Chapter 15
Recent Landform Evolution in Macedonia

Dragan Kolčakovski and Ivica Milevski

Abstract In the Republic of Macedonia, where mountains are predominant in topography, morphostructures control hillslope processes, also promoted by weathered rocks prone to erosion and steep slopes (39.5% of the area steeper than 15°). Fluvial erosion is of equal importance since rivers are short but of torrential character and flow in composite valleys. Some of the deepest canyons (1,000 m deep) and the deepest underwater cave (190 m deep) of Europe are found in Macedonia. The highest polje is at 2,050 m elevation. Lake shore erosion and deposition can be studied on the largest lakes of the Balkan Peninsula and glacial and periglacial features in the highest mountains above 2,000 m. The most typical direct and indirect human interventions in the landscape are accelerated erosion and deposition, opencast mining, road building, canal, dam and reservoir constructions on rivers. Together with the influences of changing climate, human impact will be decisive in future landform evolution.

Keywords Morphostructures • Hillslope processes • Fluvial erosion • Karst • Glacial and periglacial processes • Lakes • Human impact

15.1 Geotectonic Setting

Ivica Milevski and Dragan Kolčakovski

Tectonic movements of various direction and intensity have been active on the relatively small territory of the Republic of Macedonia (25,713 km^2) through geological history, culminating in the Alpine orogeny. In his first tectonic regionalization

D. Kolčakovski • I. Milevski (✉)
Institute of Geography, University "Ss. Cyril and Methodius", Skopje, Gazi Baba bb., 1000, Skopje, Macedonia
e-mail: kolcak@iunona.pmf.ukim.edu.mk; ivica@iunona.pmf.ukim.edu.mk

D. Lóczy et al. (eds.), *Recent Landform Evolution: The Carpatho–Balkan–Dinaric Region*, Springer Geography, DOI 10.1007/978-94-007-2448-8_15,

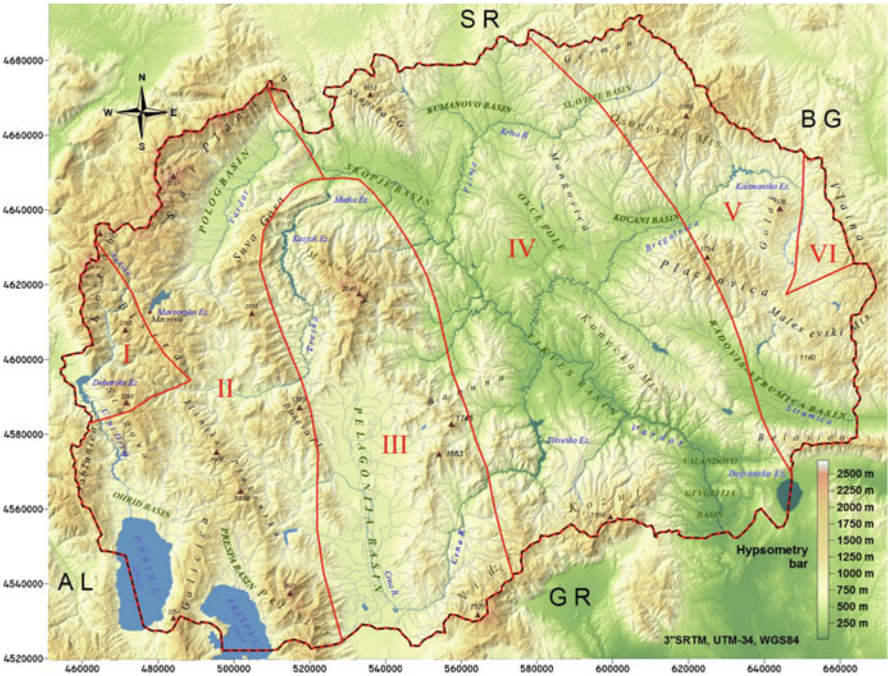

Fig. 15.1 The topography of Macedonia on a Digital Elevation Model (based on 3''SRTM; Jarvis et al. 2006), showing the major tectonic units (After Arsovski 1997). I, Chukali–Krasta zone; II, Western Macedonian zone; III, Pelagonian anticlinorum; IV, Vardar zone; V, Serbian–Macedonian massif; VI, Kraishte zone

Kossmat (1924) identified four tectonic zones. This zonation was recently refined by Arsovski (1997), in whose system the western and central part of Macedonia tectonically belongs to the Dinarides (Helenides), while the easternmost (Kraishte) zone is part of the Carpatho-Balkanic unit. The Serbian-Macedonian Massif lies between them. The tectonic units following the northwest-southeast strike of the Dinarides, from east to west are the Vardar Zone, the Pelagonian horst anticlinorium, the West-Macedonian zone, and the Tsukali-Krasta zone (Fig. 15.1).

The highly unstable *Vardar zone*, mostly along the Vardar River, is a lineament of first order, 60–80 km wide and several hundred kilometers long (from Belgrade on north to Thessaloniki on south). It is very distinctive from other tectonic units, including fragments of Precambrian crust, a Paleozoic volcanic-sedimentary complex, and Mesozoic structural complexes. Intensive volcanic activity ended in the early Quaternary (Arsovski 1997).

The ca 40-km wide *Pelagonian Massif* (or horst anticlinorium) extends nearly 150 km in north-northwest–south-southeast direction. As a relict of the Precambrian crust, it is mostly composed by metamorphic crystalline rocks, gneiss, mica-schists, and marbles. Deep regional faults clearly separate it from the neighboring units.

The *West-Macedonian zone* is recognized by Arsovski (1960) as a distinct tectonic unit, reaching from the Šara Mountains (Šar Planina) on the north to the Pelister Mountains on the south. It is generally composed of a Palaeozoic metamorphic complex, with volcanic and sedimentary formations in the lower parts, and carbonaceous formation on top.

Finally, the *Tsukali-Krasta Zone* is a small area on the border with Albania. This is a complex tectonic zone of Cretaceous sediments, overlain by Eocene conglomerates (Arsovski 1997).

The *Serbian-Macedonian Massif* represent a fragment of the Rhodopian Massif between the Dinarides and the Carpatho-Balkanides, both parts of the Alpine geosynclinal belt. Dimitrijevic (1974) claims that in the Precambrian and Paleozoic this tectonic unit was entirely separated from the Dinarides and Rhodopes, while others assume a continuous connection. The Serbian-Macedonian Massif is characterized by the domination of very old Precambrian and Riphean-Cambrian lithological complexes: gneisses, mica-schists, amphibolites, green-schists, and others. During the Mesozoic and the Paleogene this massif was temporary under transgression, while in the Oligocene and Miocene it was faulted and longitudinal depressions formed. These processes were accompanied by intensive volcanic activity with several volcanic centers.

The *Kraishte zone*, on the border with Bulgaria, is of limited extension (about 800 km^2) in Macedonia near Delčevo (Pianets Basin). With its geotectonic characteristics and different development of green schists formations with presence of meta-gabbros, meta-sandstones, and large Hercynian granitoid masses, this zone clearly belongs to the Carpatho-Balkanides. The deep mid-Alpine Pianets graben was filled with Eocene marine and Pliocene-Quaternary lake sediments. Graben formation was accompanied by major volcanic activity.

The complex geotectonic evolution of this (inner) part of Balkan Peninsula is a product of numerous *orogenic cycles*, which involved transgressions and regressions and accompanying volcanic activity. The Pelagonian and Serbian-Macedonian Massifs were created by powerful granite and granodiorite intrusions as well as regional and contact metamorphism (Kolčakovski 2004b) during the Precambrian Baikal orogeny. The separation of these tectonic units from basic Rhodope mass, and from one another by the Vardar Zone took place during the Caledonian orogeny in the early Paleozoic. The Hercynian orogeny especially powerfully affected the western parts of Macedonia, where the sediment complex is folded and metamorphosed.

The Cainozoic tectonic evolution of Macedonia consists of two periods of *extension*, separated by two episodes of crustal *shortening* (Burchfiel et al. 2004). The Paleogene extension and related basin development was diachronous and began in the late Eocene time and continued into the early Oligocene. The Paleogene basins show a general northwest-southeast strike and were formed mainly within the Vardar zone and the Serbian-Macedonian tectonic units. They are filled with Eocene–Oligocene molass sediments in thicknesses of 3,500–4,000 m (Dumurdzanov et al. 2004). Southwest-vergent folding and thrusting occurred during late Eocene and latest Oligocene–early Miocene times. Following shortening deformation, orogenic relief was greatly reduced by the end of the early Miocene. The *planated surfaces* were disrupted during the second period of extension, the predominant mode of tectonic deformation from the early Miocene to present, and are presently preserved at different elevations up to 2,000 m above sea level. Volcanic activity in eastern Macedonia occurred during the first period of extension, the two periods of crustal shortening, and continued into the second period of extension in the late Cainozoic during deposition in the Neogene extensional basins. The second period of extension, from the middle Miocene to the present, is marked by deposition in the deepest basins and extended to the whole central Balkan Peninsula (Zagorchev 1995; Burchfiel et al. 2004). Late Cainozoic extension and associated basin formation is characterized by differential vertical tectonic movements along normal, oblique and strike-slip faults, producing numerous horsts and grabens, rapidly filled with lakes. Most of these lakes (except the Ohrid, Prespa, and Dojran Lakes) desiccated or drained by the early Pleistocene (Kolčakovski 2004b). The Quaternary period saw stages of tectonic uplift of various intensity. Mountain uplift was faster than that of the neighboring depressions and this directly influenced fluvial processes and promoted valley incision. Extensional movements are still rapid, indicated by both seismic events and GPS measurements (Gospodinov et al. 2003).

15.2 Geomorphological Units

Dragan Kolčakovski

As a result of intense local and regional geotectonic movements in the past, the landscape in the Republic of Macedonia (25,713 km^2) has a typical *checkerboard topography* of mountains and basins (Fig. 15.1). Hills dominate over 78.8% of the country, while mountains only cover 47.7% (12254.5 km^2) of the total area (Markoski 1995, 2004). Among the about 40 mountain peaks, 13 rise above 2,000 m elevation (Kolčakovski 2004b), the highest, Korab, reaching to 2,753 m. Thus, the mean altitude of Macedonia is 831 m and mean slope angle is 13.5° (Milevski 2007b). There are also 16 basins, filled with lacustrine deposits (remnants from Neogene lacustrine phase), and surrounded and closed by mountains from almost all sides (Fig. 15.2). As a result of steep slopes and the human impact on the landscape, hillslopes are rapidly eroding with increased footslope accumulation. Basins are usually connected with composite valleys, deeply incised as gorges and canyons along mountain sections and broad cross-sections along basin sections. Because carbonate rocks constitute 10% of Macedonia, karst landforms (dolinas, poljes, pits, caves, etc.) also occur, mostly in the west. In high mountains (above 2,000 m) there are remnants of glacial landforms (cirques, glacial troughs) as well as fossil and recent periglacial phenomena.

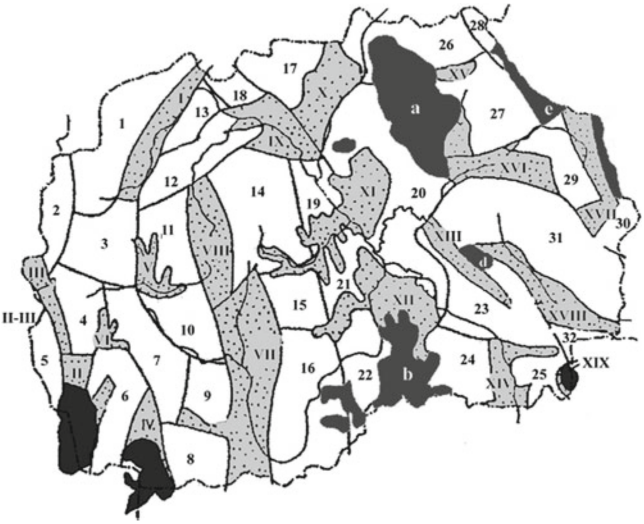

Fig. 15.2 Neotectonic regions of the Republic of Macedonia (After Arsovski 1997). *Morphostructures of uplift* (*blocks*): 1, Šara; 2, Korab; 3, Bistra; 4 Stogovo; 5, Jablanica; 6, Galičica; 7, Ilinska; 8, Pelister; 9, Šemnica; 10, Ljuben; 11, Pesjak; 12, Suva Gora; 13, Žeden; 14, Jakupica; 15, Babuna; 16, Selečka; 17, Skopska Crna Gora; 18, Raduša; 19, Kadina; 20, Bregalnica; 21, Klepa; 22, Mariovo; 23 Plauš; 24, Kožuf; 25, Furka; 26, Kozjak; 27, Osogovo; 28, Ruen; 29, Golak; 30, Maleševo; 31, Plačkovica; 32, Belasica. *Morphostructures of subsidence* (*basins*): I, Polog; II, Ohrid; III, Debar; II–III, Drim graben; IV, Prespa; V, Kičevo; VI, Belica; VII, Pelagonija; VIII, Poreče; IX, Skopje; X, Kumanovo; XI, Ovče Pole; XII, Tikveš; XIII, Lakavica; XIV, Valandovo; XV, Slavište; XVI, Kočani; XVII, Pehčevo; XVIII, Strumica; XIX, Dojran. *Paleovolcanic areas*: a, Zletovo; b, Vitačevo; c, Šopur; d, Venec; e, Pehčevo

As uplifting morphostructures *mountains* are the predominant elements of the landscape in Macedonia (Fig. 15.2). The highest mountain massifs are mostly found in the western and central parts; there are only two from 13 mountains above 2,000 m in eastern Macedonia: Osogovo (2,252 m) and Belasica (2,029 m). According to altitude, mountains in Macedonia are divided into high mountains (2,000–2,753 m) with subgroup of five very high mountains (2,500–2,753 m), medium-high mountains (1,000–2,000 m), and low mountains (below 1,000 m). Lowest altitude limit for a mountain in Macedonia is 700 m of absolute elevation and 500 m of relative altitude. Because of the geotectonic setting, mountains in western and central parts (in the West-Macedonian zone, the Pelagonian massif and the Vardar Zone) have a general northwest-southeast strike. In contrast, the ranges in eastern Macedonia are east-west aligned (because of the predominant north-south extensional regime). Mountains in the *western and central parts* are generally composed of marbles (Jakupica, Suva Gora), limestones (Bistra, Jablanica, Galičica, Šara), granites (Pelister) or other very resistant rocks. For that reasons, these mountains have usually *narrow*, *sharp ridges* and peaks and deeply incised valleys. Mountains in *eastern Macedonia* are dominantly composed of more erodible crystalline rocks (schists) and, consequently, show a more *subdued relief*, rounded ridges and peaks, and less deeply incised valleys. However, both groups of mountains were shaped during the Neogene–Pleistocene (Lilienberg 1966).

Depressions or *basins* are also basic structural units in the landscape of Macedonia. Tectonic grabens generally formed by subsidence during the Aegean crustal extension (from the middle Miocene to the Pliocene and the Quaternary). Initially basins were closed and gradually collected freshwater, forming *lakes* (Petkovski 1998). But later, with Pleistocene glacial and interglacial erosion, disintegration and subsidence of the Aegean crust and the formation of the Vardar River system, many of these lakes were connected, filled and desiccated (except the Ohrid, Prespa, and Dojran Lakes). As a consequence of the lacustrine phase, there are lacustrine deposits (sands, sandstones, clays) on the bottoms of basins up to 2,000 m thickness, which indicate stages of their development, intensity and directions of tectonic movements, climatic changes, etc. (Dumurdzanov et al. 2004). The largest basin, Pelagonija extends over 3,682 km^2, Tikveš Basin is 2,518 km^2, while the smallest are Slavište Basin (768 km^2) and Prespa Basin (559 km^2) (Markoski 1995). Altitude of the bottoms is also variable, ranging from 44 m for the Gevgelija Basin, through the Skopje Basin (220 m), Kumanovo Basin (340 m), Pelagonija Basin (600 m), Berovo Basin (700 m) to 840 m for the Prespa Basin. Similar to mountains, depressions have variable strikes: in the West-Macedonian zone and in the Pelagonian massif northwest-southeast, while in the Vardar zone and especially in the Serbo-Macedonian massif east-west directed, because of meridional extension (Kolčakovski 2004b).

Palaeovolcanic landscapes are more or less preserved remnants of Tertiary (rarely Pleistocene) volcanism. The forms include *volcanic cones*, *calderas*, *necks* and *plateaus*, highly eroded by post-volcanic fluvial erosion. Largest and morphologically best expressed is the Kratovo-Zletovo palaeovolcanic area in the northeast. From about 20 volcanic cones in this area, Plavica (1,297 m) and especially Lesnovo (1,167 m) with its top calderas are particularly well preserved (Milevski 2005a). These two volcanic centers, together with Uvo-Bukovec cones, Zdravči Kamen, Živalevo, and other volcanic necks, belong to the older, Oligocene, volcanic phases (Serafimovski 1993). Younger (Miocene-Pliocene) centers are located in the south part of the palaeovolcanic area, from Zletovo to Spancevo village (Boev and Yanev 2001), the Preslap (1,117 m), and Rajčani (867 m) cones with some remnants of (double) calderas. Here violent volcanic activity produced thick tuff and breccia deposits. Volcanic activity began in the late Eocene or early Oligocene, and with some pauses lasted up to the early Pliocene (Stojanoviḱ 1986), while it was *moving from the northeast to the southwest* (Boev and Yanev 2001), changing in intensity (violent eruptions followed by production of pyroclastic material as well as dormant and effusive phases). On the western edge of Kratovo-Zletovo volcanic area near Kumanovo, a unique phenomenon of an eroded Miocene basaltic plateau persist fragmented by erosion into eight hills of volcanic cone shape. Another palaeovolcanic landscape is south of Kavadarci stretching to the Kožuf Mountain on the border with Greece. It consists of several Pliocene volcanic cones and the extensive volcanic upland of Vitačevo. Volcanic features of polygenetic origin have been modified and destroyed by intensive erosion (Milevski 2005a).

15.3 History of Research of Recent Geomorphic Processes

Ivica Milevski and Dragan Kolčakovski

Geomorphological research in the Republic of Macedonia can be divided into *three* distinct *periods*. Before the twentieth century, only some basic descriptions were characteristic. In the beginning of the twentieth century until World War I, Jovan Cvijić set up a real geomorphological research basis for Macedonia. Between World Wars (1918–1941), several detailed geomorphological investigations were performed in the Poreče, Jakupica, Skopje Basin, and other areas (Jovanović 1928, 1931; Radovanović 1931). After World War II, these investigations intensified and extended to recent geomorphological processes too.

In the middle of August 1898, the Serbian geographer Jovan Cvijić, well known all over Europe, started academic excursions through the territory of the present-day Macedonia and neighboring areas leading to an extensive study entitled "*Basics of Geography and Geology of Macedonia and Old Serbia*," published in three volumes on 1372 pages (Cvijić 1906). In this very significant monograph, 320 pages are devoted to the geomorphological features of Macedonia. Despite some inconsistencies, this capital work has enormous scientific significance and is widely used by following generations of researchers.

Between the two world wars, some very valuable regional geomorphological studies were completed on the glacial landscape of Jakupica Mountain (Jovanović 1928), the fossil coastal and karst landscapes in the Poreče Basin (Jovanović 1927, 1928), the Skopje Basin (Jovanović 1931), the denudation of Selečka Mountain (Radovanović 1928), the karst landscape of Kožuf Mountain (Radovanović 1931) etc. Unlike the studies of Cvijić, which are mostly general in approach, the latter are more detailed and usually elaborate on one type of landscape predominant in the area.

After World War II, there are several generations of researchers who work extensively on recent geomorphic processes in Macedonia, starting with studies in the Debarska Basin (Gaševski 1953) and on the gypsum landscape in the valley of Radika (Stojadinoviḱ 1958), the periglacial landscape of Pelister (Stojadinoviḱ 1962, 1970), the coastal landscape of Lake Ohrid (Stojadinoviḱ 1968). However, the greatest contribution was made by Dušan Manakoviḱ, who worked on a wide range of issues: from karst, fluvial and coastal to glacial and periglacial landscapes. It is important to point out that he also treats the problem of recent relief evolution and anthropogenic influence of the landscape. From the late 1970s to the 1990s, in addition to further research on karst processes in Macedonia (Andonovski 1977; Kolčakovski 1988, 1992; Andonovski and Milevski 1999; Kolčakovski et al. 2007), significant attention is devoted to soil erosion due to human impact (Andonovski 1982). From the 1990s there are some investigations of the karst landscape in the Skopje Basin (Kolčakovski 1992), the periglacial landscape on the Jablanica, Stogovo, Galičica and Pelister (Baba) Mountains (Kolčakovski 1994, 1999). In recent years, geomorphological research in Macedonia has also moved toward processes of accelerated erosion (Milevski 2001, 2005b), denudation (Kolčakovski 2005) and overall human impact on the landscape with significant environmental implications (Dragičević and Milevski 2010).

15.4 Recent Geomorphic Processes

Dragan Kolčakovski and Ivica Milevski

15.4.1 Hillslope Processes

With large areas of erodible rocks, steep slopes, semi-arid climate and weak vegetation, hillslope processes are very intensive in Macedonia. Thus, most hillslopes are composed of crystalline rocks (gneiss, mica-schists, and other schists), sandstones, lacustrine and river deposits – all highly erodible. Mean topographic slope of the country is also very high, 13.5°, with 39.5% of the area steeper than 15°. In addition to relative relief, southern slopes are predominant (Milevski 2007b). Climate is semi-arid with 500–700 mm precipitation, but with frequent summer storms and heavy rains. In combination with anthropogenic influence and a sparse vegetation, this intensifies bedrock weathering and produces erosional landforms, the most famous being "Markovi Kuli" on Zlatovrv-Babuna Mountain (Kolčakovski 2005), included in the UNESCO World Natural Heritage list, as well as on the mountains of Selečka (Radovanović 1928), Jakupica (Kolčakovski 1987), Mangovica (Milevski and Miloševski 2008) and Osogovo (Milevski 2006). The most significant hillslope processes are *rain splash*, *sheet wash*, *and rill erosion*. At numerous sites *rill*, *gully erosion*, and even *badlands* are formed. There are frequent mass movements represented by *landslides*, *slumps*, and *soil creep*, especially on the rims of basins, where Pliocene lacustrine sands and sandstones are superimposed over inclined clay layers. Large landslides are present in the Tikveš, Berovo and Delčevo Basins, in the Radika Valley. In more compact weathered rocks (igneous, limestones, marbles), usually in the western mountainous part of the country, *rockfalls*, *rockslides*, *debris flows* and other phenomena occur (Stogovo, Šara Mountain, Korab, Jakupica). As a consequence of hillslope erosion, variable deposition landforms were created on the sides or bottoms: *talus cones*, *scree slopes*, *alluvial fans*, *colluvial*, and *debris deposits*. Although most hillslope processes are natural in origin, human impact greatly increase their intensity and makes them even predominant over large areas. According to the erosion map by Djordjevic et al. (1993), the average material removal by erosion in Macedonia is 690 $m^3 km^{-2} year^{-1}$, reaching even more than 2,000 $m^3 km^{-2} year^{-1}$ in some regions, which means a very high erosion rate. Most of this material is moved by processes of hillslope erosion.

15.4.2 Fluvial Erosion and Landforms

Fluvial erosion is the prevailing geomorphic process in Macedonia. The drainage network is relatively dense (1.3 km km^{-2}), but most of the rivers are rather short. The largest is the Vardar River with 301 km length in Macedonia and 388 km to the mouth in Aegean Sea. Rivers have low and very variable discharges (mostly below 10 $m^3 s^{-1}$) and are usually torrential in character. The reason for that lies in the semi-arid climate (mean precipitation: 680 mm $year^{-1}$), reduced forest cover and intense denudation. However, after the draining and drying of most lakes that existed in depressions during the Neogene (Dumurdzanov et al. 2004), the newly established (post-Pliocene) river network created a typical fluvial landscape with valleys as the most remarkable features. Because of the mosaical structural landscape, there are two major valley types: *valleys in basins* are broad, shallow and usually with well-preserved river terraces, while in mountains, they are deeper, narrow, with typical V-shaped profile, frequently with convex sides (Manakoviḱ et al. 1998). The convexity of valley sides indicates intensive Quaternary incision (at 1–2 mm $year^{-1}$ rate) caused by base level lowering due to differential tectonic uplift as well as Pleistocene climate changes (Milevski 2007a). That is especially obvious in incised valleys through mountains and hills, connecting basins. Among the *deeply incised canyons*, that of Radika River (in the western part of Macedonia) is 1,000 m deep, while the also deep canyon of the Treska River (a right tributary of the Vardar River) incised into Precambrian marbles. There are another 15 gorges and canyons on major rivers. In these sections, riverbeds are mostly narrow, rocky with steps, waterfalls and cascades. It is estimated that there are ca 150 typical waterfalls; best known are the tectonic waterfalls of the Smolarska (39.5 m high) and the Kolešinska River (15 m) on Belasica Mountain, while the highest is Projfel waterfall (136 m) on Korab Mountain. As river slopes rapidly reduce at entering basins, rivers build large *alluvial fans* (as at the footslopes of Šara and Belasica Mountains) or alluvial plains. Because of the frequent alternation of "normal" shallow *valley* sections with gorges and canyons, most of the valleys in Macedonia, especially of larger rivers are *composite* in character. Thus, the Vardar River passes through four gorges and five basins. The recent evolution of the fluvial landscape mostly depends on tectonic movements, climate change and human impact. In line with geophysical measurements showing differential tectonic uplift with higher rates for mountains than for grabens (Jančevski 1987; Arsovski 1997), rivers tend to incise more intensively in mountainous areas. Further dropping precipitation and runoff, however, will probably reduce fluvial erosion and disturb concavities in

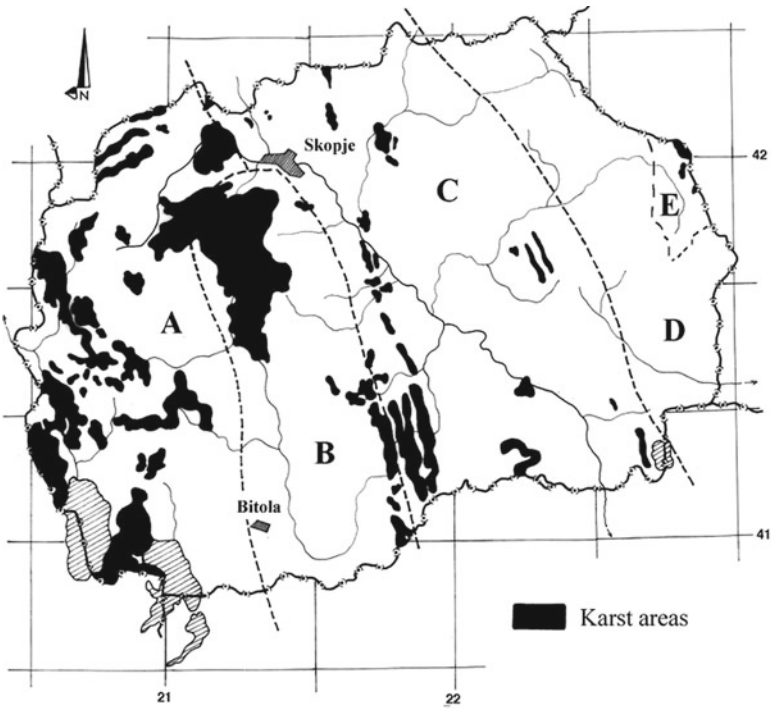

Fig. 15.3 Map of karst areas in the Republic of Macedonia. A, Western Macedonian zone; B, Pelagonian zone; C, Vardar zone; D, Serbian–Macedonian massif; E, Kraishte zone

longitudinal profiles. On the other hand, anthropogenic influence intensifies soil erosion, alters river energy and transport capacity, promoting increased deposition, especially in basins.

15.4.3 Karst Processes and Landforms

In Macedonia there are ca 2,724 km^2 (10.6%) karst landscapes in unequal distribution (Kolčakovski and Boskovska 2007) (Fig. 15.3). Most of the karstic areas are found in the western and central parts, i.e. in the West-Macedonian zone (Žeden, Bistra, Galičica, Jablanica Mountains) of Triassic limestones and in the Pelagonian Massif (Jakupica Mountain, Poreče Basin, Mariovo Basin) of Precambrian marbles (Fig. 15.4). In the Vardar zone there are only few karst areas (Taorska and Demir Kapija gorges of the Vardar River, the Veles gorge and the nearby hills, the Bislim gorge on the Pcinja River), while in the Serbian-Macedonian massif and the Kraishte zone (in the eastern part of the country) karst is insignificant with only several small patches of few square kilometers.

Fig. 15.4 Karst landscape on Jakupica Mountain

As karst areas are localized, these occurrences are referred to as “karst oases” (Manakoviḱ 1980a). Surface karst landforms in Macedonia are represented by a range of features from small *karren* through medium-sized *sinkholes* to karst *poljes*. Most of the 28 karst poljes are small (0.5–9.5 km^2) and located in mountains above 1,000 m elevation, except Brce (at 790 m; area: 1.2 km^2) on Kožuf Mountain and Cersko Pole (at 950 m; 9.5 km^2) on Babasač Mountain (Andonovski 1989). With its bottom at 2,050 m, Šilegarnik is highest karst polje on the Balkan Peninsula (Kolčakovski 1988). Underground karst landforms are represented by the ca 200 *caves* and pits described and surveyed to date but their total number is estimated at 400–500 (Kolčakovski 1989). According to the latest data, the longest cave is Slatinska Spring with 4.0 km length (Kolčakovski 2006), and the deepest pit is Slovačka Jama on Jakupica mountain, 540 m deep. Curiously, recent research (in 2009) showed that the 190 m deep Koritište (Vrelo) cave in Matka canyon (with entrance below the water surface of Matka reservoir) is one of the deepest underwater cave in Europe. It is obvious that recent karstification is slower than before because of the decreased amount of precipitation and increased temperatures. Thus, because of climate change and the dropping karst water table, most speleothems became dry.

15.4.4 Lake Shore Processes and Landforms

In the Republic of Macedonia both fossil and recent lake shores are found. *Fossil* (Neogene) *lake shores* and erosional and depositional *terraces* encircle almost all basins. The terraces are especially prominent around the Skopska Basin (Jovanović 1931), in the Berovska and Delčevska Basins (Manakoviḱ 1980b), in the Tikveš Basin (Manakoviḱ 1968) and elsewhere. However, most of them are heavily dissected and eroded by subsequent post-Pliocene fluvial erosion processes. Large deposition terraces, as those in the Berovo (Maleš) Basin, have been destroyed by anthropogenic erosion over the past millennia (Milevski et al. 2008). Recent shore processes are related to the *existing lakes*, particularly to the three largest: the Ohrid (348 km^2), Prespa (275 km^2) and Dojran Lakes (48 km^2). The shoreline of Ohrid Lake is 86 km long, generally steep and rocky (along 63.1 km length). In the remarkable cliffs numerous shallow caves formed (Stojadinoviḱ 1968). Only the southern and especially the northern shores show gently sloping sand and gravel beaches. Several short rivers form small *deltas* (Čerava, Rače, Koselska Rivers). For a higher water influx into the Ohrid Lake, recently the Sateska River is redirected from its natural channel and inflow in the Crni Drim River directly into the lake. Because of high amount of deposits, the offshore belt near the river mouth gradually extends and the lake-shore is shifted. The shore of the Prespa Lake is very similar to that of the Ohrid Lake, with steep cliffs on the east and west, and gentle slopes with sandy-gravel beaches on the northern and southern sides. The northeastern shore zone (Ezerani) is shallow and overgrown with dense vegetation (*phytogenic shore*). Because of high wave energy, the shore of the small island Golem Grad in the southwestern part of the Prespa Lake is entirely encircled by *cliffs* up to 10 m high. The Dojran Lake is somewhat different, with lower shores and no distinct cliffs. Most of the shore is flatter, with sand and gravel beaches. *Lake shore retreat* is very fast due to natural processes and recently to human impact (enormous amounts of water used for irrigation, especially in 1988). Since the water level in all of the three lakes is slowly dropping under natural and anthropogenic influence, recent lake-shore landforms are exposed. Except of the mentioned tectonic lakes, contemporary shore processes are recorded in larger *reservoirs* (Tikveš, Debar and Kalimanci Lakes), generally built in the 1960s. Thus, on most of them, micro-cliffs are formed on steep sides, while in rivers mouths deltas were built (e.g., at the Kalimanci Lake).

15.4.5 Periglacial Processes and Landforms

In the mountains of Macedonia above 2,000 m elevation (380.3 km^2 area), previous research recorded numerous fossil and recent periglacial landforms (Belij and Kolčakovski 1997). Among fossil landforms impressive *rockflows* (Stojadinoviḱ 1962) on Pelister Mountain (2,601 m), a remarkable *rock glacier* on Jakupica

(Manakoviḱ 1962), one of the largest on the Balkan Peninsula and smaller rock glaciers on Jablanica Mountain (Kolčakovski 1999) can be mentioned. On the northern slopes of most mountains, *nivation cirques* formed, where snow can persist in small patches up to the end of July. However, the mentioned landforms are generally created during the latest glacial phases in the Pleistocene (Kolčakovski 2004a), although precise measurements and observations will show if they are still active. Also several *recent periglacial landforms* were identified: *nivation niches and hollows*, *rockflows*, "*plowing blocks*," *periglacial terraces* (on Galičica Mountain, 2,288 m), *solifluction lobes*, *polygonal soils* (on Jablanica Mountain, 2,256 m) (Kolčakovski 1994, 1999). With regard to the recent activity of some landforms like rockflows and plowing blocks, precise comparison of photographs of these landforms on Osogovo Mountain (2,252 m) made in 1997 and 2004 showed that they move very slowly, ca 20 cm within this period. On the other hand, certain morphological traces (furrows, depressions, wrinkled land), particularly related to some blocks next to the rockflows, show that they were sliding (moving) in much larger amounts in the recent past (Milevski 2008), possibly during colder and more humid periods, such as the 1950s and 1960s, or even more in the Little Ice Age in the sixteenth and seventeenth centuries, when mean temperatures in Europe were about 2°C lower than today.

15.4.6 Glacial Landforms

Under the cold Würm climate, in almost all mountains in Macedonia higher than 2,100 m, mountain glaciers existed (Fig. 15.5). Most of them were *cirque glaciers* (on Pelister, Jablanica, Stogovo Mountains) or occupied short and small *U-shaped valleys* downslope (on Šara, Jakupica, Korab Mountains) as the snowline was located high (at about 2,000 m) and precipitation was relatively low (Kolčakovski 2004a). From glacial times numerous landforms have survived (Fig. 15.6): ca 30 cirques, generally between 2,000 and 2,400 m elevation, some of which are filled with lakes; U-shaped valleys with lengths of up to 2.5 km, most characteristic of Šara Mountain (2,747 m). Depositional landforms are mostly represented by *moraines* of different types: terminal, lateral, recessional, etc. Terminal moraines are significant for the determination of maximum advance of glaciers as well as for the reconstruction of Pleistocene snowline. According to Kolčakovski (2004a), who used the methods of Hoffer and Messerli, mean snowline on the mountains in Macedonia is estimated at about 1,950–2,050 m. However, the remnants of the glacial landscape are gradually destroyed mainly through processes of weathering and fluvial erosion due to Holocene climate warming. With further climate change, periglacial and glacial landforms will be destroyed even more efficiently by fluvial processes. Even now, some recent landslide occurrences that partly result from direct or indirect human impact on high mountain landscapes, rapidly mask and obliterate original landforms (Milevski 2008). Glacial and periglacial landforms are also threatened by intensive farming, overgrazing, road building and tourism activities.

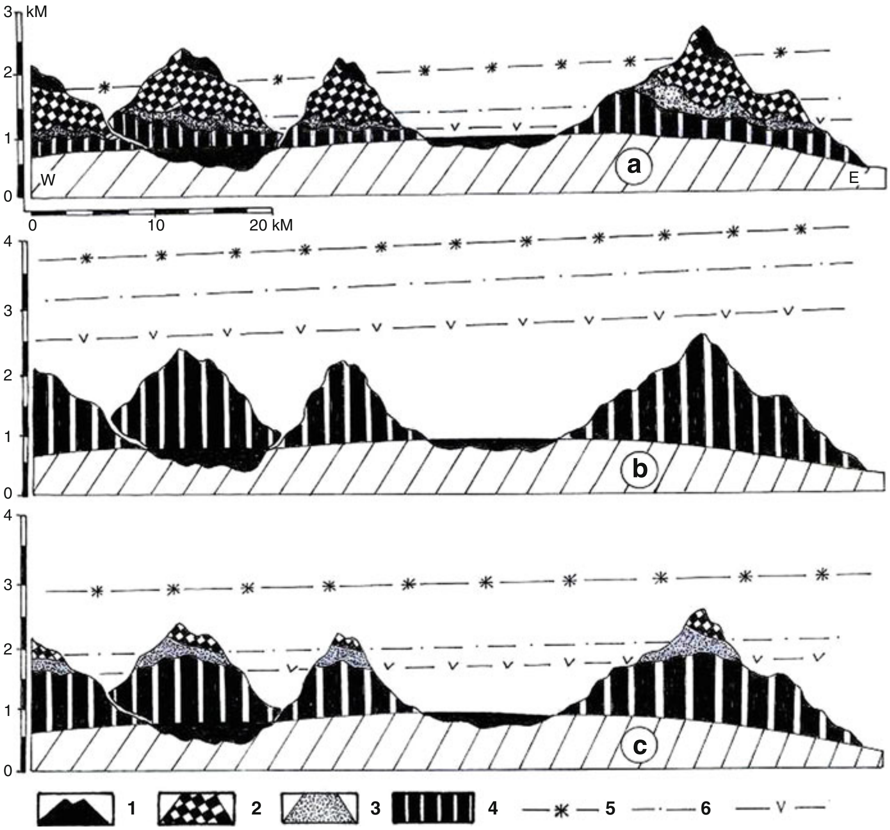

Fig. 15.5 Vertical zoning of natural geocomplexes on the mountains in southwestern Macedonia (Jablanica on the west, Stogovo, Galičica and Pelister on the east): (**a**) During the last glacial maximum – 19,000 BP; (**b**) Holocene climatic optimum – 6,500 BP, (**c**) Recent situation after Kolčakovski (2001). 1, Nivation-glacial geocomplex; 2, Periglacial geocomplex; 3, Transitional periglacial-fluvial geocomplex; 5, Snowline; 6, Treeline

15.5 Direct Human Impact on the Landscape

Ivica Milevski

In Macedonia the most typical modes of direct and indirect human impact on the landscape are: accelerated erosion and deposition, opencast mining, road building (particularly roadcuts), canal construction, river dam and reservoir construction, tailings, dump sites, influences on fluvial processes and other activities.

Fig. 15.6 Glacial landscape on Galičica Mountain with cirques (*above*) and on Šara Mountain with U-shaped valley (*below*)

15.5.1 Accelerated Erosion and Deposition

In Macedonia large areas are under accelerated erosion caused by intensive human impact on suitable environments over centuries. Such areas are steep, southern slopes of depressions and valleys, generally below 1,000 m elevation, which were most appropriate for early settlement as well. Because of accelerated erosion, the landscape is very often dissected into rills, gullies, *badlands*, *earth pyramids* etc. (Milevski 2004; Fig. 15.7). According to Djordjevic et al. (1993) some 36% of total country area is under severe and excessive erosion, the mean erosion rate is 16.9 million m^3 $year^{-1}$ (0.7 mm $year^{-1}$), and net *sediment delivery* is 7.5 million m^3 $year^{-1}$. In some landscapes extreme soil erosion has a devastating impact: on the catchments of the Upper

Fig. 15.7 Excessive erosion (badlands, gullies) and deposition in the Bregalnica catchment

Bregalnica (Milevski et al. 2008), of the Lower Crna (Trendafilov 1996) and in the Pčinja catchment (Manakoviќ 1969; Milevski et al. 2007) and many others. On the other hand, lower parts of these catchments and valleys suffer severe *deposition* of eroded material with notable impact on fluvial processes. The lower sections of the Vardar, Pčinja, Bregalnica and Crna Rivers are bordered by extensive alluvial plains with fresh deposits, where lateral erosion, meandering and even channel accretion prevail (Fig. 15.7). As a result of excessive deposition, the Kamenička and Radanjska beds (left tributaries of the Bregalnica) are now more than 10–15 m higher (Milevski 2009). Large tracts of agricultural land were abandoned with significant negative socioeconomic impacts on the rural environment. However, in the past 30–40 years there is an opposite trend in anthropogenic influence on soil erosion processes. Namely, because of decrease in rural areas, land dereliction, aging population as well as numerous measures of soil conservation (afforestation, dam construction, bioamelioration, canalization), there is a notable *drop in the rate of erosion* and sediment yield (which is still high) obvious from the analyses of gullies, badlands, alluvial fans almost fossilized and from the comparisons of older erosion maps and more recent surveys. Human activities have also modified the intensity of mass movements, quite often unconsciously. For instance, numerous *landslides* were *activated* recently in Macedonia with road and canal construction on susceptible terrain, or by building major structures on sloping terrain. A typical example is the landslide Ramina in the city of Veles, where sliding appeared in 1999 as a consequence of housing construction on unstable steep slopes and another is the large landslide near Bituše and Velebrdo villages in the Radika valley (Manakoviḱ 1974). Because of a deep roadcut in tuffs on Stracin pass (on the road Kumanovo–Kriva Palanka), a shallow landslide occurred recently, affecting an international road. Landslides quickly change the local landscape through planation at their upper section and through deposition at their tongue. One of the largest recent landslides in Macedonia on the hill Gradot near Kavadarci (with volume of 15 million m^3), even impound the valley of Bunarska River, causing ponding and significant landscape change (Manakoviḱ 1960). The overall impact of accelerated erosion in Macedonia is *surface planation*.

15.5.2 Impact of Mining and Waste Disposal

In Macedonia there are several huge opencast mines, where the landscape is significantly changed. In the Suvodol coal basin, east of Bitola city, since 1982 more than 140 millions m^3 of coal have been excavated from an area of 10 km^2. A large depression was created with almost 3 km in diameter and 50–100 m in depth, while in its vicinity, high *spoil heaps* rise. Here large mass movements occur triggered by slope undercutting, and slides of several millions m^3 volume cause significant landscape change, like the huge landslide (26.4 millions m^3) in 1995 (Manasiev et al. 2002). Similar examples are in Oslomej coal mine near Kičevo, the Sivec marble quarry near Prilep, the Bučim mine near Radoviš, the Ržanovo mine south of Kavadartci. Numerous *limestone quarries* are spread throughout the country, representing artificial depressions and elevations and also modify natural karst processes (Fig. 15.8). Extraction of gypsum on the sides of Krčin Mountain (southern extension of Korab), not only change karst processes but destroyed a unique gypsum cave called Alčia. In Macedonia there are some 10 major *tailing* sites where waste from ore mining is disposed – usually on valley floors as is the case of the Sasa lead and zinc mine near the town of Makedonska Kamenica. Here the tailing site in the Kamenička valley is 1.5 km long, 200 m wide and about 40–60 m high (Fig. 15.9). Recently, because of the collapse of an underground river tunnel, huge quantities of waste are washed downstream leading to an ecological disaster. Further tailing sites with local landscape change are found at the Toranica mine in the Kriva River valley and at the Zletovo mine with a tailing site on the Probištipska River. Some abandoned tailing sites, the Tajmište mine near Kičevo or the Bučim mine near Radoviš, have already been reclaimed, covered with soil and vegetation, and virtually cannot be distinguished from landforms of natural origin. All tailings will be reclaimed in the near future. Besides tailings, *waste landfills* also involve considerable landscape changes. In developed countries, regional waste landfills are permanently covered with soil and vegetation, and perfectly assimilated to their environment. Recently the reclamation of landfills began in Macedonia too. For instance, the large Drisla landfill near Skopje has been partly reclaimed. For landscapes under such intense human impact the term "technological landscapes" is used (Dragičević and Milevski 2010).

Fig. 15.8 Impact of stone quarrying and ore mining. Limestone quarry south of Skopje

Fig. 15.9 Tailings in the valley of the Kamenička River

15.5.3 Impact of Dam and Reservoirs Construction

Artificial lakes or *reservoirs* in Macedonia have a significant impact on the landscape in many ways. There are six reservoirs with storage capacities above 100 millions m^3, and areas larger than 4 km^2. Reservoirs also influence hillslope, fluvial, lake-shore and even karst processes. Their shorelines are often eroded, while raised base levels modify the rate of upstream fluvial erosion. For example, significant water-level regression on the Debar reservoir in 1993 activated a major landslide on the unstable eastern sandy shore near Pralenik village (Andonovski and Vasileski 1996). This reservoir largely influenced fluvial process along the Crni Drim (impounded into a lake) and its right-hand tributary, the Radika. On the other hand, the Mavrovo reservoir on Bistra Mountain, constructed on limestones, immediately affect karst processes in the area in such way that some holes and caverns appear in the cracks on the bottom and cause water losses. A similar effect on limestone processes is shown on the Matka and the newly built Kozjak reservoirs near Skopje (Fig. 15.10). In some reservoirs excessive sedimentation is also a problem.

Thus, the Bregalnica River and its tributaries, the Kamenička, Lukovica and Ribnica Rivers, yielded ca 17 millions m^3 of deposit in the Kalimanci reservoir (120 millions m^3) since its construction in 1969 (Fig. 15.11). The loss of useful storage capacity amounts to ca 14% (Blinkov 1998; Milevski et al. 2008). A similar situation occurs in the Tikveš reservoir, where about 30 millions m^3 of sediment accumulated from 1968 to 1991, or 6.5% of the total storage capacity of 475 millions m^3 (Trendafilov 1996). With such sedimentation, after some 200–300 years these reservoirs will ultimately turn into extensive alluvial plains. The tributaries to these reservoirs transport large amount of deposits and have already built minor *deltas* in their mouths.

15.5.4 Impact of Road Construction (Roadcuts)

Because of the checkerboard structural morphology of Macedonia, road construction is frequently very difficult. Across hilly and mountainous terrains numerous *roadcuts* have to be established, increasing natural slope inclination and leading to slope instability. As huge areas are composed of erodible rocks, landslides or intensive rill and even gully erosion occur on steep slopes during or after construction works. For example, along the Kumanovo–Stracin–Kriva Palanka main road (73.5 km) (Fig. 15.12), and the Stracin–Probištip regional road (30 km) across terrain of volcanic tuffs and breccias, many rills, gullies, earth pyramids, landslides, and even rockfalls affect roadside slopes. At footslopes the eroded material accumulates as scree, debris, or minor colluvial fans. Similar occurrences are recorded along the highway Tabanovce–Gevgelija (174.2 km), with number of smaller landslides, deep rills and gullies. On the other hand, the material removed during road construction is often deposited downslope in *artificial screes*, *talus*

Fig. 15.10 The dam of the Kozjak reservoir

Fig. 15.11 Shore process and delta formation in the Kalimanci reservoir

Fig. 15.12 Road incision in tuffs on Kumanovo–Stracin road

cones, and *fans*. This is well expressed on the local road to the newly constructed Matka 2 (Sv. Petka) dam in the spectacular Treska canyon (Fig. 15.13). Such features are also present down the road Zletovo–Kneževo dam (20 km) near the town of Probištip, with large masses of blocks and boulders on the hillslopes up to the valley floor of the Zletovska River. Here road construction also triggers major mass movements of scree slopes above the road. Along many inadequate aligned macadam and dirt roads, severe rill formation followed by gully erosion occur and lead ultimately to slope instability and failure. Considerable impact on the landscape is also manifested along the railway corridor under construction between Kumanovo and Devebair (76 km), where deep cuts into igneous clastic rocks and schists are common.

15.5.5 Other Processes and Forms of Human Impact

Natural fluvial processes are also altered by human impact in Macedonia. The intensive *sedimentation* of basins and lower river sections, valley floors rise and floodplains extend through intensified meandering. As a consequence, floods occur more frequently, and involve more severe damage. For flood control, some riverbed

Fig. 15.13 Debris transported downslope of the road to Sv. Petka dam

sections were channelized, embankments, concrete walls were raised (The Vardar through Skopje Basin and the Veles and the Bregalnica through Delčevo, the Dragor River through Bitola, the Kumanovska River through Kumanovo, the Strumica, Luda Mara and other rivers). Also, there are hundreds of river *sand and gravel extraction* sites, partly legal and partly illegal, along floodplains with deep alluvia. Dredging produces small depressions and hollows, most of which are then ponded, and natural channels change their directions (as in the case of rivers Pčinja, Vardar, Bregalnica and Crna).

As a result of huge accumulation of fine sediment on the Vardar alluvial plain downstream of the Demir Kapija gorge, even aeolian landforms and blown sand features (near Gevgelija) occur, a rarity in Macedonia. However, they are the consequence of indirect human impact, accelerated erosion in the Vardar catchment and the subsequent deposition.

In recent times significant human impact is evident on shore processes on the Dojran and Prespa Lakes. Thus, exaggerated use of the waters of the Dojran Lake (43 km^2; 10 m deep) for irrigation purposes in the drought year 1988, reduced water level by about 3 m and caused *shore retreat* by more than 200 m (Stojanoviḱ 1995). A new shore with a total area of 5–6 km^2 formed, and the lake itself was almost drained. But with artificial water supply from nearby springs, water level is gradually increasing again. A similar situation is characteristic for the Prespa Lake

(275 km^2; 54 m deep), which has lost significant amount of water, and water level has dropped by about 10 m since 1963. An even larger shore area resulted than that at the Dojran Lake.

Recently, some *ground subsidence* is recorded in major cities built on clastic rocks (mostly Pliocene lacustrine sediments), such as in Skopje, due to the weight of structures and the consolidation of sediments after construction (Petkovski 2002).

15.6 Perspectives on Landscape Evolution

Ivica Milevski

15.6.1 Predictable Climate Change

There are several scenarios for climate change on the territory of the Republic of Macedonia. To describe the relationship between large-scale climatic variability across southeastern Europe and in Macedonia, the results of four Global Circulation Models (GCMs) were used together with the NCEP/NCAR reanalysis data. As the simulations of future climate with GCMs are based on a limited number of emission scenarios, usually SRES A2 and B2, the regional climate change projection, developed for the first time, was additionally scaled to other marker SRES emission scenarios (A1T, A1b, A1Fl, B1) using the pattern scaling method (Mitchell 2003). Particularly summer precipitations and temperature changes seem to be dramatic. According to the scenario based on direct GCM output (Bergant 2006), a mean *temperature increase* of 1.9°C is expected for 2050 and 3.8°C for 2100, while precipitation will decrease for about −5% in 2050 to −13% in 2100 with significant seasonal variations in temperature and precipitation. The highest temperature increase for the entire country and precipitation decrease is foreseen for the summer. Thus, temperature will increase by 2.5°C until 2050 and by 5.4°C until 2100 compared to 1990, and the highest rise is expected for maximum daily temperatures (3.0°C by 2050 and 6.2°C by 2100 compared to 1990). On the other hand, a *drastic drop in summer precipitation* is predicted (−17% in 2050 and −37% in 2100). In autumn, mean daily temperatures will increase by 1.7°C until 2050 and by 4.2°C until 2100 in respect to 1990, while mean precipitation will drop by −4% until 2050 and by −13% until 2100. Winter mean daily temperature increase may reach 1.7°C by 2050 and 3.0°C by 2100, with no major change in winter precipitation. In spring, the mean daily temperature is forecast to increase by 1.5°C until 2050 and by 3.2°C until 2100 compared to 1990. Precipitation will decrease by −6% until 2050 and by −13% until 2100. As this scenario shows, there will be some regional differences too with higher temperature increase in northwestern and southern region (ca 8.5°C), while a major drop in precipitation will occur in the central and southern regions (−26 to −27% by 2100, compared to 1990) (Bergant 2006).

15.6.2 Direct Impact of Climate Change

The exact consequences of climate change on landform evolution are hardly predictable because they depend on a range of variables. Higher temperatures and increased temperature range induce more intensive rock weathering. Although at the first glimpse, lower precipitation would imply lower erosion and transport rate, in reality the situation is much more complicated. Seasonal variations in precipitations (mostly in rainfall) would reduce vegetation cover and density, and more severe storm events would cause flash floods with intense sheetwash, rill erosion, mass movements and other hillslope processes. *Extreme hydrological events*, floods and droughts, becoming more frequent with climate change (Donevska 2006), increased erosion would affect upper catchments and deposition lower catchments. Thus, the overall erosion and deposition rate will be greater, with considerable impact on the landscape in the form of desertification. That is in line with the scenarios by Zhang and Nearing (2005), Favis-Mortlock and Savabi (1996) and others. Torrential rivers and their catchments would be even more torrential with flashy discharge by the end of the twenty-first century. After Donevska (2006), it can be concluded that generally there is a drop in annual average discharges for all river basins in the Republic of Macedonia for the past half a century. The same trend is found for annual minimum and maximum discharges for the whole territory of Macedonia and will affect the nature and rate of fluvial processes (Ministry of Environment and Physical Planning 2008). *Lateral accretion* would be more pronounced than vertical accretion and this would result in the planation of the relief. Recent water levels in major natural lakes will continue to decrease with implication on shore evolution, particularly in the case of the Prespa and Dojran Lakes (Fig. 15.14), and some (post-glacial) mountain lakes and river channels may even dry out (Fig. 15.15). With estimated climate change, the rate of *karst processes* will also reduce; some stream (riverine) caves (a trend already observed) will get dry and some ice pits in high mountains may lose their ice fill. A lower precipitation would reduce the rate of karst denudation, the formation and growth of speleothems (Shopov et al. 2006). The recent lower limit of periglacial zone, at present is at 1,600–1,800 m elevation, will be significantly higher in the future. Hillslope and fluvial processes would take over the role of periglacial geomorphic action.

15.6.3 Indirect Impact of Climatic Change

In addition to the above direct influences, the indirect impact of climate change on landscape evolution will be exerted through changes of vegetation cover, soils, biota and human activities. In recent times, the number of *forest fires* as well as the size of the area burned have significantly increased. Thus, in 2000 there were 1,187 forest fire events with 37,920 ha of burned area, while in the very hot year 2007 ca 40,000 ha forest burned – much more than before 1990 (usually less than 100 fires and 2,000 ha of burned forest). It is expected that Mediterranean and sub-Mediterranean elements of the pseudo-maquis will broaden their range towards the central and northern regions,

Fig. 15.14 Recent retreat of the Prespa Lake and the formation of a new shore, mostly as a result of lower precipitation

Fig. 15.15 The dry channel of the Radanjska River: a result of erosion and climate change

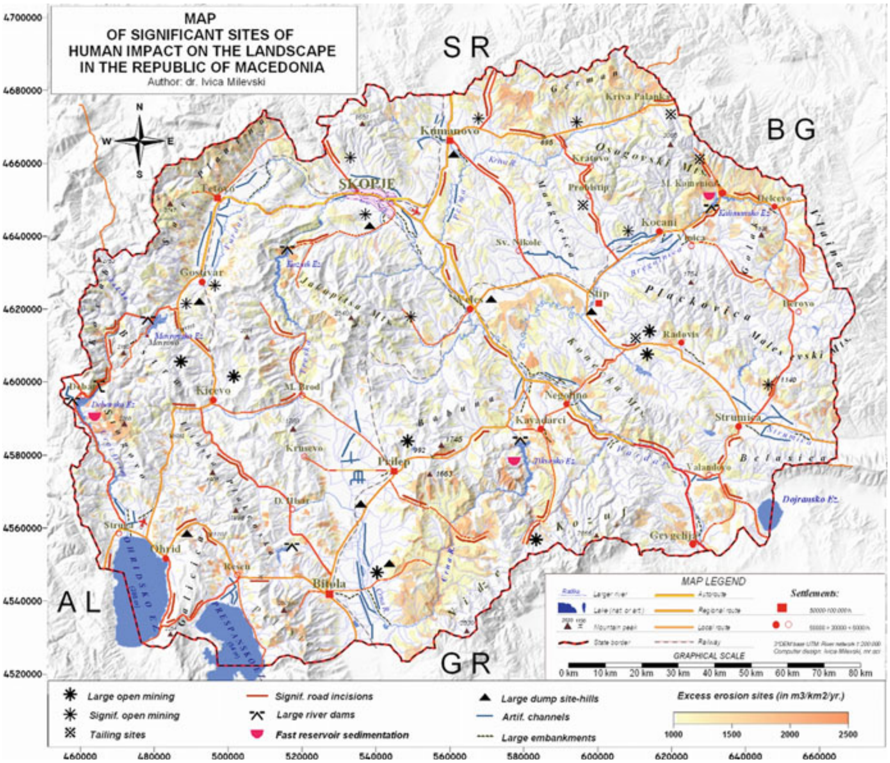

Fig. 15.16 Map of significant sites of human impact on the landscape in the Republic of Macedonia (after Dragičević and Milevski 2010)

i.e. climate change will cause an *extension of zonal vegetation* (Adžievska et al. 2008). With the reduction of forest area and overall vegetation quality and density, runoff and overland flow would increase raising the rate of erosion. Further, in lack of proper vegetation protection, soils will become more prone to erosion. As an adaptation measure to higher air temperatures and decreased precipitation, the *migration of* certain *tree species* to higher elevations (above 2,000 m) and latitudes is evident over the past decade. Periglacial processes and landforms as well as fossil glacial remnants may gradually also modify. As water resources shrink with lower precipitation, *more water* will be *extracted* from groundwater, river channels and lakes, promoting *ground subsidence*, altering fluvial and lake-shore processes. Because of a greater water demand for irrigation and decreased discharge as a result of lower precipitation, some *rivers* (even larger channels) may *partly dry out* in summer (the Bregalnica River downstream of Štip; the Pčinja, Strumica and Crna Rivers). One important issue is that because of increased summer heat in urban settlements located in basins, more and more development (houses, farms, villas) takes place in mountains and cause the visual deterioration of the natural landscape.

References

Andonovski T (1977) Underground karst landforms in the Radika Valley. Ann Fac Geogr Skopje 23:97–120 (in Macedonian)
Andonovski T (1982) Erosion areas in SR Macedonia. In: Proceedings from the 11th Congress of FRY Geographers, Budva, 1982 (in Macedonian)
Andonovski T (1989) Karst poljes in SR Macedonia. Geogr Rev Skopje 27:3–13 (in Macedonian)
Andonovski T, Milevski I (1999) Underground karst landforms in Bislim Gorge. Geogr Rev Skopje 34:5–21 (in Macedonian)
Andonovski T, Vasileski D (1996) Sliding (slump) of earth near village Pralenik in Debarska Župa. Geogr Rev Skopje 31:11–21 (in Macedonian)
Arsovski M (1960) Some characteristics of the tectonic features of the central part of Pelagonian horst anticlinorium and its relation to the Vardar Zone. Papers of Geologic Survey of SRM, Skopje 7:76–94 (in Macedonian)
Arsovski M (1997) Tectonics of Macedonia. Faculty of Geology and Mining, Stip. 306 p (in Macedonian)
Adžievska et al. (2008) Second national communication on climate change, Ministry of Environment and Physical Planning, Skopje, 118 pp
Belij S, Kolčakovski D (1997) Methodology of complex research of periglacial zone on the high mountains in the Balkan Peninsula. In: Scientific meeting "Perspectives and directions in the development of Geographic science". Brezovica, FR Yugoslavia, 1997, 7 p
Bergant K (2006) Climate change scenarios for Macedonia – review of methodology and results. University of Nova Gorica, Centre for Atmospheric Research, Nova Gorica, Slovenia, pp 1–50
Blinkov I (1998) Influence of the rains on the intensity of soil erosion in the Bregalnica watershed up to the profile "Kalimanci Dam". Manuscript doctoral thesis. Faculty of Forestry, Skopje, 127 p (in Macedonian)
Boev B, Yanev Y (2001) Tertiary magmatism within the Republic of Macedonia: a review. Acta Volcanologica 13(1–2):57–71
Burchfiel BC, Dumurdzanov N, Serafimovski T, Nakov R (2004) The Southern Balkan Cenozoic Extensional Region and its relation to extension in the Aegean Realm. Geol Soc Am Abs Prog 36(5):52
Cvijić J (1906) Basics of geography and geology of Macedonia and old Serbia. Book I. SKA, Belgrade (in Serbian)
Djordjevic M, Trendafilov A, Jelic D, Georgievski S, Popovski A (1993) Erosion map of the Republic of Macedonia. Memoir. Water Development Institute, Skopje, 89 p (in Macedonian)
Donevska K (2006) Vulnerability assessment and adaptation for water resources sector. In: Report on second communication on climate and climate changes and adaptation in the Republic of Macedonia. Ministry of Environment and Physical Planning, Skopje, 128 p
Dragičević S, Milevski I (2010) Human impact on the landscape – examples from Serbia and Macedonia. In: Zlatic M (ed) Global change – challenges for soil management, vol 41, Advances in geoecology. Catena Verlag, Reiskirchen, pp 298–309
Dumurdzanov N, Serafimovski T, Burchfiel C (2004) Evolution of the Neogene-Pleistocene basins of Macedonia. Geological Society of America, Boulder, CO. pp 1–20
Favis-Mortlock DT, Savabi MR (1996) Shifts in rates and spatial distribution of soil erosion and deposition under climate change. In: Anderson MG, Brooks SM (eds) Advances in hillslope processes, vol 1. Wiley, New York, pp 529–560
Gaševski M (1953) Debar Basin – geomorphological research. Annal SGS Belgrade 33(1):31–44 (in Serbian)
Gospodinov S, Zdravchev I, Alksandrov B, Peneva E, Georgiev I, Tzenkov Z, Dimitrov D, Pashova L (2003) Multidisciplinary investigation of the recent movements between basic tectonic structures on the Southwest part of Bulgaria. Report from the Project funded by UACEG, Sofia, pp 1–9

Jančevski J (1987) Classification of fault structures according to genesis, age and morphology, with review to their seismicity on the territory of Macedonia. Ph.D. thesis (manuscript), Sts. Cyril and Methodius University, Skopje, 247 p (in Macedonian)
Jarvis A, Reuter HI, Nelson A, Guevara E (2006) Hole-filled SRTM for the globe, Version 3, available from the CGIAR-CSI SRTM 90m Database: http://srtm.csi.cgiar.org
Jovanović P (1927) Coastal and fluvial elements in Poreče Basin. Annals SGS 13:169–194 (in Serbian)
Jovanović P (1928) Karst features in Poreče. Ann SGS Belgrade 4:1–46 (in Serbian)
Jovanović P (1931) Relief of Skopje Basin. Annals SGS Skopje 11:62–116 (in Serbian)
Kolčakovski D (1987) Denudation landforms in the basin of the Kadina River. Geogr Rev Skopje 25:229–238 (in Macedonian)
Kolčakovski D (1988) High-mountain karst of the Karadzica Mountain. Geogr Rev Skopje 26:95–113 (in Macedonian)
Kolčakovski D (1989) Historical review of speleological research on the territory of SR Macedonia with bibliographic prospective. Geogr Rev Skopje 27:133–144 (on Macedonian)
Kolčakovski D (1992) Karst relief in Skopje Basin – a geomorphological study. Special edition of FNSM, Skopje, 47 p (in Macedonian)
Kolčakovski D (1994) High-mountain areas of the mountains Jablanitsa, Galichitsa and Pelister. Ecol Environ Prot Skopje 1(1–2):43–51 (in Macedonian)
Kolčakovski D (1999) Glacial and periglacial relief on the mountain Jablanica. Annu Inst Geogr FNSM Skopje 33–34:15–38 (in Macedonian)
Kolčakovski D (2001) Chronological zoning of periglacial geocomplex in the southwest part of the Republic of Macedonia and its comparison with neighbour and distant areas. Annal Inst Geogr FNSM Skopje 35–36:61–83 (in Macedonian)
Kolčakovski D (2004) Snowline – theoretical views and its reconstruction during Würm climatic minimum on the mountains of southwestern Republic of Macedonia. In: Proceedings of the second congress of ecologists of Macedonia, Skopje, 2004, pp 23–28 (in Macedonian)
Kolčakovski D (2004b) Geotectonic characteristics of the relief in the Republic of Macedonia. Bull Phys Geogr Skopje 1:7–23 (in Macedonian)
Kolčakovski D (2005) Contribution to a research of micro-relief forms of the granodiorite rocks on the locality "Markovi Kuli". Bull Phys Geogr Skopje 2:5–23 (in Macedonian)
Kolčakovski D (2006) Geomorphology. University text-book, Skopje, 488 p (in Macedonian)
Kolčakovski D, Boskovska G (2007) Extension and age of carbonate rocks in Republic of Macedonia. Bull Phys Geogr Skopje 3–4:77–80 (in Macedonian)
Kolčakovski D, Petreska B, Temovski M (2007) New informations about the underground karst forms in the central parts of the Republic of Macedonia. Bull Phys Geogr Skopje 3–4:55–66 (in Macedonian)
Kossmat F (1924) Geologie der zentralen Balkanhalbinsel. Die Kriegsschauplätze 1914–1919 geologisch dargestellt, Berlin, 198 p
Lilienberg DA (1966) General tendency of recent tectonic movements in Macedonia. Ref. sest. SGD, Ohrid 245–270 (in Russian)
Manakoviḱ D (1960) Landslide of Gradot hill. Annu SAS Belgrade 17:119–128 (in Serbian)
Manakoviḱ D (1962) Nivation processes and landforms on the mountain Jakupica. Ann FNSM Skopje 13:47–57 (in Macedonian)
Manakoviḱ D (1968) Middle-Vardar Lake. In: Proceedings from VIII congress of geographers from SFRY, Skopje, 1968, pp 155–164 (in Macedonian)
Manakoviḱ D (1969) Soil erosion in the downstream part of the Pčinja catchment. Geogr Rev Skopje 7:43–54 (in Macedonian)
Manakoviḱ D (1974) Landslide in the village Bituša. Annu FNSM Skopje 20:37–46 (in Macedonian)
Manakoviḱ D (1980) Oasis type of karst hydrography in Macedonia. In: Proceedings of VII Yugoslavian speleological congress, Titograd, 1980, pp 293–309 (in Macedonian)
Manakoviḱ D (1980) Geomorphology of Maleš and Pianec. Maleš and Pianec II. Natural and socio-geographical characteristics of Maleš and Pianec, MASA, Skopje, pp 47–69 (in Macedonian)

Manakoviќ D, Andonovski T, Stojanovic M, Stojmilov A (1998) Geomorphologic map of the Republic of Macedonia. Memoir. Geographical Review, Skopje 32–33:37–70 (in Macedonian)
Manasiev J, Jovanovski M, Gapkovski M, Novacevski T, Petreski Lj (2002) Landslide on the NE part of the coal mine “Suvodol”: phenomenology of the event and experiences. In: Proceedings of 1st symposium of the Macedonian Association for Geotechnics, Ohrid, 2002, pp 68–77 (in Macedonian)
Markoski B (1995) Hypsometry of the space and population in the Republic of Macedonia – a cartographic method. Makedonska Riznica, Skopje, 316 p (in Macedonian)
Markoski B (2004) Cartographic definition and differentiation of the mountain areas in the Republic of Macedonia. Bull Phys Geogr Skopje, pp 25–34 (in Macedonian)
Milevski I (2001) Some aspects of morphology and genesis of gullies in the Pčinja catchment. Geogr Rev Skopje 36:197–207 (in Macedonian)
Milevski I (2004) Soil erosion in the Želevica catchment. Bull Phys Geogr Skopje 1:59–75 (in Macedonian)
Milevski I (2005a) Basic features of palaeovolcanic relief in the western part of Osogovo massif. Geogr Rev Skopje 40:47–67 (in Macedonian)
Milevski I (2005b) Characteristics of recent erosion in Kumanovo Basin. Bull Phys Geogr Skopje 2:25–45 (in Macedonian)
Milevski I (2006) Geomorphology of the Osogovo Mountain Massif. Doctoral dissertation, manuscript, Institute of Geography, FNSM, Skopje
Milevski I (2007a) Quantitative-geomorphologic characteristics of longitudinal profiles of Osogovo massif. Bull Phys Geogr Skopje 3–4:31–48 (in Macedonian)
Milevski I (2007b) Morphometric elements of terrain morphology in the Republic of Macedonia and their influence on soil erosion. In: Proceedings from international conference “Erosion 2007”, Belgrade, 2007, 10 p
Milevski I (2008) Fossil glacial landforms and periglacial phenomena on the Osogovo Mountain massif. Annal Inst Geogr Skopje 37:25–49
Milevski I (2009) Excess erosion and deposition in the catchments of Kamenička and Radanjska River, Republic of Macedonia. Annu Serbian Geogr Soc Belgrade 89(4):109–120
Milevski I, Miloševski V (2008) Denudation landforms in the Mavrovica Catchment. Bull Phys Geogr Skopje 5:87–100 (in Macedonian)
Milevski I, Dragičević S, Kostadinov S (2007) Digital elevation model and satellite images in assessment of soil erosion potential in the Pčinja catchment. Annal SGS Belgrade 87(2):1–20
Milevski I, Blinkov I, Trendafilov A (2008) Soil Erosion processes and modelling in the Upper Bregalnica Catchment. In: Proceedings of the 24th conference of the Danubian Countries on the hydrological forecasting and hydrological bases of water management, Bled, Slovenia. 2008. http://ksh.fgg.uni-lj.si/bled2008/cd_2008/index.htm
Ministry of Environment and Physical Planning of the Republic of Macedonia (2008) Second National Communication on Climate Change. Project strategy led by Adzievska M. Skopje, 118 pp
Mitchell TD (2003) Pattern scaling. An examination of the accuracy of the technique for describing future climates. Climatic Change 60(3):217–242
Petkovski R (1998) Connection between neotectonic movements and lake stadiums in Macedonia. In: Proceedings from 1st congress of ecologists of Macedonia, Ohrid, 1998, pp 855–867 (in Macedonian)
Petkovski R (2002) Possible damages of the construction objects because of unequal soil settlements. In: Proceedings of 1st symposium of the Macedonian Association for Geotechnics, Ohrid, pp 427–435 (in Macedonian)
Radovanović VS (1928) Small denudation landforms in gneiss. Annal SND Skopje 4(1):53–121 (in Serbian)
Radovanović VS (1931) Holokarst Huma bellow Kožuf. Annal SND Skopje 9(3):108–159 (in Serbian)
Serafimovski T (1993) Structural metalogenic features of the Lece Chalkidiki zone: types of mineral deposits and distribution. Faculty of Mining and Geology, Stip, Macedonia. Special Issue 2, 328 p (in Macedonian)

Shopov Y, Stoykova D, Tsankov LT, Marinova E, Sauro U, Borsato A, Cucchi F, Forti P, Piccini L, Ford DC, Yonge CS (2006) Past annual variations of the Karst denudation rates. In: Duran JJ, Andreo B, Carrasco F (eds) Publicaciones del Instituto Geologico y minero de Espana. Serie: Hidrogeologia y aguas subterraneas. Madrid, vol. 18, pp 487–494

Stojadinoviḱ C (1958) Geomorphologic observation of the gypsum relief in the Radika Valley. Annals FNSM Skopje 11:73–118 (in Macedonian)

Stojadinoviḱ C (1962) Stone rivers and screes on Pelister. Geogr Rev Skopje 1:45–51 (in Macedonian)

Stojadinoviḱ C (1968) Genesis of littoral relief on the basin of Ohrid Lake, and its tectonic and coastal elements. Annu FNSM Skopje 16(4):103–127 (in Macedonian)

Stojadinoviḱ C (1970) Geologic-geomorphic evolution of the relief of Pelister. In: Proceedings of the symposium for Molika, Skopje, 1970, pp 39–48 (in Macedonian)

Stojanoviḱ M (1986) Areas of fossil volcanoes in the territory of SR Macedonia. Ann FNSM Skopje 30:148–166 (in Macedonian)

Stojanoviḱ M (1995) Dojran Lake: origin, evolution and extinction. Geogr Rev Skopje 30:81–90 (in Macedonian)

Trendafilov A (1996) Erosion in the Crna River catchment and sedimentation of the Tikveš reservoir. Manuscript doctoral dissertation, Faculty of Forestry, Skopje, 256 p (in Macedonian)

Zagorchev I (1995) Pre-Paleogene Alpine tectonics in Southwestern Bulgaria. Geologica Balcanica Sofia 25(5–6):91–112

Zhang XC, Nearing MA (2005) Impact of climate change on soil erosion, runoff, and wheat productivity in central Oklahoma. Catena 61(2–3):185–195