 to the northeast of Dovbushanka mountain (1,755 m) was 500 m long and created a 150 m high scarp and a stone stream of 200–250 m width moving down the Fedotsyl River valley.

Numerous minor *rock* and *debris falls* in the Prut and Bystrytsia Nadvirnians'ka River valleys and its tributaries threaten railways and roads. Further rockfalls are known from the Bystrytsia Solotvyns'ka, Limnytsia, and Svicha River basins. Rock and debris falls are often associated with landslips, as in the Opir and Stryi River valleys. Most falls involve fine (0.03–0.15 m) material and are related to lower-rhythmical flysch complexes. Those of sandstone debris have grain sizes of 0.3–0.5 m.

8.6 Fluvial Erosion

8.6.1 River Network

The rivers of the Ukrainian Carpathians belong to the Dnister, Tysa, Siret, and Prut systems. The Dnister River and its mountain tributaries flow in northeastern direction, the Tysa with tributaries to the southwest, and the Prut and Siret in northeastern and southeastern directions. There are about 460 rivers in the Ukrainian Carpathians (40% of them belongs to the Dnister system) but only eight rivers are longer than 100 km (four in the Dnister basin, three in the Tysa basin, and the Prut River). The upper reaches of Carpathian rivers are mostly narrow, deep, with steep slopes, limited discharges, and high current velocity. At 700–1,400 m elevation channel *gradients* are between 50 and 100 m km^{-1} with incision depth exceeding 700 m. Riverbeds contain large boulders. In mountain forelands river gradient decreases to 10–20 m km^{-1} with incision depths of 50–150 m and deposition increases. Valley cross-sections are trapezoid with braided channels and *current velocities* from 0.7 to 5.0 m s^{-1} (locally for small streams 7–10 m s^{-1}) during flood events. Reduced stream velocity involves intensive accumulation and island formation. Many islands are stabilized by bushes. The alternation of *canyon* (across mountain ridges, with waterfalls) and *broad valley* types (between mountain ridges) are characteristic.

Steep slopes, high precipitation (above 1,000 mm), low evaporation and groundwater levels result in high *drainage density* (2.0–2.8 km km^{-2} for the Upper Cheremosh; 2.0–2.3 km km^{-2} for the Upper Tysa; and 1.9–2.7 km km^{-2} for the Upper Svicha and Limnytsia Rivers). In the Transcarpathians density is 1.8 km km^{-2} and in the Precarpathians 0.9–1.3 km km^{-2}.

Average specific *sediment delivery* in the Ukrainian Carpathians ranges from also original data are possible from Resources of the surface waters of USSR.

Table 8.2 Sediment and water discharges of rivers in the Ukrainian Carpathians (Calculated by I. Kovalchuk from hydrometeorological data)

Period number	Period of measurements, years	Average specific sediment delivery modulus, t km^{-2} y^{-1}	Sediment discharge change coefficient, Mn/M1	Average runoff, mm	Runoff change coefficient, Hn/H1	Ratio between sediment and runoff change coefficients, Hn/M1
Tysa River (at Rakhiv)						
I	1947–1962	58.0	1.00	702.0	1.00	12.10
II	1963–1970	180.9	3.12	778.9	1.11	4.31
III	1971–1975	117.0	2.02	659.8	0.94	5.64
IV	1976–1980	146.0	2.52	803.4	1.14	5.50
V	1981–1985	58.8	1.01	754.0	1.07	12.82
VI	1986–1988	64.7	1.12	690.3	0.98	10.67
Dnister (at Sambir)						
I	1946–1962	62.3	1.00	249.6	1.00	4.01
II	1963–1970	255.8	4.11	452.6	0.81	1.77
III	1971–1975	236.8	3.80	458.6	1.84	1.94
IV	1976–1980	206.0	3.31	593.2	2.38	2.88
V	1981–1985	268.0	4.30	420.2	1.68	1.57
VI	1986–1988	92.3	1.48	360.0	1.44	3.90
Stryi (at Verkhnie Syniovydne)						
I	1951–1962	73.3	1.00	520.3	1.00	7.10
II	1963–1970	134.6	1.84	591.0	1.14	4.39
III	1971–1975	352.0	4.80	530.2	1.02	1.51
IV	1976–1980	320.0	4.37	655.2	1.26	2.05
V	1981–1985	228.8	3.11	608.6	1.17	2.67
VI	1986–1988	116.0	1.58	487.7	0.94	4.20
Prut (at Chernivtsi)						
I	1947–1962	111.5	1.00	283.5	1.00	2.54
II	1963–1970	292.1	2.62	325.8	1.15	1.12
III	1971–1975	388.0	3.48	351.0	1.24	0.90
IV	1976–1980	290.0	2.60	427.6	1.51	1.47
V	1981–1985	256.0	2.12	349.8	1.23	1.48
VI	1986–1988	121.7	1.09	250.3	0.88	2.06

Main hydrological parameters for 1975–1980 and whole observation period. Vol. 1 Western Ukraine and Moldova (1985). Hydrometeoizdat, Leningrad (in Russian): 60 tons year^{-1} km^{-2} in the Dnister and Tysa catchments to 400–600 ton year^{-1} km^{-2} in the Prut and Rybnyk River basins (Kovalchuk and Mykhnovych 2004) (Table 8.2), but its maximum is 4,400 ton year^{-1} km^{-2} along the Rybnyk. Its dynamics (documented for the period 1950–2000) is a good indicator of the rate of recent geomorphic processes. Change has been calculated for the Dnister (at Strilky): 300%, the Holovchanka (at Tuchlia): 50%, for the Bystrytsia (at Ozymyna): 300%, Opir (at Skole): 200%, Stryi (at Verkhnie Syniovydne): 80%, and Dnister (at Halych): 50%.

The investigations of changes of *river systems* are based on the analyses of large scale (1:100,000) topographic maps from the nineteenth to twentieth centuries, which show drainage pattern and density as well as forests, settlements, roads, and other features. It was found that in the river basins of the northeastern Ukrainian Carpathians, first- (72–80%) and second-order (14–18%) streams dominate both for number and total length (41–52% and 17–26%, resp.). Third-order rivers make up 4–5% in number and 12–17% in length and fourth- to sixth-order rivers have only a 5–7% joint share. Between 1855 and 2000 major changes took place in river system structure: a drop occurred in the number of streams due to silting and drying, erosion, and accumulation in catchments, while elsewhere the number of streams rose due to intensified groundwater drainage, water runoff, and drainage of agricultural fields. The dimensions of such changes were studied in the Svicha catchment. The number and length of first- and second-order streams both decreased by 3.2% and 3.6%, respectively.

8.6.2 Water and Sediment Discharge

Fluctuations in water and sediment discharges between 1948 and 2004 for the mountain rivers are high (for the Stryi River: from 16 $t\,km^{-2}$ $year^{-1}$ to 880 $t\,km^{-2}$ $year^{-1}$). Sediment discharge in the period 1968–1970 was four times higher than the long-term average. Its maxima do not correlate with precipitation and water discharge (Table 8.2). This fact points to the great influence of other factors like intensive deforestation in the mountains.

The main reasons of alterations in sediment transport are *land use changes* and *gravel extraction* from the channel and the floodplain. Along with increasing precipitation in the period 1960–1975, human activities like deforestation in the late 1950s and early 1960s, and the cultivation of slopes using heavy machinery were the main drivers of the transformation. Vertical channel deformations closely follow the changes in sediment transport. For example, an increase of sediment load is observed for the Dnister River between Strilky and Sambir. River erosion intensified due to gravel extraction upstream Sambir and also near Stryi on the Stryi River.

The analysis of long-term data sets (for 1970–2005) of sediment load, precipitation, and deforestation compared with findings of field research on erosion processes in deforested areas shows correlation between precipitation (mm $year^{-1}$) and sediment delivery (tons km^{-2} $year^{-1}$) (correlation coefficient: 0.65), and no correlation between deforested area (ha) and sediment load (t km^{-2} $year^{-1}$) (correlation coefficient: 0.15). It is assumed that *deforestation impact* on sediment load occurs *with some time delay*. This assumption can be verified by a multiple regression analysis taking sediment delivery as a dependent variable and deforested areas, precipitation, and water discharge as independent variables. The regression analysis indicates that 1 ha annual growth in deforestation increases sediment delivery by 0.54 ton km^{-2} $year^{-1}$. With the present intensity of deforestation, maximum sediment delivery is expected to occur in 5 years after

Table 8.3 Rate of vertical deformations of river beds in the upper Dnister catchment (by A. Mykhnovych)

River	Locality	Period, years	Deformation, cm	Average rate, mm year^{-1}
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
Stryvihor	Luky	32	–200	–62.50
Bystrytsia	Ozymyna	32	+20	6.25
Tys'menytsia	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
Yablun'ka	Turka	32	–32	–10.00
Rybnyk	Maidan	7	–10	–14.29
Opir	Skole	10	–7	–7.00
Slavs'ka	Slavske	10	–35	–35.00
Holovchanka	Tukhlia	32	–60	–18.75
Oriava	Sviatoslav	10	–5	–5.00
Ruzhanka	Ruzhanka	8	–36	–45.00

forest clearance and minimum impact of deforestation will be observed in 7 years. A close correlation has been found between deforested areas, felling methods, and the rates of geomorphic processes by pair correlation and regression analysis for the Holovchanka catchment.

8.6.3 Channel Evolution

Vertical changes of riverbeds are studied along the mountain and foothill sections of river valleys. It was found that erosion dominates over most of the Ukrainian Carpathians. The highest rate of incision is observed for the Stryvihor (at Luky, 65.5 mm year^{-1}), Ruzhanka (at Ruzhanka, 45.0 mm year^{-1}), Slavs'ka (at Slavs'ka 35.0 mm year^{-1}), and Stryi Rivers (at Verkhnie Syniovydne, 31.3 mm year^{-1}) (Table 8.3). Channel accumulation has been recorded for the Dnister (at Sambir, 20.0 mm year^{-1}), Tysmenytsia (at Drohobych, 20.0 mm year^{-1}), Shchyrka (at Shchyrets, 7.8 mm year^{-1}), and Bystrytsia (Ozymyna, 6.3 mm year^{-1}).

Vertical riverbed deformations are caused by both dredging and increasing water discharge as confirmed for different periods and cross-sections in other river systems of the Ukrainian Carpathians (Holoyad et al. 1995; Kovalchuk 1997). Riverbed changes also influence other geomorphic processes (bank erosion, debris flows, and landslides).

8.6.4 River Terraces and Valley Types

Along the main river valleys of the Precarpathians five to seven *terraces* can be identified. The river valleys of the northwestern (Pre-Beskid) and central (Pre-Horhany) Precarpathians were formed along zones of tectonic weakness subsequently buried under Paleogene-Miocene sediments. Terraced river valleys mostly of Pleistocene age occupy almost 35–37% of the Precarpathians. The fragments of *seventh* (Pliocene) terrace can be seen on the right side of the Limnytsia catchment (Krasna mountain) with 160–180 m relative heights and 590 m elevation; between the rivers Svicha and Limnytsia (Zalissia mountain, 485 m) with gravels on top (relative height: 140 m) and also between the rivers Prut and Bystrytsia nadvirnians'ka. The sixth (Loyeva surface) and fifth terraces were formed in the Early Pleistocene. The *sixth terrace* is found on the five interfluves between the Dnister and Cheremosh Rivers. Its gravels of 5–10 m thickness overlie Miocene Molass sediments. Relative terrace heights here vary from 60–80 m (along the upper Dnister and Svicha) to 110–130 m (in the Limnytsia, Bystrytsia and Prut catchments). The *fifth terrace* is only conserved in fragmentary form among others in the Stryvihor catchment, between the rivers Stryvihor – Dnister, Dnister Stryi, Stryi – Svicha. The greatest thickness of alluvium was discovered in the Prut valley near Deliatyn (15 m) and in the river mouths of Svicha and Limnytsia (up to 20 m). The Middle Pleistocene *fourth* terrace occupies the largest areas in the Dnister and Stryi valleys, between Svicha and Sukil, headwaters of Vorona, on the left bank of the Prut and as fragments in the Limnytsia valley. Its relative height is between 25 and 45 m and alluvium thickness is 20 m (5–8 m of gravels covered by 8–12 m of loess loam). The maximum thickness of alluvium is 30 m (near Halych city). The Late Pleistocene *third* and *second* terraces are best preserved in the Precarpathians (in the Upper Dnister, Stryi-Zhydachiv, Kalush and Bystrytsia valleys, along the left bank of the Prut, in the Cheremosh and Siret river valleys). The relative height of the second terrace varies from 5–8 m (in the northwestern Precarpathians) to 10–15 m (in the Cheremosh valley), while the third terrace is located at 15–25 m height. Alluvium thickness reaches 20–25 m in the Stryi-Zhydachiv valley. The *first terrace* and the Holocene floodplain are present in all river valleys. The height of first terrace is 2.5–5 m. The widest terraces (4–5 km) are located in the Upper Dnister, Kalush and Bystrytsia valleys. *Floodplains* show a higher (1–2 m) and a lower (0.5–1 m) level. Their width is 200–300 m, but it can be 1 km or more. Alluvium thickness varies from 3–5 m (in the foothills) to 10–15 m (at river mouths).

In the Beskids wide *transversal valleys* dominate. In the mountains the Stryvihor, Dnister, and Stryi rivers run in winding valleys forming incised meanders. In the headwaters (Dividing Carpathians) the river valleys inherited relict longitudinal valleys of the Paleo-San River. P. Tsys' (1968) defined two types of the valleys: *epigenetic* valleys, typical for the Upper-Dnister Beskids (Stryvihor, Dnister, Stryi, Bystrytsia-Pidbuz'ka) and *erosional-tectonic valleys*, typical for the Skole Beskids (Opir, Oriava, Rybnyk, Sukil').

The rivers of the Lump Horhany Mountains (the Mizunka, Svicha, Limnytsia, Bystrytsia Solotvyns'ka, Bystrytsia Nadvirnuans'ka and Prut) are V-profile, locally canyon-type, deeply incised transversal valleys with steep slopes and usually longitudinal tributaries, which flow into the main rivers at right angles (orthogonal river system).

In contrast to the Beskids and Horhany, the rivers of the Pokuttia-Bukovyna Carpathians have thick alluvium on all terraces. In the Pokuttia the Pistynka, Rybnytsia and Cheremosh flow in deep erosional, V-shaped valleys with many terraces, while the river valleys of Bukovyna (the Siret and Malyi Siret) are canyon-like with fewer terraces.

There are many relict *longitudinal valleys* in the Dividing Verkhovyna Carpathians. Some of their fragments are incorporated into the transversal valleys (Slyvka 2001). Longer river sections run along synclines and cross anticlinal ridges in shorter canyons. The rivers of the Dividing (Inner) Horhany follow deeply incised transversal valleys with steep slopes (locally canyons).

The river valleys of the southwestern macroslopes (Tysa catchment) have a more complicated origin. Their development was impacted by Upper Pliocene volcanic activity of the Vyhorlat–Huta ridge. There are seven terraces of 2–3 km width here at relative heights of 1.5–3 m, 7–10 m, 15–20 m, 30–40 m, 60–70 m, 90–100 m, and 200 m.

8.6.5 Flood Hazard

The Ukrainian Carpathians is a region affected by very intensive *floods* induced by human factors (changes of vegetation cover, deforestation, cultivation and grazing of slopes, changes in land drainage, and channel conditions) combined with natural forces (precipitation conditions, soils properties, etc.). In addition, the flood situation is aggravated by the garbage, debris, and wood accumulation in the channels, at bridges and communication lines crossing river beds (Kovalchuk 1997; Szlávik 2002). The analysis of the monitoring data and literature sources indicate that during the past 100–120 years the highest floods in the Ukrainian Carpathians were observed in 1911, 1927, 1941, 1947, 1955, 1957, 1969, 1970, 1974, 1978, 1979, 1980, 1984, 1989, 1992, 1993, 1995, 1997, 1998, 2001, 2002, 2004, 2008, 2010 (Romashchenko and Savchuk 2002). During extreme flood events water level increases up to 10 m, inundated zones amount to tens of km^2. The settlements most often flooded are along the Upper Dnister, Tysa, and Teresva Rivers.

In the Ukrainian Carpathians floods occur almost in any season of the year and last from hours to 4–8 days. The water discharge curve shows several peaks (from 2 to 12 per event). Highest water levels and discharges are observed in summer and autumn (May to October). Water discharge during flood is 5–40-fold higher than baseflow. The most rapid water level rise is observed in the zones between mountains and foothills. Heavy rainfalls (120–250 mm per day) generate 2.5–3.1 $m^3\ s^{-1}\ km^{-2}$

Table 8.4 Extreme flood events in the Transcarpathians (After Lymans'ka 2001)

	Type of flood		
	Channel building	Channel-destruction	Disastrous channel destruction
Years	1974,1978, 1979, 1980	1992, 1993, 1995	1947, 1957, 1970, 1998, 2001
Average precipitation, mm	30–50	40–60	70–100
Maximum precipitation, mm	100–130	100–160	>160
Average rise in water level, m	2–4	2–3	2–3
Maximum rise in water level, m	6–7	8.3–8.5	4–7.5

runoff (Kovalchuk 1997) and, in turn, severe erosion and sediment transport in rivers, dam breaches, flooding agricultural land, settlements, and communication infrastructure.

Traditionally flood control in the Ukrainian Carpathians involves dykes, drainage canals, sluices, pumping stations, etc. Most of the dykes (built between 1950 and 1970) are imperfect: stand too close to riverbanks, and are technically deficient and deformed by recent geomorphologic processes. Along about 70% of the dykes there is a high risk of overtopping during 100-year floods and 20–30% during 25-year floods. Therefore, it is urgent to restore the existing flood-protection system in the Ukrainian Carpathians.

Most considerable environmental-geomorphological effects of floods are:

1. Rapid rises of water level (Dnister, Latorytsia, Uzh, Tysa), fields, communications, buildings, engineering constructions flooded and destroyed;
2. Large areas flooded for tens days in the premountain river segments (Dnister, Stryl, Uzh, Latorytsia, Tysa) after breaking and overtopping of dykes;
3. Extreme intensification of landslides in 5–20% of the region (more than 550 landslides over 16.2 km^2 area activated after flood in the Transcarpathians alone);
4. Intensification of mudflows (about 300 mudflows of 10–20 thousand m^3 activated by floods);
5. Deterioration of ecological conditions in agricultural and urban areas.

The major floods with their causes and effects are summarized according to the classification of Obodovs'kyi (2000) in Table 8.4.

A disastrous flood happened in the Transcarpathians on 4–9 March 2001. The main driver was extremely high amount and intensity of rainfall (90–296 mm) between 3 and 5 March 2001 all over the region. In addition, high air temperature (up to +14°C) caused intensive snowmelt (an additional 20–40 mm). Water level rose 4.3–8.55 m on the Tysa River (near Chop town even 9.5 m) and tributaries (Romashchenko and Savchuk 2002). Two hundred and fifty five settlements and 33,569 buildings were flooded, 1925 buildings and 52.7 km of roads were destroyed, 338 landslides, 81 debris flows and 102 sites with bank erosion were identified (Lymans'ka 2001). Most of the landslides occurred in the low mountains of the Molass Carpathians.

Flood hazard research focuses on geomorphic processes in recently deforested areas in the Beskids at four study sites in the Krasny sandstone catchment of northwestern exposition, 523.6–770.5 m elevations and 35–45° inclination. The findings for the years 2004–2006 showed intensive gully erosion after deforestation. Average gully length was 33–51 m, maximum length over 100 m, and gully width 1.52–1.70 m. In the summer (16 July–15 August 2004) thalwegs incised 3–5 cm at maximum daily rainfall on 31 July 2004, 90 mm in Sviatoslav, and 160 mm in Skole town. Sheet erosion amounted to 0.6 cm and in autumn accumulation of 0.5–7.8 cm followed. With the new vegetation period accumulation reached 5.3–9.2 cm, but another rainfall of 56 mm caused debris flows nearby and built fans of 43–164 m^3.

8.7 Karst

There are three types of karst in the Ukrainian Carpathians: carbonate, sulfate and evaporite (salt) karsts. Jurassic *carbonate karst* is found in the Chyvchyna Massif. In the Precarpathians, in the San moraine-outwash-alluvial plain both carbonate and sulfate karsts are observed. *Sulfate karst* is most widespread in the Precarpathians. The karst processes are intensified due to the impact of mining. The studies by the Geological Survey on karst development near the Yaziv sulfate mine between 1971 and 1991 found that groundwater levels dropped by 86 m within a depression area of 210 km^2. *Salt karst* is widespread in the Pre- and Transcarpathians. In the Precarpathians the karst belt of salt layers and lenses extends along a northwest to southeast axis. Its overall width is up to 40 km and maximum salt thickness is 600 m (Rud'ko and Kravchuk 2002). Karst processes are accelerated by aggressive waters. Locally the depression extends at 6–10 m $year^{-1}$ rate.

8.8 Nival and Glacial Landforms

In the Ukrainian Carpathians *avalanches* occur on slopes of 20–45° at elevations of 300–2,000 m. Avalanche paths are 100–500 m long, the longest is more than 3 km. The core area is from 1–5 to 40–50 ha. Avalanches usually occur once a year in the catchments of the Tysa, Teresva, Shopurka, Tereblia, Latorytsia, Borzhava, and Rika Rivers, once in 2–3 years on the Verkhovyna Ridge and in the Uzh, Latorytsia, and Borzhava headwaters (Maslova et al. 1999). The volumes of moved snow vary from hundreds to tens of thousands m^3, maxima can reach 0.5–1 million m^3.

Avalanches most often develop in winter and spring (February to March). The most endangered regions are the Chornohora, Rakhiv massif, Svydovets', Krasna, Borzhava ridges, Polonyna Runa, and Lautians'ka Holytsia. For example, in

February 1999 snow amounts fourfold exceeded the usual value (300–500 thousands m^3) and caused a number of avalanches in the Transcarpathians (Maslova et al. 1999). The avalanche started on the Polonyna Krasna was 3 km long and built a fan of 20 m height.

Landform remnants of Pleistocene glacials can be seen on the summits of the ridges Chornohora, Svydivets', Marmarosh, and Horhany. Relict glacial landforms in the Chornohora are glacial *troughs, karren,* and *kettles* in three areas: in the headwaters of the Zarosliats'kyi Prut River; in the valleys of the Dantsers'kyi Prut, Hadzhyna, and Kizi Rivers and in the headwaters of the Dzembronia and Pohorilets'. *Felsenmeers* are also relict forms of Pleistocene glacials and most widespread in the Lump Horhany (on the highest lump-ridges Skole, Parashka, Zelemyanka) and also found in the Dividing (Internal) Horhany, Chornohora, Svydivets', and Marmarosh. Above the forest belt (mostly on northern slopes) they are stabilized by dwarf pines.

8.9 Conclusions

The predominant geomorphic processes active at present in the Ukrainian Carpathians are weathering, sheet, gully, river-bank, and channel erosion, landslides, debris, and mudflows, avalanches, landslips, karst, man-induced processes, and hydrogeomorphological processes, riverine, and flash floods. Among secondary geomorphic processes wind action, chemical and biogenic denudation, and accumulation can be cited. According to their distribution and the volume of material moved, the relative significance of each process group can be estimated (Table 8.5).

In the mountains the main drivers of landform evolution are erosion, landslides, and debris flows. Human activity has increased the intensity of natural geomorphic processes hundredfold.

Table 8.5 Recent geomorphic processes in Ukrainian Carpathians

Type of the process	Percentage (%) by distribution area	Type of the process	Percentage (%) by volume of the material moved
Sheet erosion	38	Landslides	41
Landslides	23	Sheet erosion	30
River-bed erosion and accumulation	12	River-bed erosion and accumulation	11
Mudflows	9	Mudflows	7
Avalanches	6	Man-induced	6
Man-induced	6	Landslips	2
Karst	3	Avalanches	1
Landslips	2	Karst	1
Biogenic	1	Biogenic	1
Total	*100*	*Total*	*100*

References

Bogacki M, Kovalchuk I, Mykhnovych A (2000) The dynamics of the river network structure in the Dnister basin as reaction on the anthropogenic changes of nature conditions. Miscellanea Geographica, Warszawa 9:11–18

Boliukh O, Kanash A, Kit M, Kravchuk Y (1976) Stationary investigations of the sheet erosion in the Precarpathians. Higher School, Lviv, 138 p (in Ukrainian)

Budz M, Kovalchuk I (2008) Geologic-geomorphological classification of mud-flows. Bull Lviv Univ Ser Geogr 35:28–33 (in Ukrainian)

Dubis L, Kovalchuk I, Mykhnovych A (2006) Extreme geomorphic processes in the Eastern Carpathians: spectrum, causes, development, activization and intensity. Studia Geomorphologica Carpatho-Balcanica 40:93–106

Habchak N (2010) Relief-forming processes and their dynamics in the Rika River basin of the Transcarpathians. Phys Geogr Geomorphol, Kyiv 58:282–288 (in Ukrainian)

Hensiruk S (1992) Regional nature use. Svit, Lviv, 336 p (in Ukrainian)

Hofstein I (1995) Geomorphological studies of Ukrainian Carpathians. Naukova Dumka, Kyiv, 84 p (in Ukrainian)

Holoyad B, Slyvka R, Panevnyk V (1995) Erosion-denudation processes in Ukrainian Carpathians. Ivano-Frankivs’k, 114 p (in Ukrainian)

Khomyn Y, Bilaniuk V (2010) Results of the stationary investigations of the sheet erosion in the Borzhava River catchment. Phys Geogr Geomorphol Kyiv 58:154–164 (in Ukrainian)

Kovalchuk I (1997) Regional ecological-geomorphologic analysis. Institute of Ukraine Studies, Lviv, 440 p (in Ukrainian)

Kovalchuk I, Kravchuk Y (2001) 50 years of the Department of Geomorphology at the Lviv National University. Bull Lviv Univ Ser Geogr 28:3–15 (in Ukrainian)

Kovalchuk I, Mykhnovych A (2004) Recent morphodynamical processes in the forested landscapes of Ukrainian Carpathians. Sci Bull For Eng Tech Technol Environ State For Univ Lviv 14(3):273–285 (in Ukrainian)

Kovalchuk I, Liashchuk B, Pakulia M (1978) Comparison of the longitudal profiles of the Precarpathian rivers (on the examples of the Bystrytsia Nadvirnians’ka and Bystrytsia Solotvyns’ka Rivers). Bull Lviv Univ Ser Geogr 11:95–99

Kovalchuk I, Mykhnovych A, Pylypovych O (2000) River systems structure and hydrological regime transformations in the Dnister River basin. Investigations of the Upper Dnister River basin. Ivan Franko National University of Lviv, Lviv, pp 34–43 (in Ukrainian)

Kovalchuk I, Mykhnovych A, Quast J, Steidl J, Ehlert V (2008) Current problems of water management in the Upper Dnister basin. In: Roth M, Nobis R, Stetsiuk V, Kruhlov I (eds) Transformation processes in the Western Ukraine: concepts for sustainable land use. Weissensee Verlag, Berlin, pp 125–135

Kowalczuk I, Mychnowicz A (2009) Transformacja struktury systemów rzecznych w Karpatach Ukraińskich (Transformation of the structure of fluvial systems in the Ukrainian Carpathians). Prace i Studia Geograficzne Warszawa 41:115–122 (in Polish)

Kowalczuk I, Pylypowycz O, Mychnowycz A (2008) Zmiany intensywności denudacji w Beskidach Skoliwśkich (Karpaty Ukraińskie) (Changes in the intensity of denudation in the Skole Beskids, Ukrainian Carpathians). In: Międzynarodowe sympozjum “Antropopresja w górach i na przedpolu. Zapis zmian w formach terenu i osadach” (Głuchołazy, 24–27 czerwca 2008), pp 36–45 (in Polish)

Kravchuk Y (1999) Geomorphology of the Precarpathians. Merkator, Lviv, 188 p (in Ukrainian)

Kravchuk Y (2001) Studies of the Ukrainian Carpathians by the Lviv geomorphologists. Bull Lviv Univ Ser Geogr 28:16–19 (in Ukrainian)

Kravchuk Y (2003) Lviv geography during last 120 years: history, personals, scientific schools. In: Proceedings of the scientific conference dedicated to 120 anniversary of geography at the Lviv University, Lviv, pp 3–16 (in Ukrainian)

Kravchuk Y (2005) Geomorphology of the Lump Carpathians. University Publishers, Lviv, 232 p (in Ukrainian)

Krawczuk J (1999) Tradycje naukove polskich i ukraińskich badań geograficznych Karpat Wschodnich (The tradition of Polish-Ukrainian geographical scientific research in the Eastern Carpathians). Geografia na przelomie wieków – jedność w różnorodności. Warszawa, pp 46–51 (in Polish)
Lymans'ka I (2001) Extremely high floods on the Transcarpathian rivers, their types and consequences. Phys Geogr Geomorphol Kyiv 41:144–149 (in Ukrainian)
Maslova T, Hryshchenko V, Susidko M (1999) Snowy winters in the Transcarpathians and the avalanches development intensity. Scientific Papers of the Ukrainian Scientific Hydrometeorological Institute, Kyiv, pp 144–149 (in Ukrainian)
Mykhnovych A (1998) The Upper Dnister river systems structure and its transformation under the impact of natural and man-made factors. Bull Lviv Univ Ser Geogr 21:161–167 (in Ukrainian)
Obodovs'kyi O (2000) River beds stability evaluation and floods classification of the mountain rivers. In: Ukraine and the global processes: geographic dimension, vol 2. Luts'k, Kyiv, pp 205–209 (in Ukrainian)
Obodovs'kyi O (2001) Hydrologic-ecological evaluation of river bed processes (on the example of the rivers of Ukraine). Nika-Centre, Kyiv, 274 p (in Ukrainian)
Oliferov A (2007) Mudflows in the Crimea and Carpathians. Tavria, Simferopil, 176 p (in Ukrainian)
Pol W (1851) Rzut oka na polnocne stoki Karpat, Publ. Tow. Przyjaciol Oswiaty, Krakow (in Polish)
Problems… (2008) Problems of the geomorphology and paleogeography of the Ukrainian Carpathians and adjoining areas Scientific papers, University Publishers, Lviv, 320 p (in Ukrainian)
Professor… (2004) Petro Tsys'. Prepared by Prof. I. Kovalchuk. Lviv, Ivan Franko National University Publishing Centre, Lviv, 433 p (in Ukrainian)
Relief… (2010) Relief of Ukraine. Vakhrushev B, Kovalchuk I, Komliev O, Kravchuk Y, Paliyenko E, Rud'ko G, Stetsiuk V. Ed. by Stetsiuk V. Slovo Publishers, Kyiv, 689 p
Romashchenko M, Savchuk D (2002) Water disasters. Carpathian floods. Statistics, causes, regulations. Agrarian Science, Kyiv, 304 p (in Ukrainian)
Romer E (1909) Proba morfometrycznej analizy grzbietów Karpat Wschodnich (Experimental morphometrical analysis of ridges in the Eastern Carpathians). Rocznik Lwów 34:5–6 (in Polish)
Rud'ko G, Kravchuk Y (2002) Engineering-geomorphologic analysis of the Ukrainian Carpathians. University Publishers, Lviv, 172 p (in Ukrainian)
Rud'ko G, Yakovliev Y, Ragozin O (1997) Monitoring of the areas of geological processes and natural-technogenous disasters risks calculations. Znannia, Kyiv, 80 p (in Ukrainian)
Shushniak V (2004) History of geomorphologic research and actual geomorphologic problems of the Carpathians. In: Problems of the geomorphology and paleogeography of the Ukrainian Carpathians and adjoining areas. Scientific papers, University Publishers, Lviv, pp 163–176 (in Ukrainian)
Skvarchevs'ka L (1962) Geomorphologic features of the river valleys in Turka district (Lviv region). Bull Lviv Univ Ser Geogr 1:34–39 (in Ukrainian)
Slyvka R (1994) Mudflows in the Ukrainian Carpathians and the methods of their regulation. Bull Lviv Univ Ser Geogr 19:131–155 (in Ukrainian)
Slyvka R (2001) Geomorphology of the Dividing Verkhovyna Carpathians. University Publishers, Lviv, 152 p (in Ukrainian)
Somov V, Rakhimova I (1983) Recent Earth's crust movement in the Carpatho-Balcanic region and adjoining structures. Naukova Dumka, Kyiv, 142 p (in Russian)
Szlávik L (2002) The development policy of flood control on river Tisza in Hungary. ERWG Letter: 13. Land and water management in Europe 1. 1–4
Tsys' P (1956) Geomorphological regions of the Ukrainian Carpathians. Geogr Bul Lviv 3:5–24 (in Ukrainian)
Tsys' P (1964) Short overview of the recent geomorphologic phenomena in the western region of Ukraine. Bull Lviv Univ Ser Geogr 2:3–10 (in Ukrainian)
Tsys' P (1968) State of the knowledge and actual problems of the Ukrainian Carpathians geomorphology. Bull Lviv Univ Ser Geogr 4:106–120 (in Ukrainian)
Tsys' P, Stadnyts'kyi D, Slyvka R, Boliukh O, Chalyk V et al (1968) Some results of the recent exogenous processes investigations in the Ukrainian Carpathians. In: Recent exogenous processes. Part 1. Academy of Sciences of USSR, Kyiv, pp 16–18 (in Russian)
Yushchenko Y (2009) River bed studies at the Chernivtsi University. In: Ukrainian historical geography and history of geography in Ukraine. Proceedings of the International Scientific Conference, Chernivtsi, pp 36–37 (in Ukrainian)