Chapter 6
Recent Landform Evolution in the Moravian–Silesian Carpathians (Czech Republic)

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Abstract Topographic changes in the Moravian-Silesian Carpathians have been due to variations of natural conditions (climatic changes, accelerated rates of exogenic geomorphic processes during the Little Ice Age), but mainly to the growing intensity of human activities (tillage, deforestation, accelerated soil erosion, urban sprawl). In this geomorphologically highly sensitive region, land-use changes exerted a great influence on the intensity and type of exogenic geomorphological processes in the last millennium. Their impact is studied on archive maps. The density of slope deformations (like deep-seated slope failures, lateral spreading, toppling, sackung, translational and rotational landslides, earthflows, debris flows, and rockfalls) in the study area is the highest in the Czech Republic. Other geomorphic

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processes presented in this overview are erosion by water on the surface and underground (piping), wind erosion, and a range of anthropogenic processes (urbanization, mining, industry, water management, and transport).

Keywords Land use changes • Archive maps • Slope deformations • Water erosion • Piping • Wind erosion • Anthropogenic processes • Western Carpathians

6.1 Introduction

Jaromír Demek

The Moravian–Silesian Carpathians (MSC) are the westernmost member of the Western Carpathians in the southeastern part of the Czech Republic. The young mountains and lowlands are a very sensitive relief with neotectonic movements. Built of Cretaceous and Cainozoic rocks, the relief of the MSC changed substantially not only due to variations of *natural conditions*, but mainly due to *activities of human society* during the last millennium. Around 1000 AD the warm and dry climate turned wetter and colder. Soil erosion in ancient core settlement areas accelerated and abandoned settlements of the Great Moravian Empire in floodplains were buried under flood loam deposits. Slavonic villages were relocated from frequently inundated floodplains further away from river channels onto lower river terraces. In the twelfth century Carpathian flysch highlands, mountains, and floodplains were still forested, while arable land prevailed only in ancient core settlements of lowlands. Soil erosion processes were further accelerated by the medieval colonization and deforestation of highlands of the West European platform in the twelfth and thirteenth centuries. Simultaneously the studied area experienced a general deterioration of the climate between the years 1150 and 1460 and a very cold and wet climate between 1560 and 1850 transformed geomorphic processes, vegetation and land use (Little Ice Age). Two climatic minima about 1650 and about 1770 correspond with intensification of soil erosion and slope deformations. Sediment transport by watercourses was influenced by the construction of a large number of fishponds since the thirteenth century.

The character of flysch mountain landscape radically changed with the Walachian colonization at the end of fifteenth and beginning sixteenth century when Walachian pastoral tribes arrived into the MSC (Macůrek 1959). Deforestation and grazing accelerated erosion and landslides on steep mountain slopes as well as accumulation on valleys bottoms. In the eighteenth century the largest landscape user was agriculture and changes in the agriculture (e.g. the Austrian agricultural reform) significantly influenced both the type and intensity of geomorphic processes. The first stage of scientific-technical revolution in agriculture starting around 1750 resulted in the extension of arable land at the expense of permanent grassland and drying of fishponds systems. Open-cast hard coal mining in the Ostravská pánev Basin began shortly after the discovery of coal seams in the late eighteenth century.

River regulation began in nineteenth century. The deep man-made channels and dykes retained floodwater and disturbed the connectivity of valley slopes, floodplains, and stream channels. The regulation thus resulted in the fragmentation of floodplains and changes in the lengths and sinuosity of watercourses. The urban landscape was expanding in the second half of the nineteenth century. The cultural landscape in the MSC experienced essential changes in the second half of the twentieth century due to the impact of the 2nd Czechoslovak agrarian reform on the landscape and the ensuing collectivization of Czechoslovak agriculture, merging private plots into large fields.

6.2 Geomorphological Conditions

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6.2.1 Highlands and Mountains of the Outer Western Flysch Carpathians

The mountain ridges are composed of massive flysch sandstones and depressions developed mostly in shales. The system of sandstone mountain ridges and depressions shows a zonal arrangement (Fig. 6.1). Several subsystems can be distinguished: the South Moravian Carpathians, the Central Moravian Carpathians, the Moravian–Slovakian

Fig. 6.1 The zonal structure of the MSC on digital elevation model

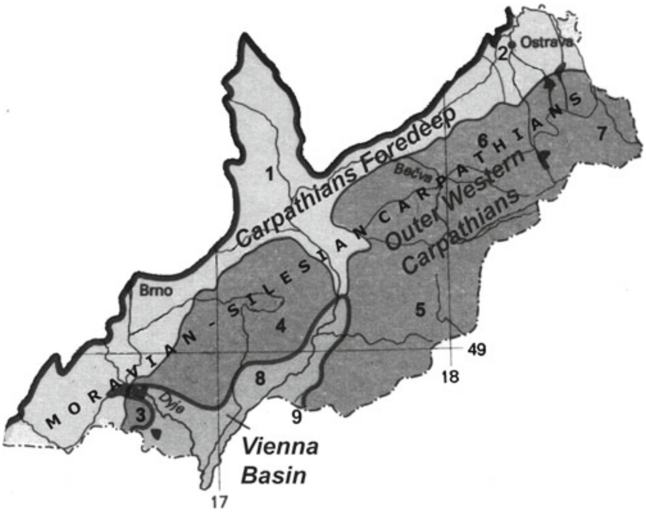

Fig. 6.2 Geomorphological divisions of the Moravian–Silesian Carpathians and environs on the territory of the Czech Republic. *1* Western Outer Carpathian depressions, *2* Eastern Outer Carpathian depressions, *3* South Moravian Carpathians, *4* Central Moravian Carpathians, *5* Moravian–Slovakian Carpathians, *6* Western Beskids Foothills, *7* Western Beskids, *8* Lower Moravian Graben, *9* Záhorská nížina Lowland. Source: Demek and Mackovčin (2006)

Carpathians, the Podbeskydská pahorkatina Hills (piedmont of the Western Beskids), and the Western Beskids on the Slovak border (see Fig. 6.2).

The *South Moravian Carpathians* (Fig. 6.2: 3) are characterized by their white limestone klippen forming the highest peaks in the Pavlovské vrchy Hills (Mt. Děvín 548.7 m elevation). Steep Jurassic and Cretaceous limestone klippen rise above the piedmont hills of the Ždánice Flysch Unit.

The *Central Moravian Carpathians* (Fig. 6.2: 4) are a strip of flysch hills and highlands extending between the Věstonická brána Gate on the Dyje River in the west and the Napajedelská brána Gate on the Morava River in the east. Their axis is formed by the Ždánický les Highland (U slepice 437.4 m.) and the Chřiby Highland (Brdo 586.7 m) surrounded by foothills. The central ridge of the Ždánický les Highland has a planation surface at 300–430 m elevation. Typical are the Tertiary pediments and Quaternary cryopediments for the hilly rim of the central ridge of the Ždánický les. The Chřiby Highland, the eastern continuation of the Ždánický les Highland, reaches as far as the Napajedelská brána Gate to the east. The central higher part of the Highland consists of two parallel forested ridges with flysch sandstone tors and castle coppies. On the watersheds expressive flats can be found truncating the surface of folded rocks (predominantly by Paleogene sandstones and claystones). The elevation of these flats is usually 350–500 m. In the north and south a lower and less dissected hills strip of variable width joins the central range: the Litenčická pahorkatina in the north and the Kyjovská pahorkatina in the south (Fig. 6.2). The Litenčická pahorkatina Hills are rounded interfluvial ridges with broad dry valleys and cryopediments on Neogene deposits.

The *Moravian–Slovakian Carpathians* (Fig. 6.2: 5) consist of two flysch ranges extending along the Czech-Slovak border (the Bílé Karpaty and Javorníky Mountains) and the Vizovická vrchovina Highland. A characteristic feature of the Bílé Karpaty Mountains (White Carpathians) is the high massive Magura flysch sandstone ridge (Velká Javořina 970.0 m) with smooth and less dissected slopes. The Bílé Karpaty Mountains are dissected by the valleys of the right tributaries of the Váh River into a series of isolated mountain groups. Numerous landslides developed on the slopes of the mountain ridge. The Bílé Karpaty continues in the central ridge of the Javorníky Mountains (the highest point is Malý Javorník 1019.2 m) built of flysh sandstones of the Rača unit. On Hradisko Mountain (773.1 m), near the village of Pulčín, the largest "rock city" in the Czech Republic developed in flysh sandstones and conglomerates of the Outer Western Flysch Carpathians with castellated rocks, gorges, and pseudokarst caves. The Vizovická vrchovina Highland extends from the foot of the Bílé Karpaty and Javorníky Mountains up to the Morava River valley in the west. The main axis is the central anticlinal Klášťovský hřbet Ridge composed of resistant sandstones (Klášťov 752.9 m). Extensive pediments and cryopediments developed on the less resistant shales of the surrounding hills.

The subsystem of the *Západní Beskydy* (*Western Beskids* – Fig. 6.2: 7) represents a mountain range extending on the territory of the Czech Republic from the Morava River in the west to the Slovak and Polish border in the east. The Západní Beskydy Mountains are divided by the Jablunkovský průsmyk Pass into a Moravian–Silesian part and a Polish-Slovakian part. With the predominance of resistant Cretaceous and Paleogene flysch sandstones, they are characterized by considerable elevation (Lysá hora 1323.3 m), massive ridges, and relatively steep slopes. The Moravian–Silesian part has its core in the Moravskoslezské Beskydy Mountains and also includes the Hostýnské vrchy and Vsetínské vrchy Hills, the Jablunkovské mezihoří Highlands and the foothills of the Podbeskydská pahorkatina. To the Polish-Slovakian part belong the Slezské Beskydy (Silesian Beskids) and the tectonic depression Jablunkovská brázda Furrow. The relief of the Slezské Beskydy Mountains is influenced by complex tectonics, deep-seated movements, and numerous block landslides (e.g. Velký Šošov 885.6 m). The topography of the Moravskoslezské Beskydy Mountains is controlled by their structure. The thick layers of the Godula and Istebná flysch sandstones are slightly inclined to the south and control the appearance of flat summits (Novosad 1966). The northern boundary of the mountains forms steep and high structural slopes on heads of dipping resistant sandstone strata. Pseudokarst features are typical on sandstone summits and due to gravitational tectonics there are numerous landslides on the slopes. The depression of Rožnovská brázda Furrow divides the Moravskoslezské Beskydy from the Vsetínské vrchy Hills. The axis of the depression forms the valley of the Rožnovská Bečva River bordered by fluvial terraces and valley pediments. The Vsetínské vrchy Hills are situated at the head of the flysch Magura nappe. The highest point is Vysoká (1,024 m) in the Soláňský hřbet sandstone ridge. There are many extensive landslides on its slopes. The mountain range of the Hostýnské vrchy Hills begins near the town of Holešov in the west and reaches to the Bečva River valley in the east. The flysch highland is limited by a steep structural slope in the north bordered by rock pediments.

The Hostýnské vrchy Hills and the Moravskoslezské Beskydy Mountains are accompanied on the NW side by the continuous belt of the *Podbeskydská pahorkatina Hills* (Fig. 6.2: 6). The Maleník Ridge between towns of Hranice na Moravě and Lipník, built of Paleozoic rocks, is partly thrust on the Neogene deposits of the Moravian Gate.

6.2.2 Outer Carpathian Depressions

The Carpathian Foredeep developed in the Neogene as a continuous depression bordering the Flysch Carpathian arc on the outside (Fig. 6.2: 1). The depression was filled with Neogene marine and lacustrine deposits, which were partly overridden by the marginal flysch nappes of the Carpathians during the Neogene orogenies. The Outer Carpathian Depressions are followed by the foredeep and represented on the territory of the Czech Republic by three basins connected by two gates, forming a pronounced boundary between the Bohemian Highlands and ranges of Moravian–Silesian Flysch Carpathians (Fig. 6.2). The outer border line of the Moravian–Silesian Carpathians is marked by an expressive fault scarp between the Bohemian Massif and Outer Carpathian Depressions along the line Znojmo–Brno–Litovel–Přerov–Hranice na Moravě and Ostrava.

The *Dyjsko-svratecký úval Graben* is the first westernmost link in the chain of the Outer Carpathian Depressions (Fig. 6.2: 8). It stretches south and southwest from the city of Brno in the north up to Czechia–Austria border in the south. With its subsidence character and unconsolidated Neogene and Quaternary deposits, its relief is flat or slightly undulating. The narrow graben around the town of Vyškov, called *Vyškovská brána Gate*, connects the grabens of Dyjsko-svratecký úval and Hornomoravský úval. The Hornomoravský úval (*Upper Moravian Graben*) represents the central link of the chain of the Outer Carpathian Depressions, filled by Neogene sediments overlain by Quaternary fluvial and aeolian deposits, along the Morava River. It is the last northeastern link of the Outer Carpathian Depressions with the Basin of Ostrava through the narrow elongated Moravská brána (*Moravian Gate*). The Ostravská pánev (*Basin of Ostrava* – Fig. 6.2: 2) in the northeast is a Quaternary accumulation plain with a lowland relief along the Odra and Olše Rivers, glaciated during the Pleistocene. The landscape is substantially changed by human activities (hard coal mining).

6.2.3 The Inner Carpathian Depressions

On the territory of the Czech Republic the Inner Carpathian depressions are the northern extensions of the Vienna Basin, such as the *Dolnomoravský úval Graben* (Fig. 6.2: 8) with lowland relief and the wide *floodplains* of the *Morava and Dyje* (Thaya) Rivers.

6.3 History of Geomorphological Research in the Czech Republic

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Karel Kirchner

The systematic study of present-day geomorphological processes started at the beginning of the twentieth century with the study of slope deformation, especially *landslides*. H. Götzinger (1909) called attention to relation of landslides on the Neogene/Quaternary boundary. More papers were published in the inter-war period, mostly on slope deformations related to road and railway construction in the Flysh Mountains between Moravia and Slovakia and on establishing water reservoirs in this sensitive terrain (Záruba 1938). Q. Záruba (1922) described landslides in the vicinity of the town of Vsetín and Stejskal (1931) in the Pavlovské vrchy Hills. During World War II J. Krejčí studied landslides around Zlín, while S. Novosad (1956) described deep-seated movements in the Moravskoslezské Beskydy Mountains in. Attention was also paid to local landslides in the MSC – e.g., in Neogene deposits on Výhon Hill near Židlochovice (Quitt 1960). A catalogue of historical landslides was compiled by M. Špůrek (1972).

Through the systematic research of landslides a wealth of new knowledge was obtained on slope processes, particularly in the years of 1962 and 1963 from the landslide hazard studies in Handlová in the Slovak Republic in December 1960 (Záruba and Mencl 1969). The database of the Geofond in Prague was compiled and supplied with further data by the Czech Geological Survey in the following years resulting in an *inventory* of landslides and other dangerous slope deformations. The constructions of dams on rivers in the MSC (Šance Dam on the Ostravice River, Karolinka Dam on the Stanovnice Stream) induced slope deformations that were monitored (Krejčí 2004; Novosad 2006). The events of extreme precipitation and flash floods in July 1997 drew attention again to the research and monitoring of slope deformations, the reactivation of landslides and other hazardous slope processes (mud flows, gully formation, etc.) with extensive damage and loss of lives. Detailed investigations of landslides, led by the Czech Geological Survey, started in the most endangered regions. In 1999 further research was initiated by the Ministry of Environment of the Czech Republic (for more details see Brázdil and Kirchner 2007). Recent slow slope movements were measured by J. Demek (1986, 1988) in the Javorníky Mountains. K. Šilhán (2010) applied dendrogeomorphology for the study of the periodicity of rockfalls in the Moravskoslezské Beskydy Mountains.

The geomorphological research of fluvial processes in Czechia is closely connected with *archeological and historical investigations*. Especially after the emergence of the concept of the Great Moravian Empire, the interests of geomorphologists and Quaternary geologists focused on problems of floodplains evolution

(Opravil 1983). The study of river processes concentrated on studies of the impacts of floods and of suspension load and bedload transport (Brosch 2005; Buzek 1977, 1991), particularly the geomorphological impact of floods in 1980 (Garguláková 1983), 1960 (Kříž 1963), and 2007 (channel configuration changes, Křížek 2008). Changes in the courses of rivers were studied by M. Havrlant and V. Kříž (1984).

Accelerated sheet and gully erosion in the Dyjsko-svratecký úval Graben, the Vyškovská brána Gate and the Central Moravian Carpathians in the eighteenth and nineteenth centuries were studied by Z. Láznička (1959) from historical data. Gully erosion in the Moravian Carpathians was described by K. Gam and O. Stehlík (1956), who also indicated extreme gully erosion after flash floods in the Kyjovská pahorkatina Hills near Bzenec (Stehlík 1954). Estimations of soil loss by water erosion in the Kyjovská pahorkatina Hills were published by V. Vaníček (1963) and by Demek and Stehlík (1972). Related deposits in the Outer Carpathians depressions deposited in connection with soil erosion after 1000 AD were studied by R. Netopil (1954), J. Demek (1955), and E. Opravil (1973, 1983). A general overview of soil erosion was published by O. Stehlík (1981), while the impact of hollow roads on gully development was revealed by J. Demek (1960). Interesting quantitative studies of the importance of wood felling and forest roads for soil erosion in the Moravskoslezské Beskydy Mountains were published by L. Buzek (1977, 1981, 1986, 1993, 1996).

Wind erosion in the Vizovická vrchovina Highland was studied in several papers, especially by R. Švehlík (1978, 1983, 1985). *Piping* in the Moravian-Silesian Carpathians was described by L. Buzek (1969), K. Kirchner (1981, 1982, 1987a, b), V. Cílek (2000), and P. Kos et al. (2000). The investigation of *pseudokarst* phenomena in the Silesian and Moravian-Silesian Beskids, Hostýnské vrchy Hills, Vizovická vrchovina Highland, and Javorníky Mountains substantially contributed to knowledge on deep-seated deformations in the Flysh Carpathians (Wagner et al. 1990; J. Wagner 1994).

Anthropogenic geomorphic processes and landforms were studied in the Ostrava Region (Havrlant 1979; 1980). From the geomorphological point of view, the Moravian-Silesian Carpathians are a very sensitive area. The intensity of natural endogenic and exogenic geomorphological processes is very high. In the last millennium the intensity of many natural exogenic geomorphological processes was accelerated by human activities.

6.4 Land-Use Changes and Their Impact in the Last Millennium

Jaromír Demek

Land-use changes influenced the intensity and type of exogenic geomorphological processes in the last millennium. The map *Landscape in the 12th century* compiled by B. Nováková at the scale of 1:500,000 published in the *Landscape atlas of the*

Czech Republic (Hrnčiarova et al. 2009) shows ancient *core settlement areas* of Outer Carpathians depressios, the Dolnomoravský úval Graben and flat foothills of Carpathians (e.g., Milovická pahorkatina, Kyjovská pahorkatina, Hlucká pahorkatina, and the western Podbeskydská pahorkatina) as agricultural landscapes with small isolated forests. Floodplains are mostly depicted as wetlands, but the extent of floodplain *forests* was probably greater than shown on the map. On the other hand, highlands and mountains of the MSC are shown as continuous forest landscapes.

Important administrative centers of the Great Moravian Empire (as Mikulčice, Staré Město, and Uherské Hradiště) in the floodplain of the Morava River and Pohansko of the Dyje floodplain were situated in the ancient core settlement areas of the grabens Dyjsko-svratecký úval and Dolnomoravský úval. These centers were buried under floodplain loams due to climatic changes and simultaneous accelerated soil erosion during floods becoming more frequent after the end of the Empire in the tenth century AD. Major international *trade routes* ran through the Moravian-Silesian Carpathians, along the Morava, Bečva, and Odra Rivers (e.g., the Amber Road from the Baltic to the Mediterranean).

Changes in landscape structure reflected the introduction of a new land administration in the late twelfth and early thirteenth centuries. The beginning of the Little Ice Age in the twelfth century brought higher precipitations causing *floods* and accelerated accumulation in floodplains. Most of the settlements located at riverbanks had to move from the floodplains up to higher ground not regularly inundated by floods (e.g., onto low river terraces). Settlements gradually spread into the higher parts of Carpathians from the ancient core areas.

Less fertile and forested flysch highlands and mountains of Eastern Moravia and Silesia were sparsely inhabited for a long time. The *colonization of forested landscapes* of Moravian-Silesian Carpathians started in the thirteenth century when settlers began to occupy mountain valleys. Towns were also founded (e.g., Rožnov pod Radhoštěm in 1267). The character of mountain landscapes radically changed only by the *Walachian colonization* in the late fifteenth and early sixteenth centuries, when Walachian pastoral tribes arrived into Moravian-Silesian Carpathians migrating westwards with their herds of shaggy sheep and goats from southern Romania along the Carpathian ranges. The local feudal lords did not profit from those forested mountain areas until the arrival of these mountain shepherds. The local Czech population was involved in agriculture in the valleys and did not have skills in mountain economy. Throughout the summer the Walachians' sheep and goats grazed in the mountains, where at the same location milk, wool, and other products were processed (alpine cottage production). The mountain grazing season started usually in May, when sheep and goats were driven from valleys to the cottages on mountain slopes and ranges. New land was gained mainly from clearing the woods for grazing cattle and growing crops. *Deforestation* and *grazing* on steep slopes naturally caused acceleration of geomorphological processes on less permeable flysh deposits, especially soil erosion due to distortion of grass cover, landsliding, and mudflows. Eroded material accumulated on valley bottoms. This situation is evidenced by deep accumulations on the floodplain of the Bečva River in the town of Vsetín (0.7–0.8 m of flood loam upon Late Holocene gravels). The base of the

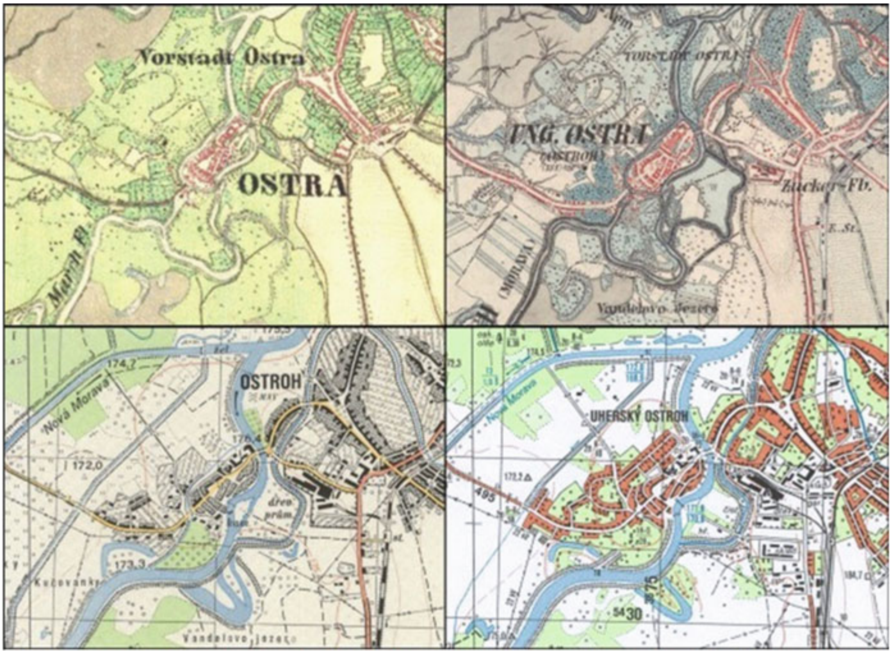

Fig. 6.3 Examples of topographic maps used for land-use evaluation. *Upper left*: map of the first Military Survey – Morava floodplain, 1768, *upper right*: map of the second Military Survey, 1836, *lower left*: map S52 of the Czechoslovak Military Survey, 1955, *lower right*: map of the Czech mapping, 2006

flood loam layer is dated 410 ± 30 ^{14}C years BP (calibrated years 1430–1510 AD), evidencing major environmental changes after Walachian colonization (Baroň et al. 2008). Deforestation also caused more frequent *flash floods*. Catastrophic processes occurring on slopes were the reason for a Decree of Empress Maria Theresa, which made it the duty of local citizens to plant trees. A similar decree was issued in 1796.

The construction of *fishponds* and entire fishpond systems changed the character of agricultural landscapes in the period of flourishing pisciculture in the fifteenth and sixteenth centuries and also influenced the water and sediment discharges of lowland watercourses. Fishponds changed runoff conditions and intercepted suspended load. An extensive fishpond system was established in the Dyjsko-svratecký úval Graben near the town of Pohořelice in the sixteenth century and near the village Lednice in the Dolnomoravský úval Graben, including the largest Moravian fishpond, Nesyt (296 ha). Many fishponds occur in the Dyjsko-moravská pahorkatina Hills in the catchment of the Kyjovka River.

Useful information on land-use changes is contained on detailed *topographical maps* drawn since the second half of the eighteenth century (Fig. 6.3). Land-use changes in the Moravian-Silesian Carpathians and their impact on the type and intensity of geomorphological processes are studied at the Department of Landscape Ecology of The Silva Tarouca Research Institute for Landscape and Ornamental

Gardening, using manual and computer supported analyses of topographical maps from the periods 1764–1836, 1836–1875, 1875–1950, 1950–1990, and 1990–2006 (Mackovčin 2009). The topographic maps from the firtst Austrian Military Survey of Moravia in 1764–1768 (at a scale of 1:28,800) provide a unique picture of the landscape at the beginning of the agricultural revolution. In the period of the first Survey, Europe was mainly agricultural. The largest landscape user was agriculture and its changes (e.g., Austrian agricultural reform) significantly influenced both the type and intensity of geomorphological processes. The agricultural revolution was followed by the first stage of scientific-technical revolution in agriculture that resulted in the extension of arable land at the expense of permanent grassland and in changes of runoff. In this period major elements of the agricultural landscape were wet floodplains with prevailing floodplain forests, meadows, and fishponds. Some fields appear in the warm floodplain Středodyjská niva on the boundary to Austria. In the floodplains, rivers freely meandered and formed anastomosing channels. The Morava River was markedly anastomosing in the vicinity of the town of Strážnice in the Dolnomoravský úval Graben (Culek et al. 1999). An elaborate network of river arms formed in floodplain forests in the region of Soutok near the confluence of the Dyje River with the Morava River on the border with Slovakia and Austria. Typical landscape features were fishpond systems. The low hills were typically rural landscapes dominated by arable fields, vineyards, and rural settlements. The landscape to the south of the town of Bzenec (Dúbrava in older maps, Doubrava in modern maps) still featured freely moving sand dunes. Rivers, their floodplains, and adjacent low hills were mutually linked in the landscape. Meadows and pastures locally reached up to the watersheds in highlands and deforested mountains on the boundary to Slovakia. Especially in regions of Walachian mountain farming, farms were also built on higher mountain slopes (called *kopanice* in Czech). Forests were affected by forest grazing.

The fact that the maps from the first Austrian Military Survey were not based on a triangulation network did not allow computer-aided evaluation, only manual analysis.

Landscape structure and geomorphological processes in the first half of the nineteenth century are well depicted on topographical maps from the second Austrian Military Survey, carried out in Moravia between 1836 and 1841, at 1:28,800 scale. For the survey a triangulation network was already employed and thus the maps can be georeferenced and computer processed. The 1:200,000-scale land-use map sheet M-33-XXIX (Brno) was compiled by the Silva Tarouca Research Institute for Landscape and Ornamental Gardening in Průhonice. The map includes the Dyjsko-svratecký úval Graben, the Výškovaká brána Gate, the Southern Moravian and Central Moravian Carpathians, and part of the Dolnomoravský úval Graben. Results of the computer-aided quantitative analysis of land use on the 1:200,000-scale map sheets M-33-XXX (Zlín) and the Czech part of sheet M-34-XXV (Žilina) showing the Carpathians in southeastern Moravia are presented in Table 6.1.

Rural landscape still dominated in the Moravian-Silesian Flysch Carpathians. In 1823 reforestation started in the Doubrava blown sand area (Vitásek 1942, p. 1 – Fig. 6.4) near the town of Bzenec in the Dolnomoravský úval Graben. A number of

Table 6.1 Land use changes on map sheets M-33-XXX (Zlín) and M-34-XXV (Žilina, Moravian part) in the period 1836–2006

		1836		1876		1956		1996		2006	
Code	Categories	sq.km	%	sq.km	%	sq.km	%	sq.km	%	sq.km	%
1	Arable land	1,907.47	45.55	2,215.93	52.92	2,291.87	54.73	1,889.79	45.13	1,727.13	41.26
2	Permanent grassland	1,010.16	24.12	640.30	15.29	291.96	8.97	373.38	8.92	476.95	11.39
3	Garden and orchard	19.73	0.47	24.53	0.59	37.34	0.89	67,99	1.62	38.11	1.62
4	Vineyard and hop field	53.73	1.28	41.28	0.99	27.72	0.66	54.49	1.30	1,475.11	0.91
5	Forest	1,089.64	26.02	1,153.18	27.54	1,317.70	31.47	1,430.07	34.15	1,475.11	35,23
6	Water surface	5.27	0.13	0.61	0.01	6.64	0.16	19.33	0.46	20.88	0.50
7	Built-up area	101.20	2.42	111.10	2.65	209.82	5.01	331.16	7.91	354.93	8.48
8	Recreation area	0.00	0.00	0.00	0.00	2.12	0.05	17.48	0.42	22.44	0.54
0	Other areas	0.21	0.01	0.38	0.01	2.24	0.05	3.62	0.09	3.80	0.09
	Total	4,187.31	100	4,187.31	100	4,187.31	100	4,187.31	100	4,187.31	100

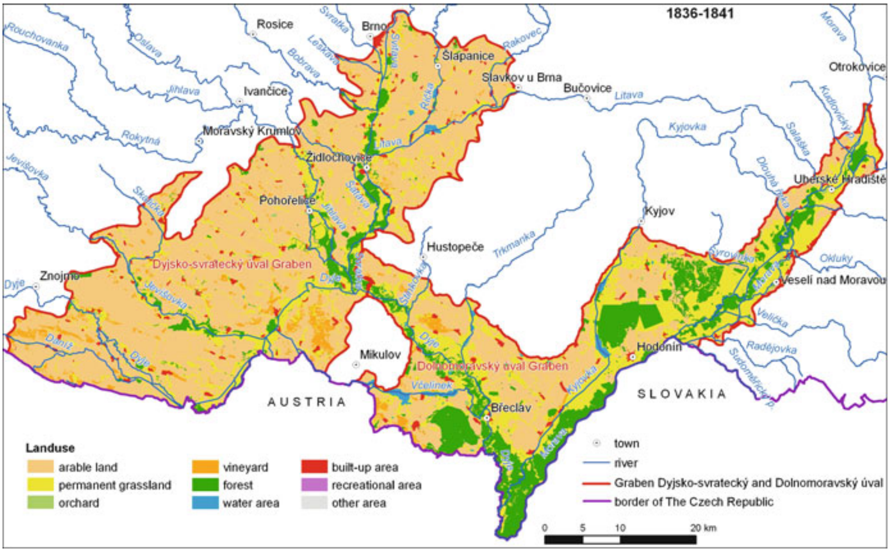

Fig. 6.4 Example of a land-use map of the Dyjsko-svratecký and Dolnomoravský úval Grabens based on computer-aided analysis of topographic maps of the second Austrian Military Survey in 1836. Rivers are not trained and in wet floodplains there are floodplain forests and permanent grasslands

fishponds were drained and replaced by country estates (Hlavinka and Noháč 1926, p.11) in this period. The river patterns experienced considerable changes. The main channel of the Olšava River shifted from the direction of the town of Uherské Hradiště to the west of Kunovice and then meandered as a yazoo towards the south parallel with the main channel of the Morava River, reaching it at the town of Ostroh. To the south of the town of Hodonín, the Morava River was braided. The degree of connectivity, both longitudinal and lateral, was still considerable in the Moravian-Silesian Carpathians. The map shows a dense network of gullies, especially in loess, many of them developed from abandoned medieval hollow roads that concentrated runoff. A group of new parallel hollow roads from this period were used up to the twentieth century.

For the assessment of landscape pattern and geomorphic processes in the second half of the nineteenth century maps from the third Austrian Military Survey, prepared at a scale of 1:25,000 for Moravia in 1875–1877, are useful. The period between the second and the third military surveys was a period of a very rapid spreading of the cultural landscape. Land use changed over 20.37% of the flat area of the Dolnomoravský úval Graben (Table 6.2).

The agricultural revolution leading to higher intensity of agricultural production was responsible for the increasing proportion of arable land (Table 6.1) – again at the expense of permanent grassland. In lowlands and flat hills the cultivation of sugar beet expanded and led to soil exhaustion and the application of manure as well

Table 6.2 Land use changes in the Dolnomoravský úval Graben, 1836–2006 (Demek et al. 2009)

Code	Categories	1836	1876	1955	1992	2006
1	Arable land	38.06	46.46	49.61	49.26	49.52
2	Permanent grassland	32.00	22.96	14.95	6.92	5.70
3	Orchard	0.67	0.50	0.87	1.44	1.78
4	Vineyard and hopfield	1.62	1.24	1.26	2.83	2.36
5	Forest	23.86	25.42	26.46	26.51	27.09
6	Water surface	1.42	0.74	1.21	3.41	3.57
7	Built-up area	2.35	2.67	5.42	9.14	9.47
8	Recreational area	0.00	0.00	0.03	0.26	0.31
0	Other area	0.01	0.01	0.19	0.23	0.18
Total		100.00	100.00	100.00	100.00	100.00

Table 6.3 River channel length changes (in km) in the Dyjsko-svratecký úval and Dolnomoravský úval Graben in the course of time (Demek et al. 2008a,b)

River	1836	1876	1944	1954	1991	2007[a]
Svratka	52.50	44.62	40.25	40.21	35.33	36.75
Cézava	28.24	26.48	n.a.	24.46	24.41	24.48
Jihlava	26.32	25.20	25.36	25.55	24.52	24.97
Dyje	68.39	67.14	n.a.	61.46	59.11	60.15
Jevišovka	31.82	32.36	n.a.	31.79	31.46	31.49
Morava[b]	145.53	144.51	n.a.	112.12	97.29[c]	n.a.

[a] Mapping scale 1:10,000

[b] From Napajedla up to the confluence with the Dyje River (Kilianová 2001)

[c] Data for 1999 (Kilianová 2001)

as mineral fertilizers. Agriculture, however, remained backward in highlands and mountains in this period.

The floodplains showed a reduced share of forests and arable land sprawled from the adjacent hills into the floodplains. The number of fishponds in the landscape was dramatically reduced (e.g., in the Dyjsko-svratecký úval Graben from 0.21% to 0.003%). The development called for the regulation of the Svratka and Svitava river channels, launched in 1848. The original confluence of both rivers was artificially moved (Demek et al. 2007). A new deep channel was excavated and embankments built between the city of Brno in the north and the village of Přízřenice in the south. Channelization disturbed the connectivity of valley slopes, floodplains, and stream channels. The regulation thus resulted in the fragmentation of floodplains; also changing river length and sinuosity (see Table 6.3).

During the extreme flood in Moravia (1877) the dykes of the Bečva River breached (Peřinka 1911, p. 397) and the floodplain Středomoravská niva was inundated. A large flood also occurred in 1894 (Peřinka 1912, p. 577). Urban growth in floodplains accelerated after river regulations (Table 6.1). The construction of transport networks and extension of settlements required the extraction of buildings materials. Gravels and sand pits were opened in the floodplains and raw materials for brick making (namely loess and clay) were extracted in the adjacent hills.

No integrated set of large-scale topographic maps exists for the first half of the twentieth century that would make it possible to follow land-use changes continually. Only the maps from the third Austrian Military Survey were gradually revised. The first Czechoslovak agricultural reform after World War I led to the reduction of large estates, allotting land to small farmers and creating a more conspicuous mosaic of small fields in the rural landscape. The Morava River in the Carpathians was regulated as late as the twentieth century. At the beginning of the twentieth century, river training started between the towns of Napajedla and Lanžhot and the main channel was shortened (Table 6.3). The topographic map at 1:75,000 scale dating from about 1930 already shows a new navigation canal named Morávka excavated between the towns of Veselí nad Moravou and Vnorovy in Slovakia. The longitudinal connectivity of rivers was greatly disrupted by weirs. The area of blown sands in the Doubrava was already fully reforested and the dunes stabilized. Settlements were sprawling, also on floodplains, and the share of urban landscape was increasing (Table 6.1).

In the second half of the twentieth century, the cultural landscape in the Moravian-Silesian Carpathians experienced essential changes and geomorphological processes were accelerated. After a long break of about 75 years, another integrated set of Czechoslovak military topographic maps was published in 1952–1955 (S52). The post-war period saw the second Czechoslovak agricultural reform, and the industrialization and collectivization of Czech agriculture after 1955. The maps document the re-establishment of several large fishponds (e.g., in the vicinity of Pohořelice in the Dyjsko-svratecký úval Graben). A network of three large water reservoirs (Nové Mlýny) was constructed at the confluence of the Dyje and Svratka Rivers in the Dyjsko-svratecký úval and Dolnomoravský úval Grabens in 1975–1982.

Renewed Czechoslovak color military topographic maps (S42) from 1990–1992 document the impact of the second Czechoslovak *agrarian reform* on the landscape as well as the subsequent *collectivization*. The private field boundaries were obliterated and large fields were created. A system of shelter belts was planted in the dry and warm Jaroslavická pahorkatina and Drnholecká pahorkatina Hills in Southern Moravia. The maps S42 also document a considerable expansion of urban landscapes and *suburbanization*. At the same time the connectivity of ecologically more stable landscape segments and patterns was decreasing. An unfavorable fact was the further spreading of built-up areas into floodplains (resulting in major damage during the 1997 catastrophic flood).

The contemporary landscape structures are shown on the digital grid Basic Map of the Czech Republic at the scale 1:10,000 and on recent aerial and satellite images. The share of arable land slightly decreased after 1989 (Table 6.1), while large fields still prevail. The share of forests increased to its historical peak (Table 6.1). The digital maps also represent a rapid growth in built-up land (Table 6.1). The number of anthropogenic landforms in the landscapes has extremely grown.

6.5 Hillslope Processes and Landforms

Tomáš Pánek
Karel Kirchner

The extensive occurrence of hillslope processes in the MSC is explained by both suitable *preparatory* and *triggering factors*. To the first category belongs (1) the susceptible anisotropic flysch substrate, (2) dissected mountain terrain with river incision, (3) large portions of slopes weakened by deep-seated slope failures or old landslides, and (4) intensive anthropogenic activity – mainly deforestation during the past centuries. Main triggering factors especially include extreme hydrometeorological events, i.e., local heavy downpours, incessant rains with regional extent followed by heavy downpours or intensive snowmelt (often enhanced by rainfall events). Some slope failures have been induced by active undercutting of slopes. The MSC are the most hazardous landslide terrain on the territory of Czech Republic with 9100 inventoried active and dormant slope failures until 2007 (Krejčí et al. 2008).

According to the classification of R. Dikau et al. (1996), in the last millennium the territory of the MSC has been affected by almost a full range of slope processes, including deep-seated slope failures (lateral gravitational spreading, toppling, and sackung), translational and rotational landslides, earthflows, debris flows, and rockfalls. The highest ridges formed by most resistant sandstones of the Silesian Unit (e.g., Moravskoslezské Beskydy Mountains) have been mostly modeled by slow and massive deep-seated slope failures and debris flows, less dissected uplands on the fine-rhythmical (clay-rich) flysch of the Magura Unit (e.g. Hostýnsko-vsetínská hornatina Mountains or Javorníky Mountains) are extremely susceptible to landslides and earthflows (Krejčí 2005).

Deep-seated slope failures (mainly lateral gravitational spreading) have been described from numerous places situated especially in the most elevated parts of the Silesian and Magura Units (Baroň et al. 2004; Krejčí et al. 2004; Hradecký et al. 2007; Hradecký and Pánek 2008). Suitable conditions for such failures involve mainly high ridges formed by jointed and/or faulted sandstones underlying by weak (plastic) fine-rhythmical flysch. Many manifestations of deep-seated failures are connected with widespread landslide terrains; some of them present incipient stages of landslide evolution (Baroň et al. 2004; Hradecký and Pánek 2008). Morphological expressions of deep-seated failures involve double (or multiple) ridges, counter-slope scarps, and crevice-type caves (Fig. 6.5). Dilatometric or extensometric measurements performed within crevice-type caves and on surface ruptures in the last decade have revealed very slow, often reversible movements do not exceeding 1 mm year^{-1} (Rybář et al. 2006). For instance, maximum amplitude of movements within the longest Cyrilka cave in the mountain Ridge Radhošťský hřbet in the Mountain Moravskoslezské Beskydy (>370 m long) in the period 2000–2007 was 0.03 mm year^{-1} (Klimeš and Stemberk 2007). Higher amplitudes were measured by J. Stemberk and J. Rybář (2005) in the Kněhyňská cave (shaft) (0.3 mm year^{-1}), and in the

Fig. 6.5 Morphological expressions of deep-seated slope failure (Lukšinec ridge, Moravian–Silesian Beskids). Some of the opened trenches (not visible on this picture) originated after July 1997 event (Photo T. Pánek)

Lukšinec hills (0.5 mm year^{-1}). Most of these results indicate pulse-like movements with seasonal shortening and dilatation also indicating external (climatic) influence. Despite the fact that monitoring of slow movements of deep-seated failures brings valuable information, due to the limited number of measurements, it cannot cover the full range of movement intensities. Periods of much faster opening of some gravitational trenches were observed, e.g., just after high-intensity rainfalls in July 1997. J. Wagner (2004) described that some new tensional cracks on the Lukšinec ridge (Lysá hora mountain, the Moravskoslezské Beskydy Mountains) opened within several days/week after mentioned extreme hydrometeorological event.

The most abundant and geomorphologically effective slope processes are *landslides* involving *translational*, *rotational,* or *compound* movements. They are often associated with and/or gradually evolve to the earthflows with protruding lobes. Nearly 40% of recently activated landslides are nested on slopes weakened by older landslides or deep-seated failures (Krejčí et al. 2002, 2008). Historic sources (e.g., Špůrek 1972) and case studies (e.g., Adámek, 1973; Pečeňová-Žďárská and Buzek 1990; Krejčí et al. 2002; Baroň et al. 2004, etc.) indicate more than 50 landslide events in the MSC that have taken place since 1770. While some of these events were isolated phenomena (e.g., Burkhardt et al. 1972), some phases had catastrophic dimensions with genesis and reactivation of several tenths to thousands slope failures (Krejčí et al. 2002; Bíl and Müller 2009). Four types of hydrometeorological regimes in the study area can be recognized as leading to landslides: (1) prolonged rainfalls enhanced by heavy downpours; (2) rapid snowmelt accompanied by rainfalls; (3) localized short-term heavy downpours exceeding 100 mm day^{-1}, and (4) prolonged (several years) abnormally humid periods. Of the above-mentioned triggers only the first two categories usually induce landslides over vast areas, whereas the two last types cause rather spatially localized and isolated failures.

The most pronounced landslide event arose during *extreme rainfalls* in July 1997 when 5-day (from 4th to 8th July) precipitation amounts in the Moravskoslezské Beskydy, Hostýnsko-vsetínská hornatina, and Javorníky Mountains reached 200–400 mm at meteorological stations, whereas a 1-day precipitation record was measured on the Lysá hora (234 mm on 7th July 1997). The hydrometeorological events of July 1997 caused or reactivated more than 1,500 landslides with the highest concentration in the clay-rich substrate of the Magura Unit in the Vsetín and Zlín districts (Krejčí et al. 2002) (Fig. 6.6a).

The melting of an anomalously deep snow cover coupled with the intensive rainfalls of March/April 2006 caused another major landslide event (Bíl and Müller 2009). The cumulative precipitation (both rainwater and snowmelt) reached 143 mm during the thaw season and led to the formation of more than 90 rather shallow landslides situated preferentially on the deforested slopes in the Bílé Karpaty Mountains and Vizovická vrchovina Highland (Bíl and Müller 2009; Klimeš et al. 2009) (Fig. 6.6b). Similar snowmelt combined with rainfalls induced the catastrophic January 1919 Hošťálková landslide in the Hostýnské vrchy Hills (Záruba 1922).

Localized heavy downpours (usually summer rainstorms) could also trigger landslides, especially if their intensity (or sum of several events during 1 day) exceeds 100 mm day^{-1} (Hradecký and Pánek 2008). If catchments are not saturated by antecedent rainfalls, such events are capable of activating only a limited number of shallow landslides (e.g., debris slides) concentrated at the sites of rainstorms, as the rainstorm event on 24th August 2005 in the Lysá hora. Several shallow debris slides (up to 100 × 40 m) developed within one day during the rainstorm. Their preferential location was on the deforested steepest slopes, e.g., headscarps of older deep-seated landslides or roadcuts (Fig. 6.6c).

Rather isolated but often pronounced deep-seated landslides occur after prolonged anomalously wet periods, not directly associated with particular rainfall events. Deformation in this category was described by Burkhardt et al. (1972) from the Oznice site in the Hostýnské vrchy Hills (Fig. 6.6d). A structurally preconditioned rotational landslide evolved in August 1967 as a short-time event (observed directly by a local resident) during which large, internally almost non-deformed block moved ca 40 m downslope in the direction of the brachysynclinal axis. A landslide emerged suddenly after a period of two abnormally wet years (121% of average annual precipitation) and just after a wet spring/summer period.

Detailed geomorphological mapping, geophysical survey, and dating reveal that most of the largest recent landslides (e.g., during July 1997 or March/April 2006

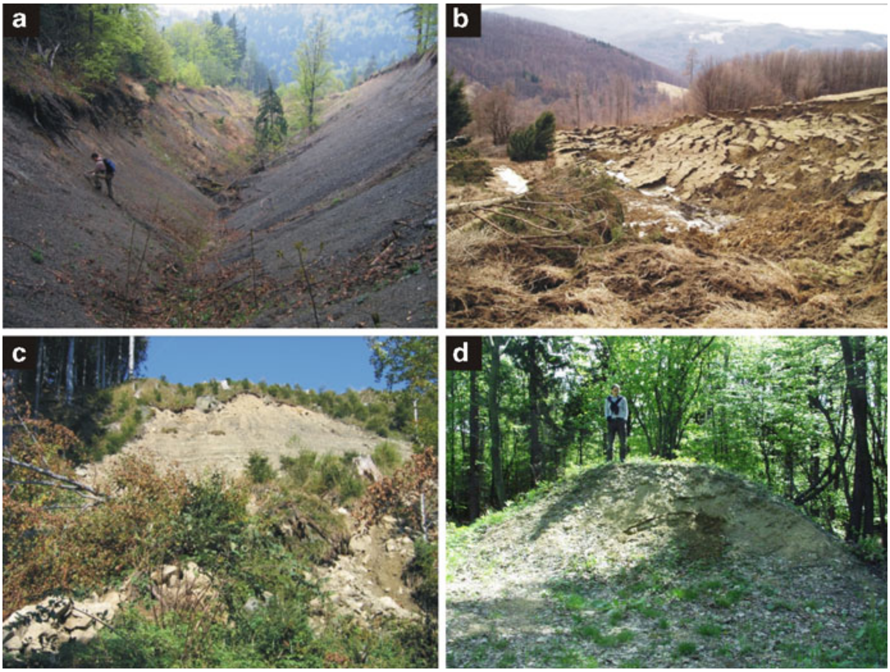

Fig. 6.6 Landslides triggered by different types of hydrometeorological events. (**a**) Brodská landslide with protruding lobe evolved in older, structurally preconditioned landslide area during the extreme rainfalls in July 2007 (Photo T. Pánek); (**b**) *Upper part* of the Hluboče landslide, evolved after massive snowmelt and rainfalls of March/April 2006 (Photo T. Kosačík); (**c**) An example of shallow landslide in the Jestřábí Stream (eastern slopes of Lysá hora), happened after localized downpours on 24th August 2005 (Photo T. Pánek). (**d**) Middle part of the Oznice landslide with small activated area (Photo I. Baroň)

landslide events) are in fact reactivated movements in older landslide bodies (Fig. 6.7). For instance, the Hluboče landslide (Bílé Karpaty Mountains) of March/April 2006, the largest and most catastrophic landslide, is situated in an older failure that was AMS dated to the 1,337 ± 22 cal year BP (Klimeš et al. 2009). The analysis of historical aerial photographs reveals that the catastrophic movement in early April, 2006, was anticipated by more than 50 years long period of creeping and gradual evolution of the headscarp area (Fig. 6.8).

Similar observations of recurrent behavior of landslides were obtained from other parts of the region (e.g., Baroň 2007, 2009; Pánek et al. 2009b), like the Hlavatá ridge (Moravskoslezské Beskydy Mountains), where a landslide reactivated at least three times over 1,500 years (Pánek et al. 2009b). The catastrophic January 1919 Hošťálková landslide (Hostýnské vrchy Hills) that destroyed several houses and caused blockage of a valley is situated on a fossil landslide of a minimum age 1.4 cal ka BP (Baroň 2007, 2009). In the past 100 years, on the Skalice hill (Podbeskydská pahorkatina Hills near Frýdek-Místek) numerous activations of

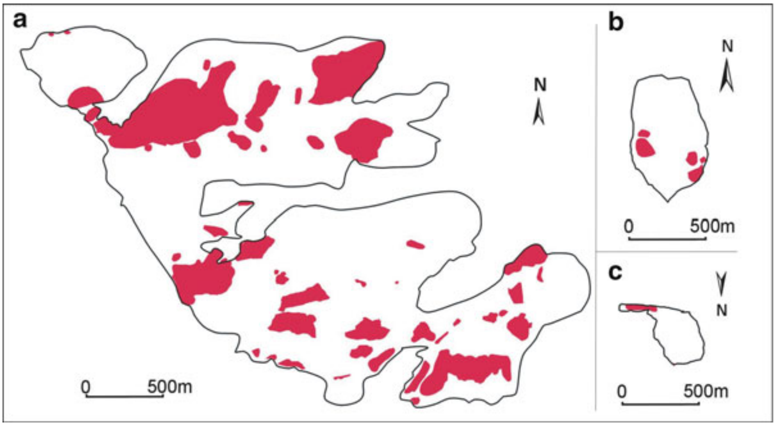

Fig. 6.7 Spatial connection between old deep-seated landslides in the Magura Unit (around Vsetín) and failures activated during July 1997 event (*red patches*). All displayed landslides show a complex Holocene history. The Vaculov–Sedlo landslide (**a**) has a minimal age 6.1 ka BP, the Kobylská landslide (**b**) is older than 9.0 ka BP and the Kopce failure (**c**) is older than 2.5–3.0 ka BP (After Baroň et al. 2004)

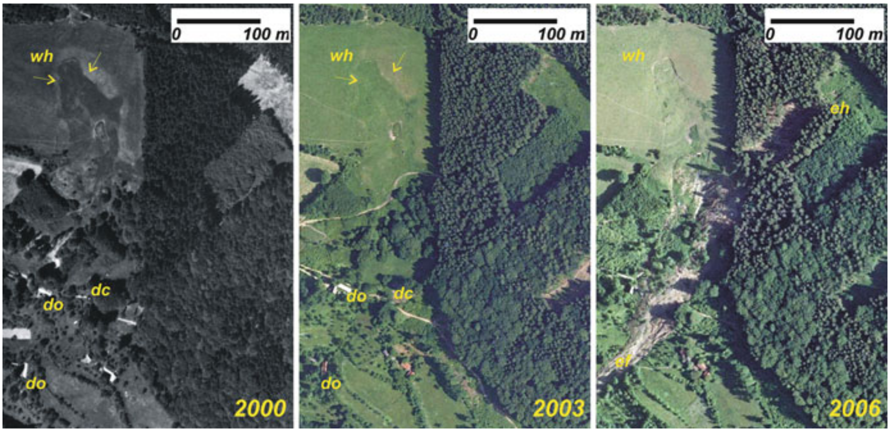

Fig. 6.8 Evolution of the Hluboče landslide. Note the very pronounced, but not fully developed, western branch of the headscarp (*wh*) already 6 years before catastrophic movement. At the turn of March/April 2006 catastrophic earthflow (*ef*) originated after intersection of western (*wh*) and eastern headscarps (*eh*). Several buildings (*do*) and roads were destroyed. A disastrous earthflow affected the ca. 1.3 ka old landslide body (Klimeš et al. 2009)

frontal landslide area were associated with extreme events and undercutting of slopes by the anabranching the Morávka River (Adámek 1973; Pečeňová-Žďárská and Buzek 1990; Pánek and Hradecký 2000). *Slow creep*-like movements (inclinometric measurements provided by (Kovář et al. 2006), show cumulative movements in 2005 up to 6 mm) are disrupted once in 10–20 years by catastrophic landslides causing significant economic losses at each time (e.g., destroyed road in August 1972 or five recreational objects in July 1997).

Less pronounced hillslope processes in the MSC are *debris flows* and *rockfalls*. Their low abundance in the area is due to the lack of major rock faces and steep hillslopes above the timberline. They only occur in the highest regions, mainly in the Moravskoslezské Beskydy and Hostýnsko-vsetínská hornatina Mountains. A higher activity of debris flows and rockfalls is assumed for the Pleistocene/Early Holocene periods with different climatic conditions. A rare example of Late Holocene catastrophic rock-avalanche/debris flow was described from the northern slope of Mt. Ropice (Moravskoslezské Beskydy Mountains) by T. Pánek et al. (2009a). An extensive rock avalanche originated ca 1.4 cal ka BP as a consequence of the collapse of vast rock packet situated in the unstable part of the deep-seated landslide (Pánek et al. 2009a). A large number of debris flows were described by K. Šilhán and T. Pánek (2006) from the highest parts of the Moravskoslezské Beskydy Mountains, the majority of them, however, being prehistoric landforms. Historic events only comprise accumulations of 10^2–10^4 m^3 volume. The analysis of historical sources and dendrochronological record points to 33 minor debris flow events since 1939, mostly after daily rainfalls above 100 mm (Šilhán and Pánek 2010). More than 20 years history of active debris flow fan at the outlet of a high-gradient valley on the steep western slopes of Mt. Travný was described by K. Šilhán (2008) (Fig. 6.9). Rockfalls are relatively more common processes in the study area (associated with failure scarps, structural and undercut slopes), but, due to their small dimensions, their geomorphic impact is quite negligible. Preliminary dendrochronological investigations in the highest parts of the Moravskoslezské Beskydy Mountains indicate that triggering factors for rockfall activity could be both extreme rainfalls and freeze-thaw cycles (Šilhán 2009). On the western slopes of Smrk Mountain (Moravskoslezské Beskydy Mountains) average rockfall frequency is up to two events year^{-1} (Hradecký and Pánek 2000; Šilhán 2009). A rainfall-triggered rockfall from an active landslide area took place in the Bystřička valley (Vsetínské vrchy Hills) in July 1997 (Kirchner and Krejčí 1998).

6.6 Water Erosion and Landforms

Jan Hradecký
Aleš Létal

About 25% of the MSC territory is forested and about 60% is arable land. As in other areas of Central Europe, human activity is the predominant cause of water erosion. In the last millennium, streams of the Czech Carpathians recorded a few fundamental changes consequent to global climatic changes and regional environmental processes, many of which were induced by *human action*. The rate of erosion is directly proportional to man-induced changes in the landscape.

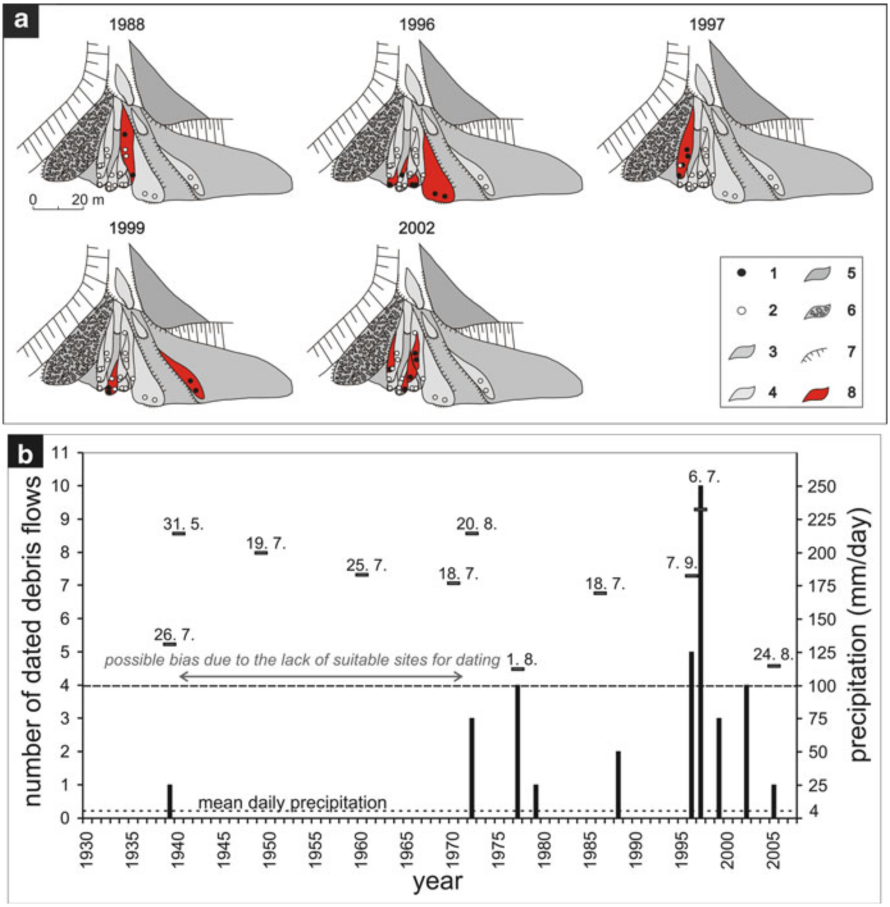

Fig. 6.9 (**a**) Spatial-temporal reconstruction of debris flows on a minor debris fan on the western slope of the Travný Mountain. The present-day fan developed gradually over several tens of years due to low-magnitude events: *1* tree affected by debris flows in particular years, *2* sampled tree, *3* area of the debris fan, *4* lobe of debris flow deposits, *5* old generation of fan, *6* accumulation of hyperconcentrated flow, *7* scarp, *8* active part of the fan in particular years. (**b**) Dendrochronological reconstruction of debris flows in the Moravian–Silesian Beskids for the last 80 years. Mean daily precipitation is shown by the *lower dashed line*. *Numbers* above indicate dates of extreme daily rainfalls exceeding 100 mm (*higher dashed line*) (Both figures after Šilhán and Pánek 2010)

O. Stehlík (1981) found four periods of increased erosion activity in the Czech Republic (750–850, 1300–1400, 1750–1850, and 1952-). The last two periods have been particularly effective. The MSC is an area of increased erosion activity and the central and southern parts present the highest erosion hazard in the Czech Republic (Fig. 6.10). Anthropogenic pressure in relation to erosion has evolved over time and ordered in importance as

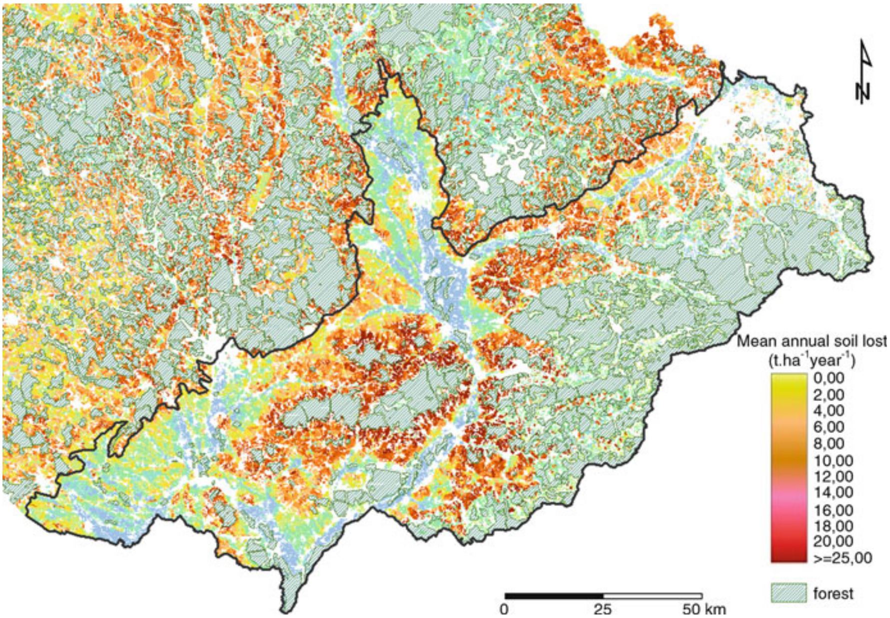

Fig. 6.10 Map of soil loss (Dostál 2007)

- Deforestation;
- Intensification of agriculture (agrarian revolution – change to fallow system – three-field system, change to Norfolk crop rotation, industrialization and collectivization of agriculture – land consolidation);
- Forestry (forest grazing, heavy mechanization in forestry).

Climatic fluctuation of the last 1,000 years has led to a wide range of flood phases accompanied by *increased geomorphologic activity of streams*. Studies focusing on the reconstruction of the historic climate of the last millennium assume the alternation of warmer and colder episodes and also of wetter and drier intervals (Brázdil and Kotyza 1998). In wetter phases increased *flood frequency* (Brázdil et al. 1999, 2005; Brázdil and Kirchner 2007) changed channel and floodplain morphology. Extreme discharge values are related to climatic periods such as the Little Ice Age between 1300 and 1850 AD in Europe. According to Brázdil and Kotyza (1998), it commenced in the Czech Republic between 1400 and 1419 AD. The highest frequency of floods on the Morava River is observed in the following periods: 1591–1610, 1711–1720, 1831–1880, and 1871–1880 (Brázdil et al. 2005). The period between 1501 and 1880 witnessed 75 historic floods, 48 of which is documented in our study area, while the rest of them are related to upper reaches of the Morava River. Less information is available for floods in the Odra River basin (Brázdil et al. 2005). Historic sources contain records of 31 floods (Brázdil et al. 2005), 20 of which are related directly to the wider Carpathian territory (1501, 1531, 1533, 1542, 1571, 1584, 1593, 1649, 1713, 1723, 1740, 1741, 1831, 1845, 1871, 1878, 1879, 1880, 1891, and 1892). For example, the Bečva River basin (Brázdil and Kirchner 2007), which was affected by 83 flood events in the years between 1494 and 1899. The data are even more valuable considering the fact that the Bečva River is a typical gravel-bed Carpathian stream with channel branching. An even higher number of floods (151) was recorded in the Dyje River basin (the Morava River right tributary), namely in the period of 1519–1900 (Brázdil and Kirchner 2007). However, it must be stressed here that the discharge of the Dyje River is largely influenced by precipitation events outside the area of interest. The twentieth century, on the contrary, was much poorer in flood events. According to records, in July 1903 the studied area was hit by a flood (Řehánek 2002; Brázdil and Kirchner 2007) that significantly affected the character of gravel-bed Carpathian streams that flow into the Ostravská pánev basin, streams springing in Nízký and Hrubý Jeseník Mountains, or into the above mentioned Bečva River. Another larger flood hit the Bečva, Morava, and Dyje Rivers and streams in the Odra River basin in early September 1938. The last extreme flood events affecting Carpathian streams and streams of the Carpathian Foreland with visible impact on channel morphology were the floods of the 6th and 8th July 1997 (Demek et al. 2006). Many streams within the Odra River basin experienced 50- or 100-year floods and in some places even higher discharges (Řehánek et al. 1998). As a result, the Bečva River considerably widened and recorded renaturalization of its gravel bed and developed branches (Klečka 2004). The Morávka River, by contrast, was affected by extensive deep incision (Hradecký and Pánek 2008). Similarly large floods also occurred in the basins of the Morava and Dyje Rivers, whereas in the case of the Dyje River others followed in the spring of 2006. Particularly strong influence on stream morphology and transport of large amounts of sediments is exerted by the *flash floods* that occurred in the MSC area a few times during the twentieth century. The latest extreme floods of this type took place in the area of the Štramberská vrchovina Highland (e.g., Jičínka and Zrzávka Rivers) in June 2009.

Important information on stream fluvial activity not only in the last millennium but also in the preceding phases has been obtained from the study of *floodplains*. Research on the Morava and Dyje floodplains revealed a relatively long time span of the beginning of flood loam sedimentation: from 965 ± 95 BP to 3,720 ± 60 BP (Havlíček and Smolíková 1994). Floodplain accretion is particularly related to deforestation and the advent of agricultural activities, which led to the loss of a large amount of fine-grained soil that had deposited in the floodplain zone during the floods (Opravil 1983; Havlíček 1991). In areas of high relative relief increased run-off from deforested areas might have led to voluminous coarse bedload transport, which, consequently, resulted in increased channel sedimentation (Hradecký and Škarpich 2009).

The most complex research was performed on part of the Morava River floodplain (Strážnické Pomoraví) over the last few years (Kadlec and Beske-Diehl 2005; Kadlec et al. 2009; Grygar et al. 2009), applying modern scientific *tools* (e.g., radiocarbon dating, clay mineral identification and quantitative analysis of expandable clay minerals, micromorphology of sediments, magnetic susceptibility, particle size distribution, ICP/MS including isotopic analysis, X-ray fluorescence analysis, xylotomy analysis, ^{137}Cs measurement, etc.). The fluvial archive of the Morava River, preserved in the study reach from the last millennium, consists of up to 5-m-thick formations of clayey or silty overbank sediments exposed in the eroded banks (Kadlec et al. 2009).

The *rate of deposition* (channel aggradation and lateral accretion) is a very important indicator of human influence on floodplain evolution (mainly the impact of deforestation and arable farming) (Grygar et al. 2009). The rate of deposition for the topmost sediment layers of the analyzed profiles was probably influenced by past land-use changes and flow regulations (e.g., flood defense constructions and channelization) of the river upstream during the twentieth century (Grygar et al. 2009). Different rates and quality of overbank aggradation are evident within the whole sediment sequence. The lowest rates are typical of distal floodplain sediments (0.2–0.3 cm year^{-1}) for the periods of 720–1320 AD and 1140–1900. The floodplain aggradation during the first half of the last millennium is a consequence of medieval farming boom. Similar rates are identified with upward coarsening clayey sediments grading from distal to proximal floodplain deposits (Grygar et al. 2009). Kadlec et al. (2009) recognized a pronounced change in the *grain size composition* of the sediment that took place in the sixteenth century when a shift from more clayey deposits (assigned here to the distal floodplain) to more silty and sandy deposits (assigned here to the proximal floodplain) occurred (probably as an effect of the LIA).

From the complex analyses of the sediment record it was possible to identify three simultaneous *changes in depositional conditions*: one in ~1200 AD, another in ~1600 AD and the last one in ~1900 AD. Faster accumulation (0.42–0.55 cm year^{-1}) is accompanied with upward coarsening (Kadlec and Beske-Diehl 2005), mostly silty and proximal floodplain deposition in the period from 1535 AD to 1900 AD (Grygar et al. 2009). The topmost 50 cm of the flood sediments reveal anthropogenic pollution caused by leaded gasoline, DDTs, and PCBs. The rate of deposition within this industrial layer is estimated at 0.8 cm per year (Kadlec et al. 2009). The upper 12-cm layer of sediments deposited after the Chernobyl nuclear power plant accident in April 1986 (Kadlec et al. 2009). High sedimentation rates in the topmost part of the floodplain sequence are attributed to increased erosion in response to intensive agricultural activities observed in the Morava River basin over the last 50 years (Kadlec et al. 2009) and due to intensive collectivization after 1950 (which caused higher rates of soil and gully erosion in the upper parts of the river basins and accelerated accumulation along the lower sections).

The percentage of arable land in the MSC is relatively high and, therefore, *sheet erosion* is of decisive significance. The rate of sheet erosion has only been studied in a few localities of the Central Moravian Carpathians, where long-term erosion loss from the loess watershed was estimated at 17.6 t ha^{-1} year^{-1} (Mařan 1958), and in the southwestern part of the Central Moravian Carpathians (in the Trkmanka River catchment) it was found to be 43.5 t ha^{-1} year^{-1} (Vaníček 1963; Demek and Stehlík 1972). Due to the industrialization, collectivization, and intensification of agricultural production (farming on large fields, use of heavy machinery), the rate significantly increased in the second half of the twentieth century.

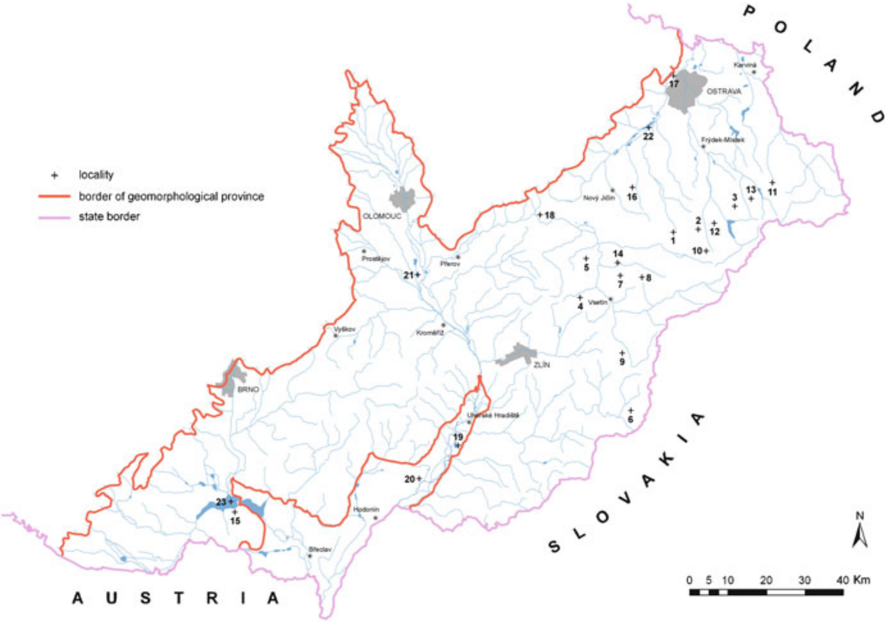

Fig. 6.11 The main localities described in the paper

Permanent gullies are important indicators of the historical evolution of anthropogenic pressure on the landscape. Rill and gully erosion spring from human activity and directly contribute to land degradation. The present permanent gully system in the MSC is mostly older than 200 years (Láznička 1957). Gully density does not exceed 0.5 km km^{-2} with maximum values of 3–5 km km^{-2} (Gam and Stehlík 1956). Increased erosion was caused by a combination of several factors: the massive colonization of forested areas, spreading arable land, cold and wet climate periods (Little Ice Age) (Havlíček 1994; Stehlík 1981), and extreme precipitation events. Gully erosion is triggered by extreme downpours, flash floods, and/or continuous rainfall. These extreme precipitation events have strictly local effect and, therefore, eroded sediments only appear in the third or fourth level subcatchments.

6.6.1 Recent Soil Erosion

Water erosion is one of the major problems of agriculture in the Czech Republic. Over 40% of arable land in the CR is potentially at risk by water erosion, mainly *sheet wash* and *ephemeral rill erosion*. Ephemeral rills have a limited duration because of tillage, but their occurrence is evident throughout the cultivated area. Ephemeral rills are directly linked to row crops (maize, root crops). The most recent episodes were documented in 1997, June and July 2009, and August 2010 floods. The floods in the Luha River catchment (tributary of the Odra River) involved the development of numerous ephemeral rills and gullies, with soil loss from the largest gully (474 m length, width at the mouth 4 m, depth 1.25 m) being 264 m^3. Recent erosion is due to compaction by soil tillage and the use of heavy machinery, which affect about 45% of agricultural land in the Czech Republic (Javůrek and Vach 2008). Rill and gully erosion do not only occur on arable land, but also in forests – directly influenced by human action (logging in the dormancy period, mechanization and forest roads). The relationship between logging and soil erosion has long been studied by L. Buzek (1981, 1986). Erosion induced by human activity in the forests of the MSC is mainly observed in the past 50 years. It could be associated with overexploitation of forests (forest grazing) around settlements in some areas even before the twentieth century. Gullies in the Carpathians often form on landslides of the Carpathian flysch (Vizovická vrchovina Highland, Bílé Karpaty Mountains, and Chřiby Highland). A new phenomenon emerging in the recent erosion processes springs from the disruption of drainage system during amelioration. *Amelioration drainage* systems were frequently built in the 1960s and 1970s to increase arable land. This technique is quite often applied for erosion control on slopes as well. Without technological and financial conditions of maintenance, combined with the decline of intensive agriculture after 1989, it may be a serious problem in the near future, especially in areas with steeper slopes. Rapid erosion associated with growing crops (maize, root crops) on graded areas remains as a major issue. Given the present constraints on agricultural activities, erosion rates are likely to have reached their peak between 1960 and 1990. Rainfall activity is also a decisive factor in determining the type and extent of erosion processes. If land use pressure is coupled with humid weather, as it probably happened in some past periods, we can expect even higher rates of water erosion of all forms.

6.6.2 Piping Landforms and Processes

Piping (suffosion) landforms and processes in the MSC were first described by Buzek (1969) and Kirchner (1981). Most of the piping forms studied in the MSC are underground features with some manifestations on the surface (Kirchner 1987a, b). The *piping channels* and *depressions* studied are several meters long and 2–3 m deep. Minor features preferentially occur along rodent pathways, root systems of trees, or even on the surface of block fields. In the Štramberská vrchovina Highland present piping forms under cliffs are 2–5 m deep and are up to 8 m long, on the surface of debris fans reach 2 m length and 0.5 m depth (Buzek 1969). A piping depression of 4.6 m long, 1.9 m wide, and 1.1 m deep was described in the clay-loamy sediments of the Vizovická vrchovina Highland (Kirchner 1987a, b) and a piping *tunnel* 4.5 m long and 1.4 m deep from the Hostýnské vrchy Hills (Kirchner 1981). Smaller forms are found on loess and loess-loamy soils in the Chřiby Highland (Hořáková 2007). The maximum depth of monitored forms was 1.5 m with maximum lengths of 4.5 m. Piping processes are mostly associated with spring snowmelt and extreme summer rainfall events. V. Cílek (2000) and P. Kos et al. (2000) described a pseudokarst system of chimneys, piping wells, and two suffosion caves in loess at the foot of the Pavlovské vrchy Hills in the South Moravian Carpathians.

Piping induced by *burrowing* (tunnels less than 10 cm diameter) is significant in the reactivation of permanent gullies in the area of Chřiby Highland and Vsetínské vrchy Hills. Piping processes directly induce the formation of new lateral branches of gullies and transformation of gully heads. The various piping features may survive for several hours or even several years under favorable conditions. Interesting permanent gully development was detected in the Vsetínské vrchy Hills, where sediments flushed out from piping tunnels accumulated around trees on gully slopes. Lateral tunnel branches longer than 3 m may develop during short but heavy rainfall events. In general, however, piping processes and forms are not common in the MSC and they are of limited geomorphological significance.

6.7 Wind Erosion and Landforms

Aleš Létal

Wind erosion in the MSC occur in the Dyjsko-svratecký úval Graben, the Kyjovská pahorkatina and Hlucká pahorkatina Hills, and in the Bílé Karpaty Mountains (Dufková 2007). The occurrence of wind erosion and its manifestations are directly proportional to the intensity of land cultivation. The intensity of wind erosion has increased markedly in the second half of the twentieth century through the processes of collectivization (land consolidation). About 90% of wind erosion occurs on cultivated land (Pasák 1970). The most endangered areas lie on lighter soils (light sandy soils, loamy-sandy soils) (Pasák 1970), but in the Hlucká pahorkatina Hills and Bílé Karpaty Mountains wind erosion occurs in areas with heavier clay-loamy soils. While the maximum size of soil particles blown away by wind erosion is generally 0.8 mm, in these specific regions soil particles of size 1.12–2 mm, in exceptional cases about 4 mm, are also entrained (Janeček 2002) by strong and dry southern, southeastern, and eastern winds in autumn, winter, or spring. The long-term systematic research of wind erosion in that area has been carried out by R. Švehlík, who found that the annual removal of soil is about 4–5 mm, in dust storms about 1–2 cm. Higher rates of wind erosion were identified in the Hlucká pahorkatina Hills in 1972 (193 m^3 ha^{-1} $year^{-1}$) (Švehlík 2002). The long-term monitoring of wind erosion is coupled with a detailed classification of aeolian forms (Švehlík 2002).

6.8 Anthropogenic Impact on Topography

Irena Smolová

Anthropogenic features in the Czech Carpathian region are dominated by mining, aquacultural (fishponds), and transportation features, markedly concentrated in the zone of the Outer Carpathian depressions and the northern extension of the Vienna

Basin (Kirchner and Smolová 2010). Human impact usually reaches down to hundreds of meters and sometimes even more than a kilometer in the case of underground mining. The deepest mines in operation are those in the Ostrava Basin (Doubrava III is 1,176 m deep with shaft top at 281 m above, and bottom at 895 m below sea level). Direct influence in the form of exploration and test borings usually reaches the depths of 1–2 km. The deepest borehole in the Czech Carpathian Mountains is Jablůnka 1 (near the town of Vsetín) with a depth of 6,506 m, drilled in 1982 (closed at present).

From the *historical aspect*, the first known anthropogenic impact on the relief of the Czech Carpathian Mountains dates back to the Lower Paleolithic period, well documented by archaeological finds and closely connected to the colonization of the Moravian Grabens. The oldest documented settlement was in karst areas. Caves utilized as shelters were not heavily transformed (as shown by the archeological finds in the Šipka Cave in the Štramberk Karst). The core residential area was the Vienna Basin and the Outer Carpathian depressions, where the most important Upper Paleolithic cultures evolved (Gravettian and Pavlovian), and some Moravian locations became world famous (e.g., Dolní Věstonice and Pavlov). Early *residential communities* (settlements on hills, rondels typical of the Neolithic Age, strongholds or *grad*s), the regulation of watercourses and the cultivation of land involved erosion processes. Burial sites (barrows) are preserved from the early historical period. A historically important Roman settlement is the Mušov stronghold in a strategically important site at the confluence of the Svratka and Dyje Rivers (preserved aqueduct, defence ditches, etc.) and the sites Pasohlávky, Olomouc-Neředín, and Hulín.

Along with human settlement in the Moravian Grabens, flood-control dykes were constructed in numerous locations and houses were often built on artificial mounds. (In Otrokovice, for instance, the waterlogged ground at the confluence of the Morava and the Dřevnice Rivers was elevated artificially by 1–4 m in the 1930s using material from the nearby Tresný Hill.

Human impact on the relief culminated in the period of the Industrial Revolution (second half of the nineteenth century) and towards the end of the socialist industrialization (second half of the twentieth century), characterized by extensive extraction of minerals for heavy industry in the city of Ostrava, especially underground mining of hard coal in the Ostrava Basin, one of the areas most affected by human activities in the Carpathian Mountains with abundant *underground* as well as *surface features of mining*. At the initial stage, shortly after coal deposits had been discovered in the late eighteenth century, opencast mining prevailed. The first underground mine in the Ostrava Basin (Anselm Mine) was established in Landek in 1782. At present, the mines in operation reach depths of ca 1 km, and after 1990 are concentrated in the eastern part of the Ostrava Basin, around Karviná (mines Československá armáda, Lazy, ČSM, Darkov, Paskov). In the area of the Moravian-Silesian Beskyds there is the now conserved mine Doubrava in the town of Frenštát pod Radhoštěm, excavated in the 1970s. Underground mining in the Ostrava Basin resulted in a number of spoil heaps, disposal, and subsidence areas. At present, more than 300 *spoil heaps* are registered, 5 of them are still active, one of the largest being Ema (82 ha area, 315 m altitude, the highest peak of the Ostrava district). The heap includes more than 4 million m^3 of mine waste from the already closed mine Trojice. The creation of anthropogenic surface features, especially *subsidence areas*, also heavily influenced the drainage conditions within the Ostrava Basin. J. Maníček (2003) describes the *influence upon the watercourses* of the Ostrava Basin in the overall length of almost 120 km, including 23 km along the Ostravice River, 15 km along the Odra River, and more than 20 km along the Olše River. Because of the subsidence, artificial watercourses were established in the Ostrava Basin, primarily for the *drainage* of subsidence areas (e.g., the Černý příkop Canal, constructed to drain the area around the mine Odra in the 1950s). An example of markedly influenced watercourse is the Karvinský potok Stream, originally a tributary of the Stonávka River, but connected, to the parallel lateral canal along the Olše River in the 1960s to allow the drainage of the most intensively subsiding areas.

The subsidence in the undermined section of the Ostrava Basin influences the statics of buildings and induces *seismic activity*. Since 1989, disturbances have been recorded by a network of seismic stations situated directly in the mines areas. According to the statistics, 20,000–50,000 disturbances of various energy levels are recorded annually by the Czech Geological Survey. The strongest of them often cause mining accidents and reach the local magnitude of 2–4 (e.g., tremor at mine Doubrava on 13 June, 2002, 3.9 M; at mine Lazy on 11 March, 2004, 3.1 M, 7 victims).

Materials mined underground in the Western Carpathians include lignite, oil, and natural gas in the Neogene deposits in the South Moravia. The first prospect *oil and natural gas wells* were drilled in 1899 and reached the depth of 649 m. The first exploited well was 529 m deep near Slavkov, which, in 1908, reached gas reserves. More than 10,000 prospect borings were realized along the Moravian-Slovak border to date aimed at the extraction of oil and natural gas. The deepest exploitation well is near the village of Jarošov (5,587 m) near Uherské Hradiště. The well near the village of Hrušky at the town of Břeclav is 3,885 m deep. The Outer Carpathian Depressios have the highest concentration of *exhausted reservoirs* in the Czech Republic. The oldest was established in 1965 (aquifer-type underground gas storage in the village of Lobodice), followed by other reservoirs, e.g., at village Tvrdonice (formerly Hrušky) near Břeclav (at depths of 1.1–2.5 km), at Třanovice (formerly Žukov) near the town of Český Těšín, at Štramberk (Příbor) on the boundary between the Bohemian Massif and the Carpathians, at Uhřice, at Dolní Dunajovice in the Dyjsko-svratecký úval Graben, or at Dolní Bojanovice near the town of Hodonín (in the depth of 750–2,070 m). The impact on the Earth's crust is documented by repeated surveying. (For instance, at the gas storage site Hrušky documents periodic oscillations and an annual increase of tilt by 0.4–0.5 mm since 1978 was found with subsidence towards the center of the depression.)

For building materials production in the Carpathian area, the largest *quarries* are a limestone quarry in the town of Štramberk (1.18 km^2) and a stone quarry near Hranice (0.17 km^2). The largest yield is produced by the stone quarry Podhůra near the town Lipník nad Bečvou where Culm greywacke is quarried. The Outer Carpathian Depressions and the Lower Moravian Graben are also heavily influenced by the extraction of gravel and sand, mostly by wet process from the floodplain, creating new water surfaces. The largest sand pits are found at Ostrožská Nová Ves (working area 5.17 km^2), Vracov-Bzenec (2.66 km^2), and Žabčice near the town of Břeclav (2.41 km^2).

Important *industrial anthropogenic features* in the Carpathian area include industrial spoil heaps, industrial platforms, especially in new industrial zones (e.g., the Nošovice Zone with an area of 260 ha, from where 2.2 million m^3 of soil was removed), and large industrial sites, from where considerable volumes of material were removed during construction. One of the largest industrial spoil heaps is at Třinec (on the left bank of the Olše River), which consists of clinker and waste from the local iron works piled up from 1839 to 1995. At present, the spoil heap area exceeds 65 ha and its relative height is more than 40 m.

The water regime is being influenced by the construction of *water-management structures*. The oldest interferences with the natural regime derive from agriculture: ponds, flumes, and canals for irrigation, land drainage or supply of water to mills (mill races). The largest pond is Nesyt (296 ha) near Břeclav; other extensive pond systems are in the surroundings of towns of Hodonín, Tovačov and along the Odra River. Artificial canal systems are found around Břeclav and Hodonín. In numerous locations, the stream flow was trained by modification of riverbeds and straightening of watercourses, resulting in changes of longitudinal profiles, intensified erosion, and reduced natural infiltration caused by the modification of banks. H. Kilianová (2001) claims that in the period from 1836 to 1999, the course of the Morava River was shortened by 67.34 km, most fundamentally along the lower course of the Morava River in the Lower Moravian Graben (shortening by 48 km between 1836 and 1999), while the length of the middle course in the Upper Moravian Graben was cut by 13 km and by 6 km in the Mohelnická brázda Furrow. The upper course of the Morava River remains relatively unaffected by regulation, excluding head and mill races. The most prominent water-management structure is the three reservoirs of the Nové Mlýny barrage system at the confluence area of the Svratka, Dyje, and the Jihlava Rivers, completed in the late 1980s. Numerous barrages were constructed for the regulation of the upper courses of rivers in the Bečva River basin and in the Moravian–Silesian Beskids. To provide sufficient volume of drinking and industrial water for the dynamically developing Ostrava region, a water-supply system in the Odra River basin was built in the 1970s and 1980s. After repeated floods in 1997 and subsequent years, new dry polders (emergency reservoirs) were constructed in order to provide flood protection for the municipalities.

The Outer Carpathian Depressions are an important *transport corridor*. The most important and oldest route crossing here was the Amber Road between the Baltic Sea coast and the Adriatic Sea via the Moravian Gate (Moravská brána). As transportation developed, *railways and roads* were constructed. Their *embankments* lie in the axis of the Outer Moravian Depressions, vast areas are occupied by transportation platforms (including the Mošnov Airport in the Moravian Gate) and other kinds of transportation infrastructure.

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