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Geomorphology and hydrogeology of an exposed evaporite dome: the Dumre karst area, Central Albania

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The Dumre area, located in Central Albania, is distinguished by a landscape whose main features consist of low altitude, mosaic and irregular relief, and the presence of a large number of depressions with lakes. These features result from karst development related to the presence of a tectonically affected dome of Triassic evaporite rocks, mainly gypsum. Gypsum karstification has operated since the Pliocene, and the present-day geomorphological appearance of the area indicates an advanced, mature stage of karst development. Signs of this maturity include the widespread occurrence of large depressions, many of which are water-filled, forming lakes, the occasional presence of gypsum hills in the form of monadnocks, a thick "coating" of residual sediments largely isolating the karstic gypsum substrate from precipitation and surface waters, and the fragmentary pattern of a degraded river network. The karst character of the relief is largely "camouflaged" by clastic terrigenous and residual deposits of considerable thickness which cover the gypsum and form a caprock. At the present stage, the caprock is being strongly reshaped and eroded. Chemical analyses show a mean dissolved gypsum content of 1.9 g/l and mean dissolved NaCl content of 0.4 g/l. The mean flow rate of subaqueous springs is calculated as 1.84 m^3/s. The density of gypsum is 2.3, and that of rock salt is 2.17, thus the total volume of gypsum dissolved each year is 47,420 m^3 and of rock salt 10,680 m^3, making a total volume of dissolved material released by the subaqueous springs in one year of 58,100 m^3. This corresponds to a cubic void of side length 38.7 m.

Key words: Albania, gypsum karst, Dumre area, chemical denudation.

INTRODUCTION

Evaporitic rocks such as gypsum, anhydrite and salt occur beneath ~25% of the continental surface (Ford and Williams, 2007). Karst associated with gypsum and anhydrite occurs on all continents and on many islands. It occupies significant areas in Eurasia, North America and Africa (Klimchouk and Andreychouk, 1997). In Europe, the largest areas of gypsum karst are within the East European Plain. In Western Europe, areas of gypsum karst cover smaller areas, but examples are numerous, especially in Central Europe and Southern Europe. In Central Europe and the British Isles, gypsum karst develops mainly in Permian and Triassic rocks, while in Southern Europe it is mainly in the Neogene (Messinian) and, to a lesser extent, in the Triassic. In Albania, Triassic gypsum occurs in several areas.

Albania is situated on the western part of the Balkan Peninsula, on the eastern coast of the Adriatic and the Ionian seas. The karst landscape in Albania covers 6750 km^2 or 24% of the country's territory, which are represented mainly by carbonate rocks. Evaporite rocks cover 260 km^2, comprising 1.7% of the Albanian territory. They are represented mainly by gypsum and form two karst areas: Korab is in the northeastern part of the country and Dumre is in its central part. Both areas are characterized by specific geological, tectonic, geomorphological and hydrogeological conditions. While the Korab area is a part of the inner tectonic zone, the Dumre area is an evaporite dome located in the central part of the Pre-Adriatic Depression. The relief of this area represents a hilly plateau with karstic landscape distinguished by the presence of ~80 karstic lakes and by active recent subsidence (Fig. 1).

The formation of the Dumre evaporite dome, and the age and relations of the gypsum deposits to the surrounding rocks represent one of the key problems for the regional geology of Albania and particularly for oil prospection (Plaku, 1966;

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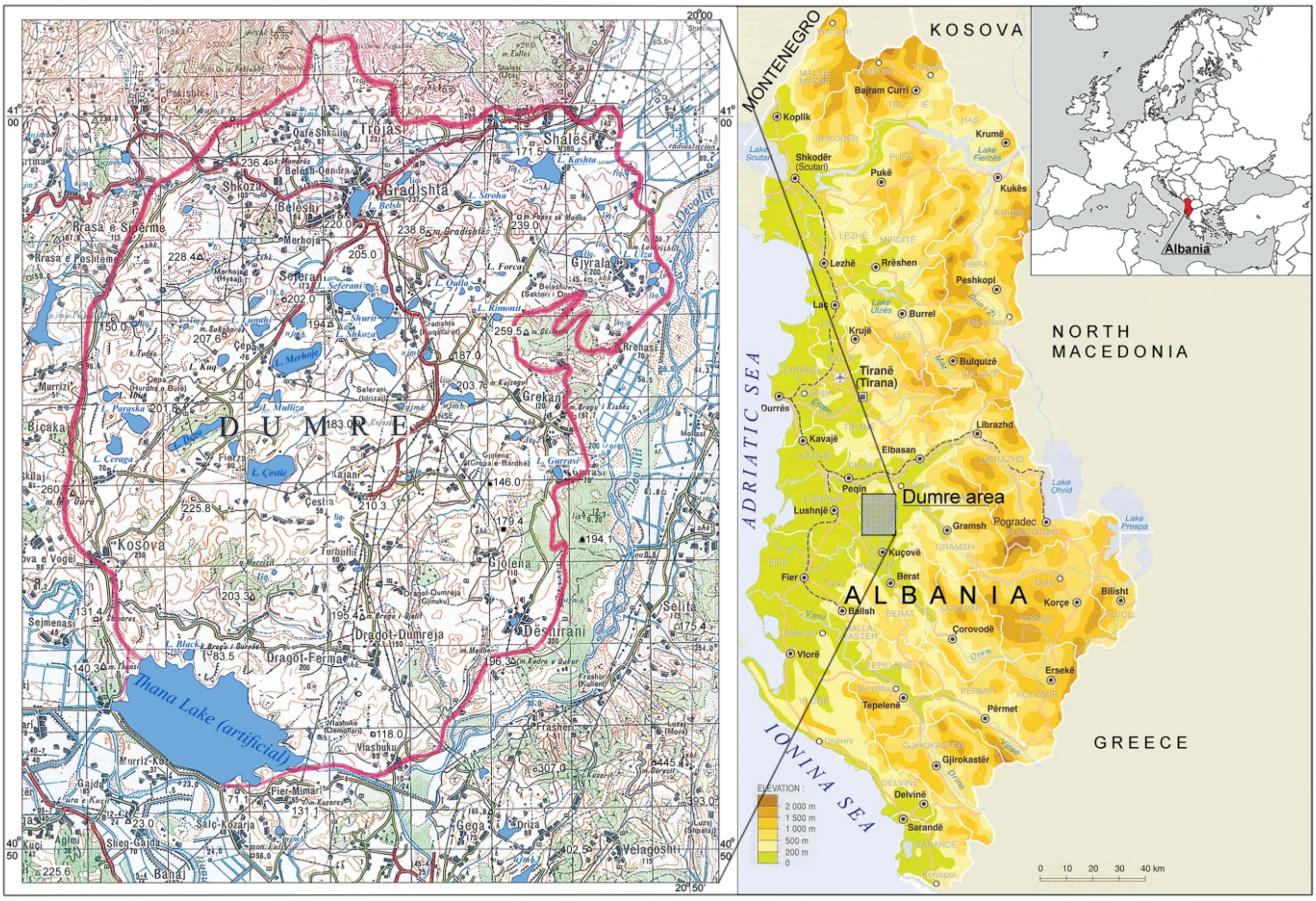

Fig. 1. Location (right) and topography (left) of the Dumre area (defined by a red line)

Gjikopulli, 1968; Plaku and Murataj 1974; Velaj, 2001). The geology of the area is also presented in most geological books and maps of Albania (Meço and Aliaj, 2000; Xhomo et al., 2002; Aliaj, 2012). The geomorphology of Dumre has been described (Kabo, 1990; Kristo, 1994, 2002; Qirjazi, 2019), while interest in the environmental problems of this area has increased during the last 20 years (Parise et al., 2004, 2008; Sala, 2009; Cane et al., 2010). The hydrogeology of the Dumre area has not been studied in detail but some important data are provided by the Hydrogeological Map of Albania at 1:200,000 scale (Eftimi et al., 1985).

The physiognomic and landscape distinctiveness of the area is the result of its development in specific tectonic and geological conditions. The karst character of the landscape is largely “camouflaged” by clastic terrigenous deposits of considerable thickness, which cover the gypsum and form a caprock – a secondary formation of carbonate and clay deposits that accumulated *in situ* owing to the gypsum karstification. The loose caprock deposits are prone to erosion and the accumulation of erosional products. These processes, due to the residual material they redistribute, have in general smoothed the landscape. They also allow retention and accumulation of water in depressions, and thus the agricultural utilisation of the land (ploughlands in the depressions and on gentle slopes, pastures on steep, more rocky slopes).

Due to the particular geomorphological characteristics of the area – a gentle topography, extensive depressions, the presence of numerous irregular-shaped lakes (Fig. 1), the sparse parent rock (gypsum) exposures, caves, and “fresh” collapse sinkhole – the karstic nature of this area was long “concealed” from researchers. The gradual transformation of the sinkholes into lakes and the accumulation of residual material above the karstified gypsum during the Pliocene and Pleistocene resulted in the gradual disappearance of typical karst features from the area, whereas erosion and sedimentation in the caprock succession resulted in the development of the physiognomic features of an erosive landscape.

Nevertheless, karst plays a decisive role in the development of the area. We describe here our pilot research into this landscape, and draw attention to the potential for more detailed studies of the area.

STUDY AREA

The area studied is a compact and oval in shape, extendijng for 17 km N–S and 13 km E–W, and covering ~170 km^2. The eastern and southern boundaries run along the valley of the Devoll River, while the northern and western boundaries are geomorphological, characterized by changes to higher relief landscapes underlain by flysch-like and molasse strata. The southwestern border is determined by the bank of the Thana reservoir connected by a recharge canal to the Devoll River. The area lies some 35 km from the Adriatic Sea. Administratively, the Dumre area is almost entirely located within Elbasan County.

The altitude of the area gradually and irregularly decreases from 160–240 m a.s.l. in the north to 30–200 m in the south. It is difficult to define the "status" of the area hypsometrically and geomorphologically. In general, it comprises a slightly raised hilly plain surrounded by eroded uplands.

Most of the area is agricultural (Fig. 2). A significant part of the land is used for pastures, some of the land is tree-covered, and a very small percentage of the land is wasteland (in the few places where gypsum is exposed).

The Dumre evaporite dome is located along the Lushnje-Elbasan transtensional strike-slip zone (Fig. 3A). The evaporites have intruded into Oligocene flysch deposits from the Permian-Lower Triassic evaporite succession through the strike-slip zone of Dumre (Aliaj, 1999; Meço and Aliaj, 2000; Velaj, 2001; Xhomo et al., 2002). The Dumre diapir has intruded from the east as an overthrusted diapir of "mushroom" shape with a chimney extending from the eastern side, from Cerrik to Kuçova (Plaku and Murataj, 1974; Xhaçka, 1981). The western flank of the Dumre dome is thrust not only onto Oligocene flysch, but also onto Miocene and Pliocene molasse, showing that the Dumre diapir is active and is characterized by general uplift that began in Pliocene times (Aliaj, 2012; Fig. 3B).

The Dumre evaporite dome is composed of gypsum, anhydride and halite, with scarce intercalations of dolomitized limestone and dolostone, reaching an overall thickness of >6000 m (Plaku and Murataj, 1974). It is covered by caprock consisting of calcareous and dolomite breccias (Fig. 4). As seen on the land surface, the caprock is composed of gypsum with subordinate limestone or dolomite breccia, sandstone, clays, volcanic tuffs, quartzites and other lithologies. In some places, Pliocene limestone has been deposited over the caprock. As seen in some erosional exposures at the tops of hills, the caprock thickness reaches some tens of metres, but it is believed that in depression areas its thickness exceeds 100 m.

The gypsum rock seen in rare exposures in gypsum hills has a coarsely crystalline structure. The crystals are chaotically arranged and reach some centimetres long. The spaces between crystals are filled with clayey-carbonate material that is visible to the naked eye. This facilitates rapid weathering and disintegration of the rock, and the accumulation of loose material at the foot of the hills. We infer that the residual clay material may be an important source of the formation and accumulation (by erosional redistribution) of clay deposits in the bottoms of valleys and especially – in depressions. The consequence of this was the appearance of a weakly permeable layer of clay deposits in the bottoms of the depressions and the formation of permanent lakes. This was an evolutionary process which continues today.

The Dumre area has a typical Mediterranean plain climate (Climate of Albania, 1980). The average annual rainfall varies around 1050 mm and is unevenly distributed through the year. About 70–80% of rainfall occurs during the October-March period (Fig. 5). The annual average air temperature of the area is 15.1°C.

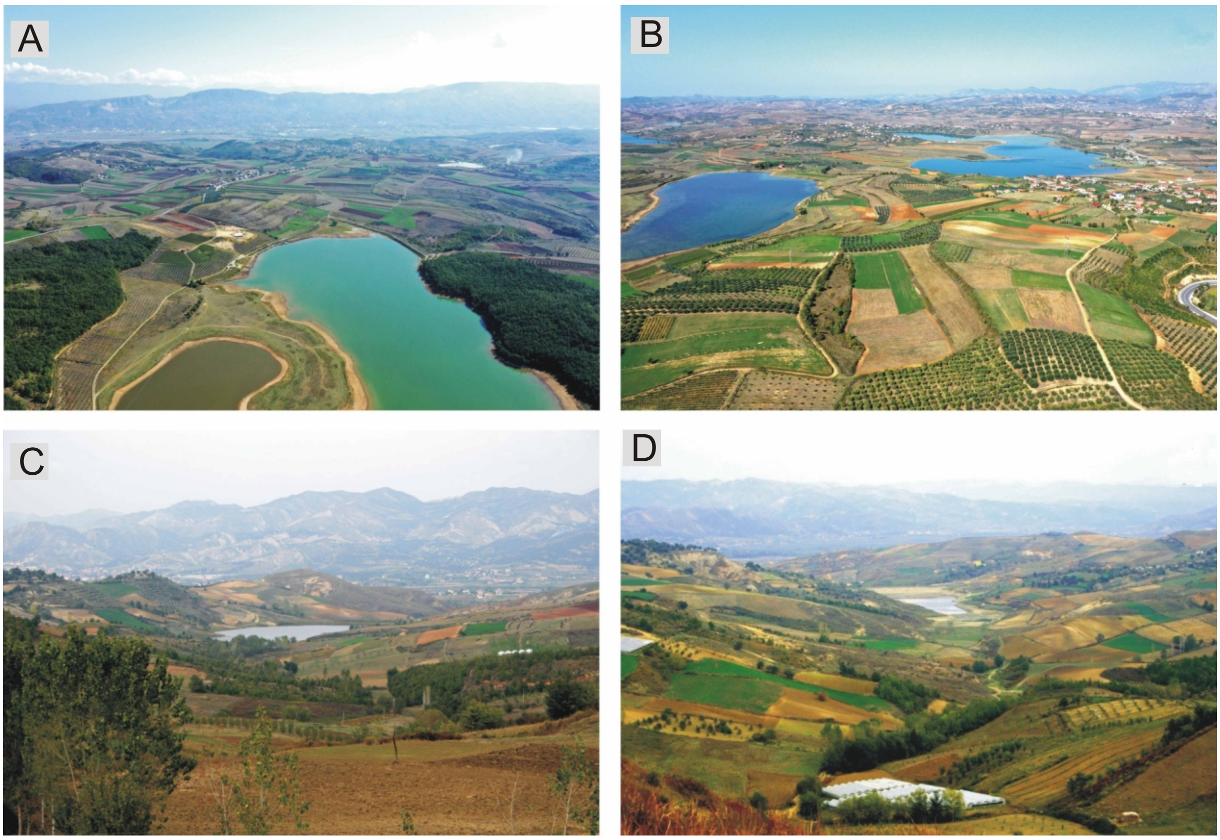

Fig. 2. Photographs of the Dumre area: bird's eye view (A, B – by drone) and landscape (C, D)

The bottoms of the depressions are filled with natural (karst) lakes (A and B); some of the reservoirs located at the bottom of the valleys (shown in photos C and D) are of artificial origin (ponds) (photos by: A, B – A. Klimchouk, C, D – V. Andreychouk)

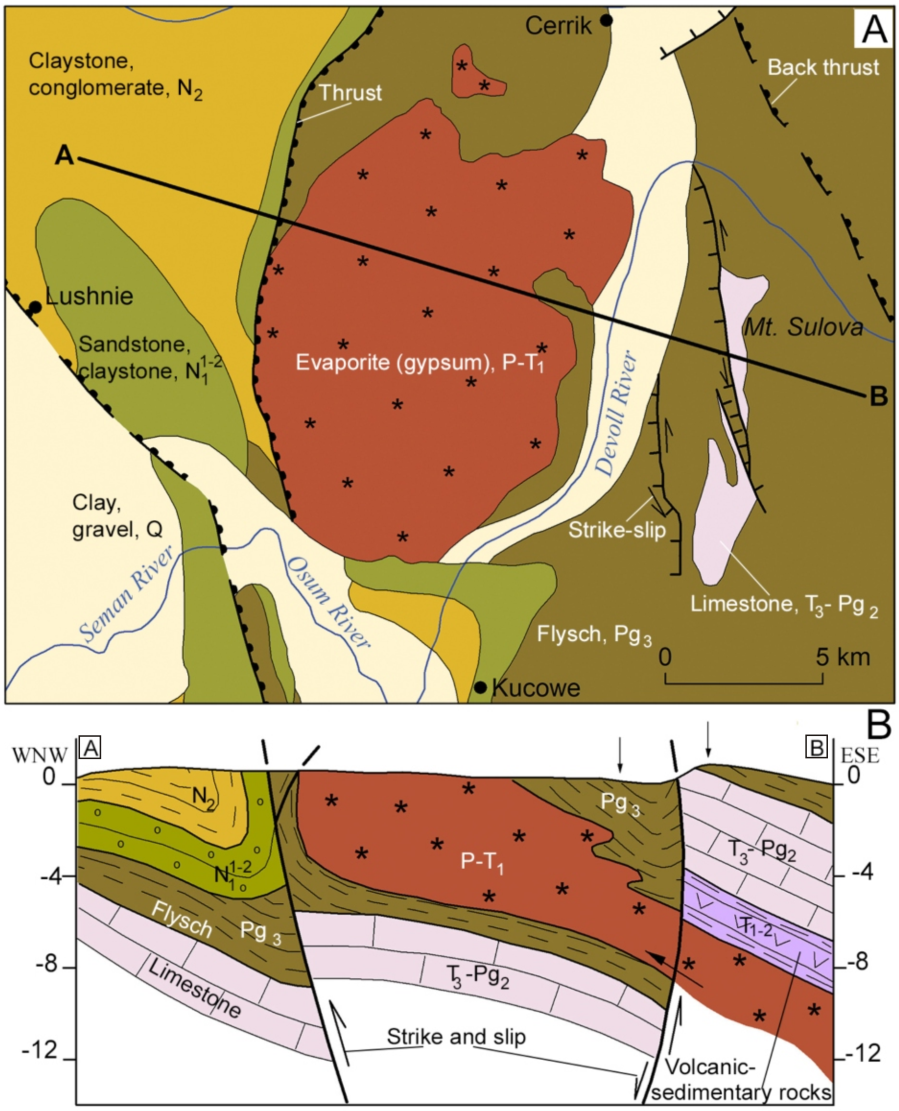

Fig. 3. Geologic-tectonic map of the Lushnje-Ebasan transversal fault zone (A) and a cross-section through the Dumre evaporite dome (B) (simplified from the Geologic Map of Albania 1:200,000; Xhomo et al., 2002)

RESEARCH METHODOLOGY

The study of the landscape of the massif comprised mapping employing GIS tools and field observations. The division of the area into geomorphological units was performed "manually" according to the criterion of homogeneity of the landscape, on the basis of clear visual differences between the units on detailed topographic maps at a scale of 1:25,000, orthophotos, satellite photos, and drone photos. The units distinguished units and corresponding types of landscape (i.e. unit boundaries and their topographic character) were checked during fieldwork within selected transects through the massif in various directions.

Then, the typologically homogeneous geomorphological areas distinguished were subjected to numerical analysis in order to calculate basic parameters and indicators, and to generate appropriate models and maps.

The following maps and orthoimages were acquired for the purpose of the study:

– 1:25,000, 1:50,000 and 1:100,000 scale topographic maps;
– orthophotomaps and satellite images (*LandSat-8*, *Santial-2*);
– data for the NMPT Digital Area Coverage Model (DEM and DSM);
– 1:50,000, 1:100,000, 1:200,000 scale geological maps;
– 1:50,000 scale hydrographic maps;
– Corinne maps of land management and urbanization, forests and land use;
– thematic maps for digital data processing.

The following GIS software was employed to process the data acquired: *Global Mapper, QGIS, SAGA, MapInfo*, and *ArcGIS*. This software was used for compilations of the thematic maps and spatial analyses related to the inventory and interpretation of karst features. Based on DSM images, detailed analyses of inclinations and slope exposures, as well as precise

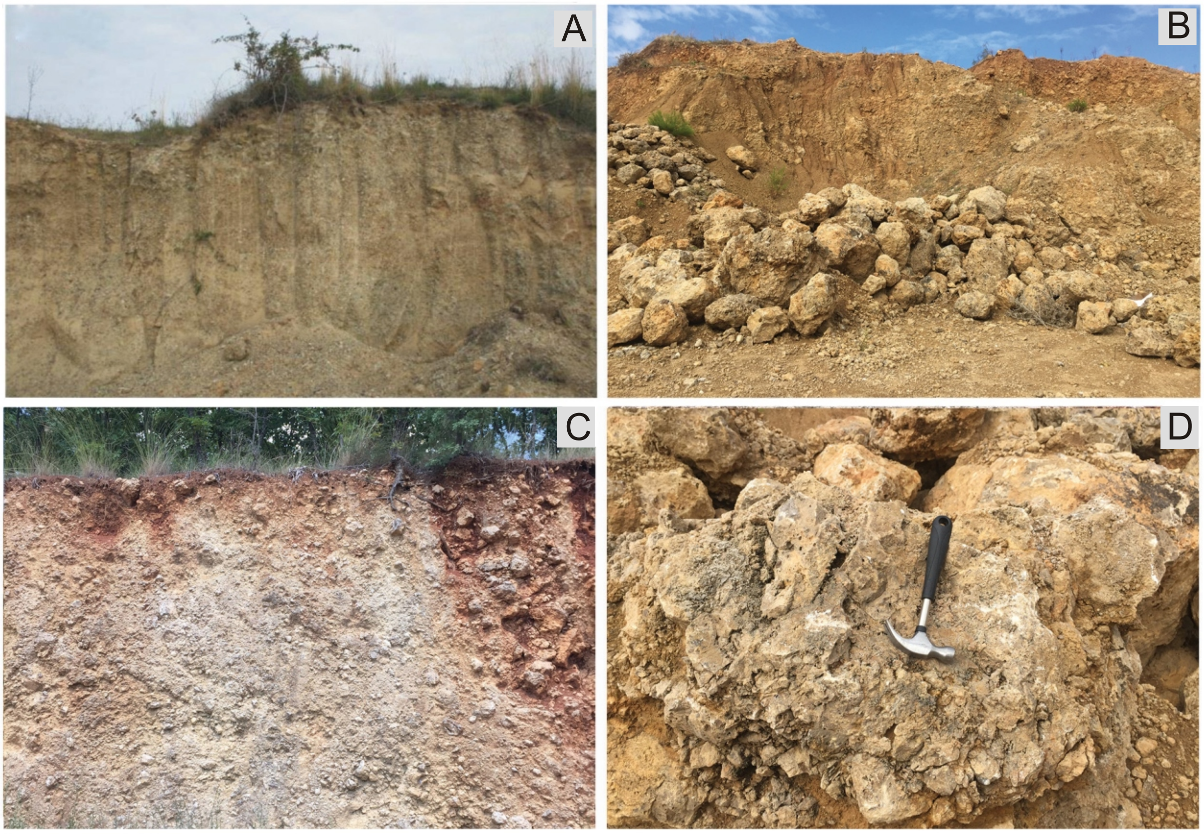

Fig. 4. Some examples of the soil cover (caprock) and weathering products present within the Dumre area

A – soil profile formed on the gypsum weathering products; **B** – blocks of carbonate occurring in the caprock, artificially accumulated during road construction; **C** – cemented caprock breccia; **D** – cemented caprock breccia with karst and erosional voids (photos by: A – V. Andreychouk, B–D – R. Eftimi)

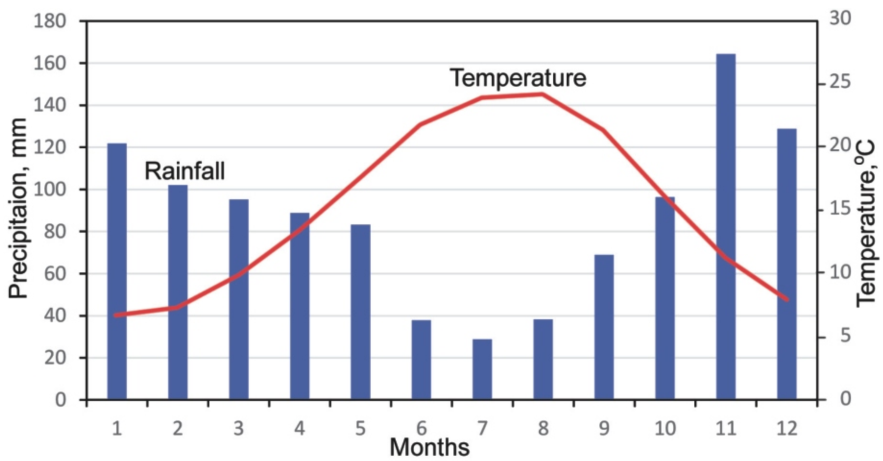

Fig. 5. Average monthly precipitation and temperature at the Belsh meteorological station (Climate of Albania, 1980)

calculations regarding the dimensions of the objects, were performed. Spatial data were processed using the following projections: EPSG 4326, EPSG 6870, EPSG: 28404 (Pułkovo 1942), and Gauss-Kruger zone 4.

The orthophoto data obtained, of 20 cm pixel accuracy on both RGB and CIR channels, came from 2015–2016. Mosaics of super-high resolution orthoimages from the Copernicus information services were also utilized. In addition, data from *LandSat8* were used for general visualization; output format: *GeoTIFF*, UTM projection (output data: WGS 84). Numerical data for the DTM (Digital Terrain Model) and DSM (Digital Surface Model) came from 2015–2017, the pixel size on the model is 0.1 m (DTM) and 0.1–0.2 m (DSM). Moreover, the EU Digital Elevation Model (EU-DEM), which combines data from various sources (Copernicus on SRTM and ASTER data), was employed for general purposes.

A data set for a DSM with a horizontal resolution of ~30 meters (1 arc second) was also used, obtained with the Panchromatic Remote-Sensing Instrument for Stereo Mapping (PRISM), from the ALOS satellite (World 3D – 30 m – AW3D30).

The numerical data obtained were used to generate the DTM and DSM models and for further analyses (slope, aspect, LS factor, plan curvature, closed depressions, total catchment area, valley depth module, relative slope position, flow directions, and others).

The field research was carried out in 2010–2019 and included geomorphological observations and sample collection for laboratory tests of their chemical and elemental composition, water samples from karst lakes and springs, and samples of rock formations and soils from caprock and gypsum (from exposures).

In May 2019 and in November 2020, 4 water samples were collected from the Black Lake (1 sample) and springs (3) on the north-west bank of the Thana Lake, with simultaneous measurement of water temperature, pH and air temperature. Water was placed in plastic 0.5 l containers and transported and stored at low temperatures (2–7°C) until analysis. The water's chemical composition was determined at the laboratory. All samples were filtered through a standard membrane filter (pore size 0.45 μm). Filtered samples were placed into two polyethylene containers. The sample destined for the cation analysis was acidified with nitric acid down to pH <2.

The chemical composition of the water, including macro- and microelements, was determined by two Perkin Elmer spectrometers located at the certified Hydrogeochemical Laboratory at the University of Science and Technology in Kraków; *Elan 6100* ICP-MS, *Plasma 40* ICP-OES. The sulphur concentration was converted into SO_4 concentration. The concentrations of HCO_3 and Cl were determined by titration.

RESULTS

GEOMORPHOLOGICAL FEATURES OF THE AREA

HYPSOMETRY AND THE HILLY CHARACTER OF THE LANDSCAPE

The area represents a hilly plain slightly rising from south to north. The highest point of the entire area is Pognit Hill (242.0 m), located in its northern part, 2 km west of Belsh. There are many other hills whose elevations range above 200 m (Fig. 6). They have more or less round or oval shapes and are fairly evenly distributed throughout the area. Some elevations are topped with rocky peaks comprised of exposed gypsum, whereas the lower slopes of the hills are gently inclined. The average altitude above sea level of the entire area is 131 m. The lowest point (~25 m) is the bank of the Thana reservoir at the southern edge of the area (Fig. 6)

The hills are separated from each other by depressions of various sizes and by valleys of permanent rivers and intermittent streams. The depressions, especially the large ones, are filled with water. The majority of the flooded depressions are closed, but there are also "semi-closed" ones, merging with other adjacent depressions. Diameters of major depressions range from 1 to 3 km. Open and blind valleys also occur along the linear forms i.e., river valleys. The hypsometric pattern of the area is illustrated in Figures 6 and 7.

The relief between topographic highs and lows usually ranges from 20–80 m, locally up to 130 m. The gypsum substrate of the area, the isometric shape of the elevations and depressions, the closed character of the latter, and the general outline of the landscape, indicate the basically karstic nature of this hilly landscape. At the present stage, it is being strongly modelled and destroyed by ongoing erosive processes, but nevertheless it retains the basic features of a mature karst landscape.

The isometric nature of the elements of the landscape described, namely hills and depressions, and their fairly even spatial distribution are reflected in the character of the inclination of the hills and valley slopes and their exposures, which show a generally similar pattern (Fig. 8).

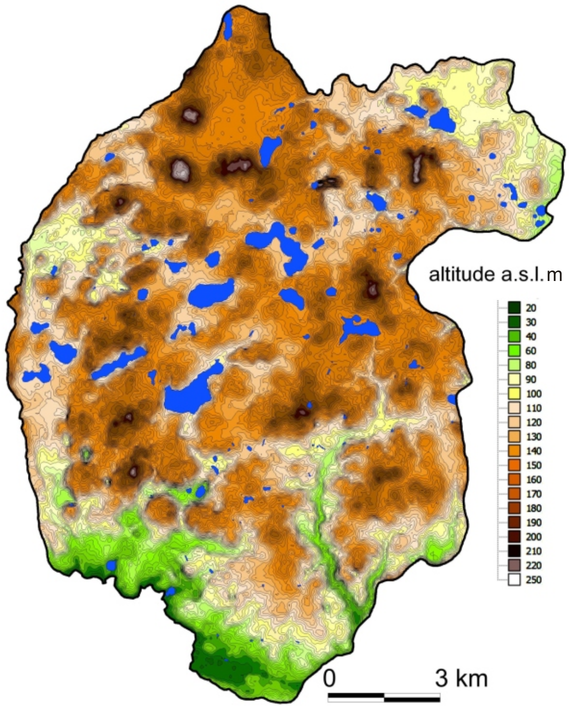

Fig. 6. Hypsometric map of the Dumre area

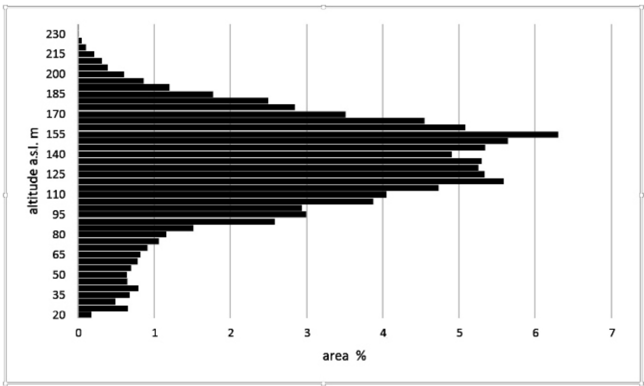

Fig. 7. Percentage of the area elevation above sea level

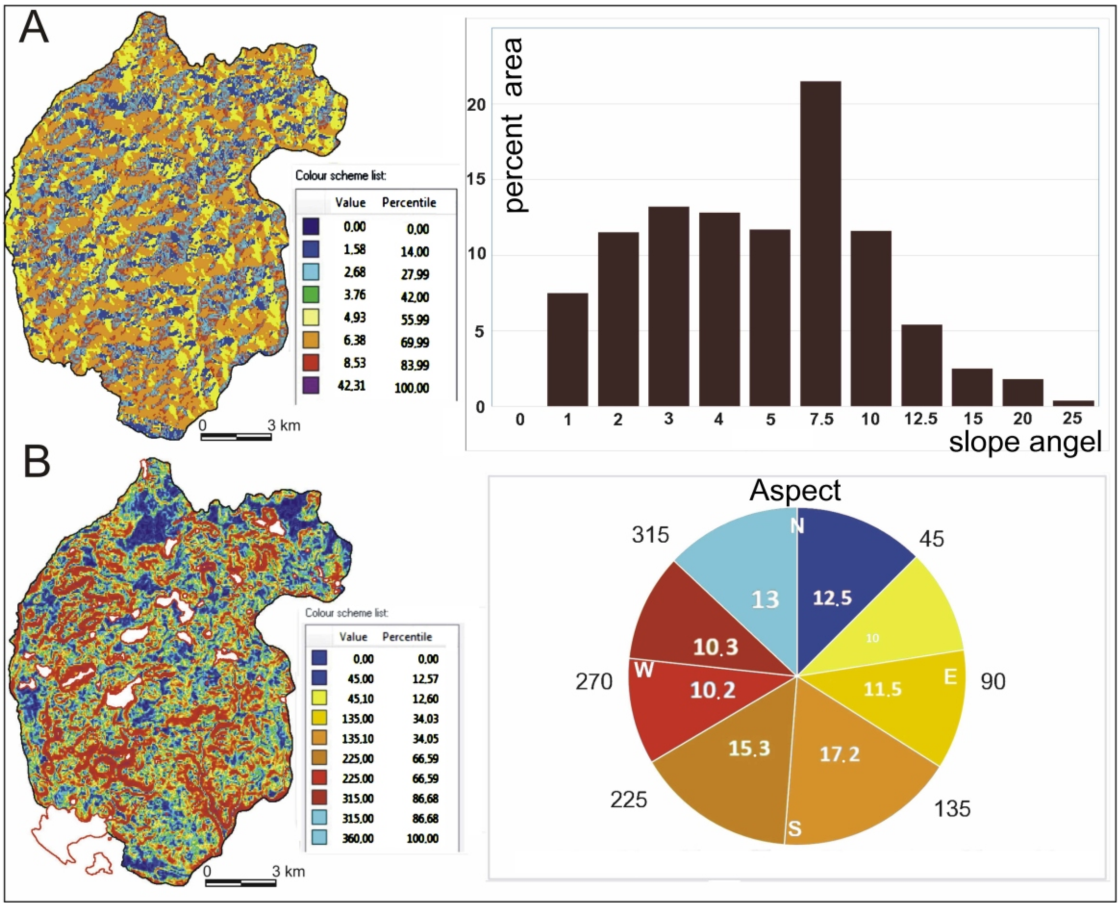

Fig. 8. Charts of the inclination of the terrain within the Dumre area (A) and of the slope exposures (B)

KARST LANDSCAPE

A characteristic feature of the karst landscape of this area is a clear dominance of large forms, both convex (elevations) and concave (depressions) (Fig. 9H). Because the gypsum is isolated from the surface by a residual caprock layer of a thickness of a few to several tens of metres, with limited exposure, there is almost no bare exposed karst in the area, with the exception of the top parts of the higher hills (Fig. 9E, F) where the gypsum is uncovered and exposed to the direct influence of rainwater. In such places, there are various types of karst grooves on the surface of the gypsum, the size, shape, nature, and expressiveness of which depend on the degree of weathering of the gypsum rock, its structure, inclination, size of the exposures, and the presence or absence of vegetation (mosses, lichens, algae, and grass). Within the >10 rock massifs, there are small caves up to several metres deep/long (Fig. 9G) that are relicts of larger caves destroyed by denudation or younger features related to the widening of crevices by infiltration or processes taking place on the slopes of the massifs (weathering, decompression, delamination, gravitational displacement of rock blocks, etc.). The shapes of the gypsum massifs make it possible to classify them as monadnock forms (Fig. 9E, F).

Smaller forms, such as sinkholes, are rare (Fig. 9A, B). The caprock layer creates a dense cover that prevents the formation of sinkholes on the surface. The exceptions are places where relatively large cavities occurred beneath the caprock, which consequently resulted in the collapse of the ceiling. Sinkholes thus formed turned over time into lakes with steep shores. Black Lake, located in the very south of the area (cf. Fig. 14E) where the thickness of the caprock layer is reduced, may serve as a good example. Nevertheless, due to the large size of the lake, its formation was most likely phased and may have involved several sinkhole events close to each other, separate in time.

Another reason for the relatively scarce occurrence of sinkholes may be the currently hindered flow of groundwater, both local, towards individual depressions, and regional, towards the valleys in the south, due to the fragmentation of the relief and the deposits filling the depressions, and therefore a weak current development of underground karst (see Discussion section). Collapses occurs from time to time all over the area (Tafilaj et al., 1998; Qirjazi, 2019; Fig. 10).

For example, a funnel-shaped pit was formed at Fierza village on January 1998 (Fig. 10A); in the village of Shales in 2009 a vertical pit was formed with a depth of 15 m and diameter of 3 m, and another pit was formed in the garden of the Belsh hospital. A collapse pit with a depth of 5 m and diameter of nearly 2 m formed in the forest near Grekan village in March 2018 (Fig. 10B). In the southern sector of the Dumre area sinkholes are much more frequent than in its northern part and may reach a density of 15–20 per square kilometre (Kristo, 2002, Parise et al., 2008). Among various types of karst hazards (Klimchouk and Andreychouk, 1996; Andreychouk and Tyc, 2013), the greatest threat within the Dumre area is the formation of sinkholes. Nevertheless, there is a need for a comprehensive assessment of environmental hazards that may be present in the area from karst development (see Parise et al., 2015).

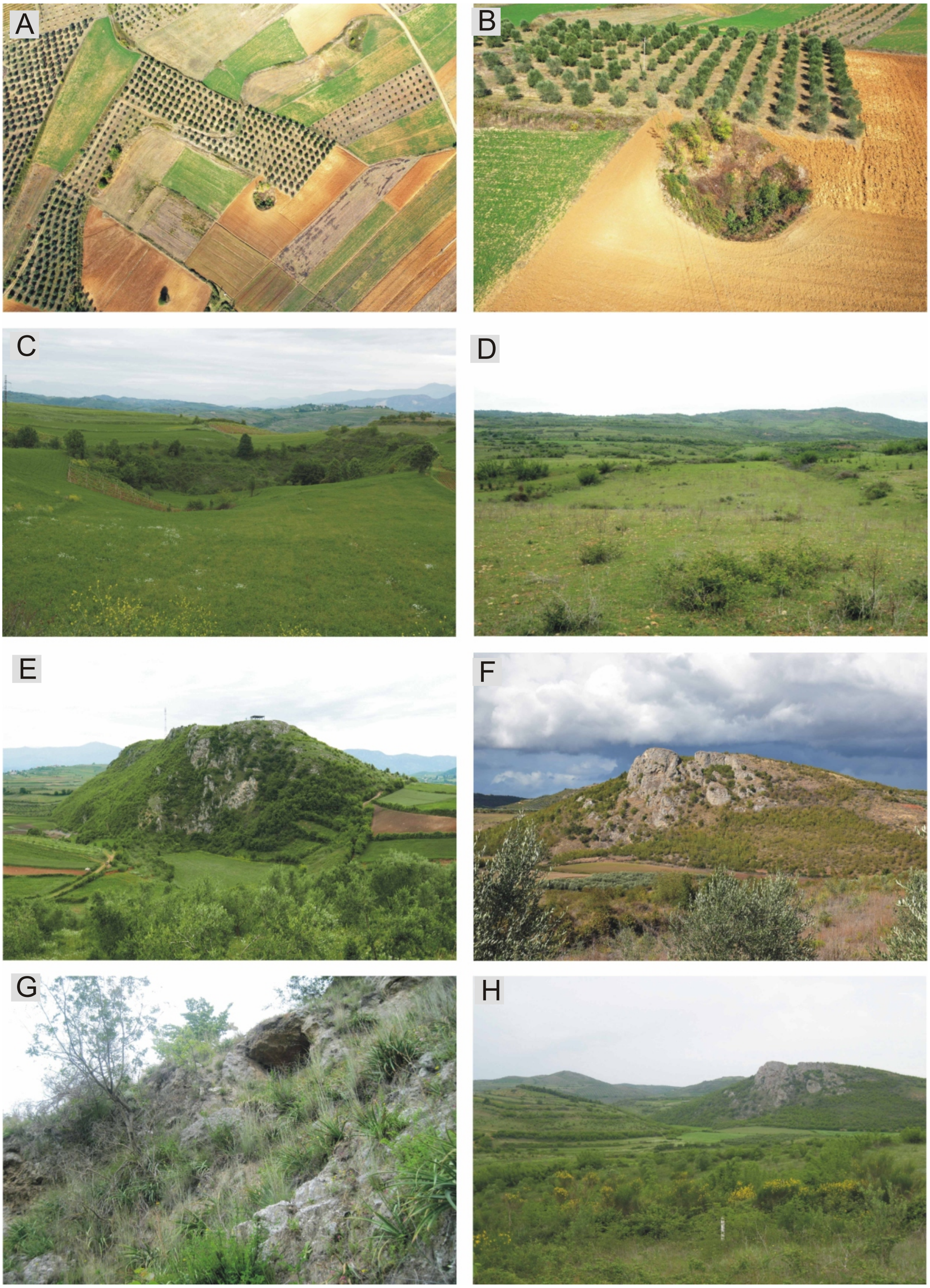

Fig. 9. Some characteristic elements of the karst relief of the Dumre area

A, **B** – sinkholes (the same form seen from different perspectives); **C** – depression developed within another larger one; **D** – large flat-bottomed depression; **E**, **F** – gypsum hills; **G** – small cave on the upper slope of a gypsum hill covered with gypsophilic vegetation; **H** – typical view of the southern part of the Dumre area with gypsum hills and depressions between them (photos by: A, B – A. Klimchouk, C, D, E, G and H – V. Andreychouk, F – R. Eftimi)

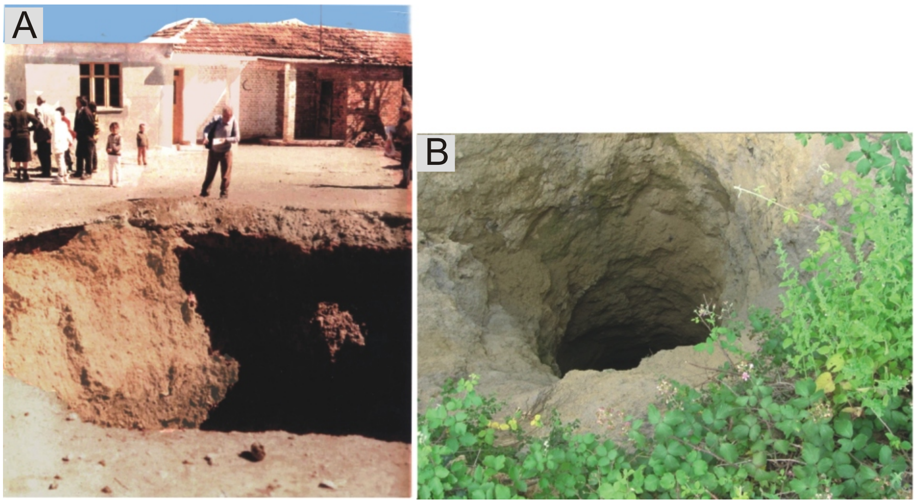

Fig. 10. Examples of recent collapse sinkholes which formed in the study area in the last few decades

A – a collapse doline in the central part of Fierza village, 38 m deep and 7 m in diameter, formed in February 1998; **B** – a collapse doline 5 m deep and nearly 2 m in diameter in the forest near Grekan village, formed in March 2018 (photos by P. Qirjazi)

The most characteristic and prominent elements of the karst landscape of the area are depressions. These vary in size and shape – from small, oval, 50–100 m diameter, some with superimposed caprock sinkholes at their bottoms, to large forms, 1–2 km and more in diameter, with complex irregular shapes. The small depressions are partially closed, whereas the larger ones are locally integrated with the river network. The depressions serve to collect rainwater and the surface runoff. Hence their bottoms, including the bottoms of the lakes, are clay-covered. The clay blanket effectively prevents the infiltration of lake water. This results in relatively stable water levels in the lakes and a clear correlation between lake level changes and weather and climate factors.

These characters of the landscape of the study area, and the size and proportions of particular landforms, are well illustrated in a topographic map from its southwestern part (Fig. 11).

HYDROLOGICAL FEATURES OF THE AREA

RIVER NETWORK

The chaotic, hilly nature of the landscape, the presence of a large number of partially or fully closed depressions and the infiltration of some rainwater into the permeable substrate determine the nature of the fluvial network. Within the area, the network is much sparser in comparison to the surrounding areas (Fig. 12A), a result of the subsurface karstic drainage of surface water. Karst ponors that intercept the waters of permanent or intermittent watercourses are very rare. In the areas studied, ponors were not found. However, in places where caprock is poorly consolidated and weakly cemented, it does not constitute a barrier to infiltration of water into deeper parts of the evaporite massif.

Within the area, watercourses do not form an uninterrupted network but occur sporadically, creating their own mini-catchments that developed around major depressions. Most of watercourses, especially the small ones, are temporary, occurring during periods of increased precipitation. Their length ranges from 0.5 to 2.0 km. Permanent watercourses that are fed mainly by groundwater are longer (2.5 km and more). They are present at the periphery of the Dumre area and are integrated into the networks of the surrounding areas (Fig. 12A).

The lowest density of the network and its most fragmentary character occur in the central part of the area. The density increases towards the peripheries, as does the number of permanent watercourses. Throughout the entire area, especially in its central and northern parts, the dry bottoms of major depressions are intersected by irregular channels. Single canals connecting adjacent depressions (lakes) are common. In several places, at the bottoms of the depressions located at higher altitudes, dams have been built and reservoirs created to collect rainwater and water from intermittent or permanent watercourses.

In Figure 12B, the catchments of the highest rank within the study area are outlined. At this level, they are integrated into the regional river network. Nevertheless, as the importance of watersheds decreases, more and more closed catchments occur within larger catchments.

LAKES

There are 121 lakes in the study area, covering a total area of 667.38 ha (Table 1). The lakes are fairly evenly distributed, though larger ones are located in the central and northern parts (Fig. 13). The area of the lakes varies widely: from 0.01 to 94.8 ha. The largest water bodies (excluding the reservoir located at the southwestern border of the area and occupying the flat bottom of the river valley) are lakes Çestije (94.84 ha), Seferan (84.86 ha), and Merhoje (59.6 ha) in the centre of the area (Fig. 13). Fifteen of the lakes are relatively large, with an area >10.0 ha (Table 1). The lakes differ in shape: small lakes are usually round or oval, while larger ones, especially the largest that fill the flattened bottoms of large depressions, have complex shapes (Figs. 13 and 14). The longer axes of larger lakes are usually oriented SW–NE and NW–SE.

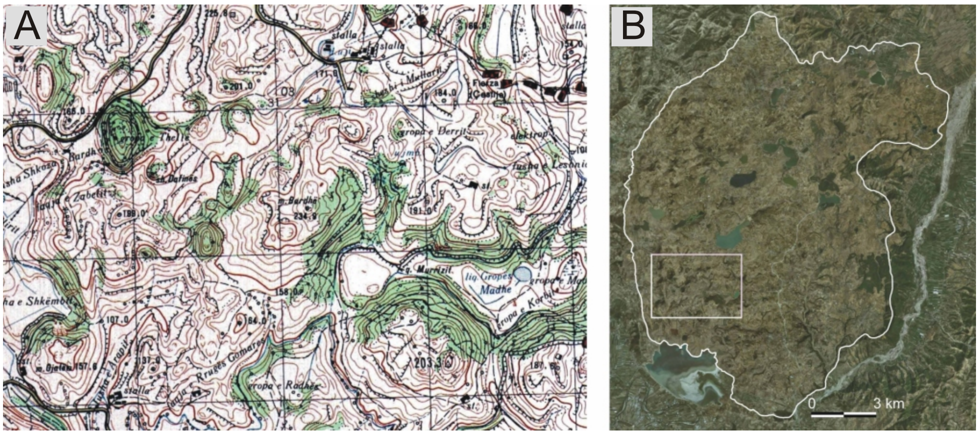

Fig. 11. Characteristic example of topographical map (scale 1:100,000) of the SW part of the Dumre area (A) and its location on the ortophotomap (B)

The long side of the rectangle measures 1 km

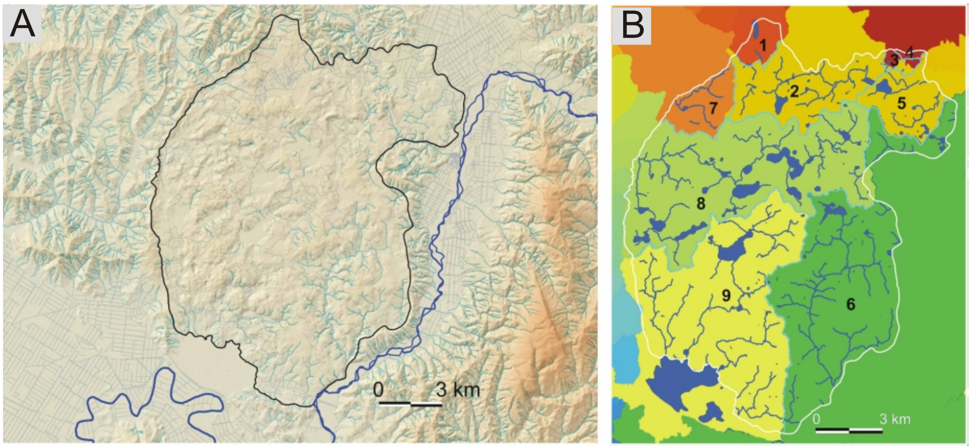

Fig. 12. Fluvial network (A) and main watersheds and catchments (B) of the Dumre area

In A, karst lakes and artificial reservoirs have been removed for a better demonstration of the sporadic and sparse character of the network

More than 80 lakes are of karstic origin. Karst lakes usually fill closed depressions and are round. They occupy an area of 660 ha and are characterized by highly variable morphometric parameters. 38 lakes considered as large are deeper than 10 m, and cover areas between 3 and 100 ha. Some of the largest lakes of the Dumre area occupy merged depressions. Karst lakes situated at different elevations have no underground connection (Qirjazi et al., 1999) because the lake bottoms are sealed with practically impermeable deposits.

The lakes are rain-fed sporadically during the rainy season also by groundwater. In summer, the lake levels decrease due to evaporation and especially due to water consumption for irrigation.

The lake levels show great variation. Indeed, no lakes have the same water level. The water tables of individual lakes are at altitudes varying from 30 to almost 200 m and they show no correlation with the size of the lakes or the basins in which they are located (Fig. 15).

As the area is highly populated (170 people/km^2) and is used for agriculture, i.e. land cultivation in the valleys and depressions, cattle-breeding on farms, and sheep-farming (on the slopes of the less rocky hills), the lake waters are widely utilised for agricultural purposes. Irrigation canals, single or forming small networks, run from larger lakes situated in large, flat-bottomed depressions (Fig. 13). The agricultural use of the water and the location of the villages – in many cases on the lake shores, contribute to high levels of pollution of the lake waters. General field observations leave no doubt as to the poor condition of the water in most of the lakes, especially the large, more actively used ones, and those with villages adjacent to the shore (Parise et al., 2008; Cane et al., 2010).

The varied degree and nature of water pollution may be indicated, inter alia, by the lake colour. Within the larger lakes, eutrophication takes place on a large scale, which is clearly visible in the photos and orthophotomaps.

Table 1

Morphometric parameters of lakes within the Dumre area (lakes with area >1 ha)

No	Name of the lake	Altitude [a.s.l. m]	Area [ha]	Area [m^2]	Circuit [m]	SI Shape Index	FD Fractal Dimension	The longest axis [m]	SSPI Shape Index Shumma
1	Çestia	108.01	94.84	948351.3	5721.65	1.7	1.26	1896.35	0.58
2	Seferan	124.01	84.86	848586.7	6037.69	1.8	1.28	1731.88	0.60
3	Merjoja	110.03	59.60	596023.0	3675.41	1.3	1.23	1337.29	0.65
4	Marina	149.73	38.25	382534.3	4704.71	2.1	1.32	1146.68	0.61
5	Dega	106.03	36.36	363647.9	4002.10	1.9	1.30	1635.52	0.42
6	Kashta	100.01	30.61	306132.8	2384.71	1.2	1.23	733.55	0.85
7	Belshi	154.00	27.26	272618.1	2446.81	1.3	1.25	896.47	0.66
8	Paraska	108.03	27.10	270993.1	2235.07	1.2	1.23	744.02	0.79
9	Plevica	146.01	22.04	220401.7	2124.00	1.3	1.25	752.16	0.70
10	Çerraga	116.01	20.65	206479.9	2579.72	1.6	1.28	735.58	0.70
11	Artificially filled ?	148.01	16.17	161700.3	2240.67	1.6	1.29	803.75	0.56
12	Turbollt Plane	102.56	15.22	152245.8	2104.57	1.5	1.28	739.09	0.60
13	Dorbini	133.14	11.67	116685.8	1371.80	1.1	1.24	474.08	0.81
14	Thate	102.42	11.22	112159.4	1626.35	1.4	1.27	568.56	0.66
15	Tomthi	119.31	10.33	103322.3	1646.59	1.4	1.28	596.64	0.61
16	Izba	111.77	9.85	98509.6	1422.68	1.3	1.26	477.11	0.74
17	Ulza	105.63	7.32	73220.3	1545.86	1.6	1.31	502.00	0.61
18	Kuq	131.05	6.67	66669.9	1018.72	1.1	1.25	324.38	0.90
19	Miloshi	71.74	5.86	58564.0	895.04	1.0	1.24	280.65	0.97
20	Gropa Madhe	49.98	5.85	58524.6	931.57	1.1	1.25	343.4	0.80
21	Black Lake	30.74	5.84	58428.5	980.73	1.1	1.26	338.76	0.81
22	Mulliza	111.90	5.58	55829.5	1557.06	1.9	1.35	435.59	0.61
23	Gurresi	124.94	5.40	54011.8	913.12	1.1	1.25	297.82	0.88
24	Omli	148.57	5.23	52261.5	872.02	1.1	1.25	272.24	0.95
25	Civiles	128.58	5.11	51112.9	997.90	1.2	1.27	365.13	0.70
26	Bazi	152.17	4.73	47301.0	1140.95	1.5	1.31	445.22	0.55
27	Mullinja	113.72	4.41	44136.0	945.79	1.3	1.28	348.09	0.68
28	Dragoti	28.08	4.26	42630.1	935.58	1.3	1.28	307.24	0.76
29	Gjermulla	118.11	3.96	39620.9	783.44	1.1	1.26	287.31	0.78
30	Pocilave	164.80	3.84	38396.1	929.42	1.3	1.29	215.29	1.03
31	Bicit	76.15	3.20	32031.6	822.41	1.3	1.29	263.88	0.77
32	Trija 2	103.82	3.17	31741.1	738.50	1.2	1.27	214.61	0.94
33	Trija	134.96	2.97	29718.7	634.83	1.0	1.25	188.77	1.03
34	Katundi	99.85	2.92	29245.2	695.49	1.1	1.27	288.03	0.67
35	Rimonit	131.88	2.84	28385.1	758.37	1.3	1.29	216.35	0.88
36	Gropa Selmanit	142.46	2.81	28138.4	875.66	1.5	1.32	275.47	0.69
37	Tudes	85.88	2.73	27275.2	731.46	1.2	1.29	285.64	0.65
38	Forca Fogel	149.28	2.58	25801.9	643.28	1.1	1.27	237.05	0.76
39	Gjate	140.96	2.52	25243.3	634.31	1.1	1.27	209.71	0.86
40	Trija	103.94	2.36	23616.1	735.64	1.4	1.31	220.14	0.79
41	Godes	121.70	2.19	21889.4	551.52	1.1	1.26	136.52	1.22
42	Temporary lake	97.00	2.18	21765.0	730.33	1.4	1.32	294.6	0.57
43	Kamecit	133.86	2.06	20598.5	534.07	1.0	1.26	163.50	0.99
44	Forces	118.89	1.95	19510.3	631.01	1.3	1.31	189.78	0.83
45	Gjazes	115.37	1.83	18281.3	537.68	1.1	1.28	188.77	0.81
46	Kashaj	113.60	1.82	18162.0	502.60	1.1	1.27	148.49	1.02
47	Rezervoir	120.37	1.72	17214.9	642.48	1.4	1.33	271.73	0.54
48	Rezervoir	147.27	1.71	17068.5	840.90	1.8	1.38	329.18	0.45
49	Golloces	155.75	1.63	16332.5	512.81	1.1	1.29	184.35	0.78
50	Xhiklazit	197.86	1.62	16232.1	608.14	1.3	1.32	158.74	0.91
51	Liqene	163.88	1.59	15902.1	698.73	1.6	1.35	188.7	0.75
52	Gjoli Turbullt	130.90	1.56	15636.5	575.34	1.3	1.32	203.09	0.69
53	Gropa Madhe	61.92	1.45	14539.9	554.50	1.3	1.32	150.6	0.90
54	Plain	150.73	1.43	14344.2	512.08	1.2	1.30	152.92	0.88
55	Temporary lake	100.52	1.28	12787.3	423.90	1.1	1.28	0.1604	795.70
56	Liku	128.01	1.16	11634.3	412.09	1.1	1.29	145.46	0.84
57	Trojas	140.96	1.11	11099.8	415.18	1.1	1.29	114.59	1.04

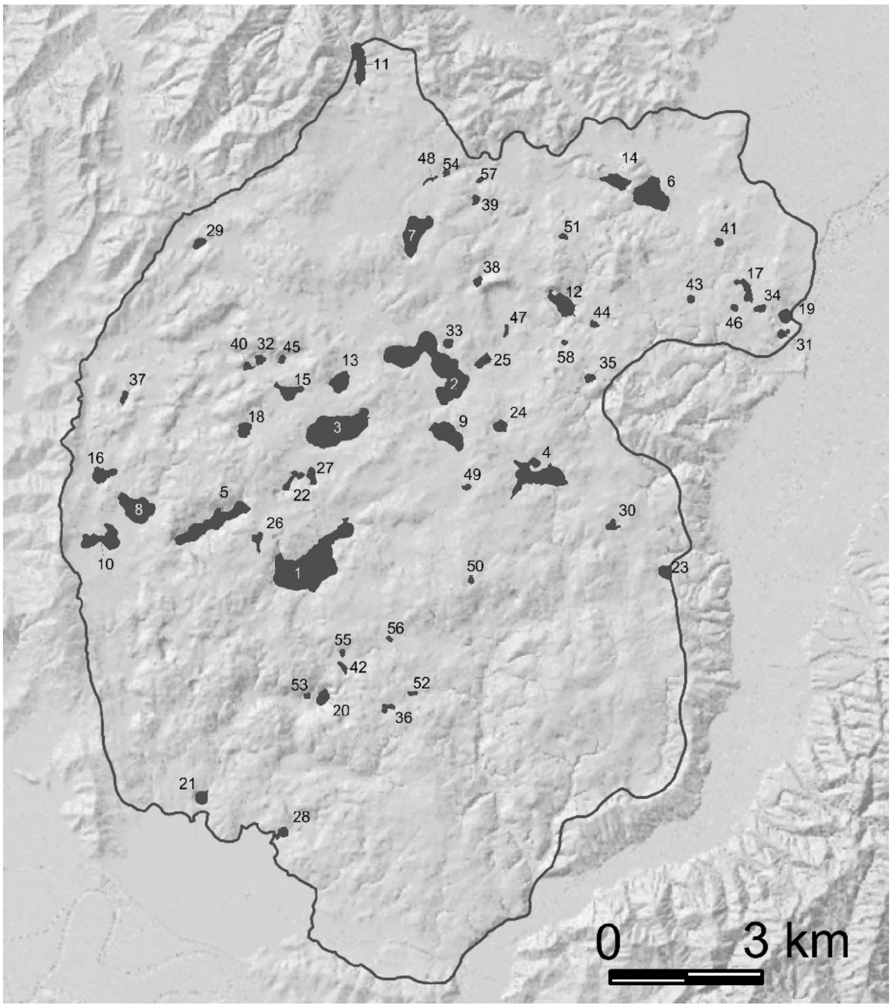

Fig. 13. Lakes of the Dumre area

There are 121 water bodies within the area, most of which are associated with karst; on the figure above 57 lakes of karst origin >1 ha in area are shown; numbers are explained in Table 1

KARST AQUIFER AND SPRINGS

The hydrogeology of the Dumre area is controlled by the presence of the karstified gypsum deposits overlain by a caprock layer. The caprock is represented by various materials, from cultivated soil layers to cemented conglomerates with varying degrees of lithification (Fig. 4), but is normally quite permeable. The caprock thickness at the top of gypsum hills is usually limited, up to several metres, but increases to a few tens of metres in the depressed areas. Easy infiltration results in the general absence of surface flow, excluding the nearly 10 km long Ververrica River in the southeastern part of the gypsum plateau (Fig. 16). The infiltrated water moves more or less vertically across the vadose zone in the upper part of the caprock until it reaches the phreatic zone developed in its lower part and at the top of the gypsum deposits (Fig. 17B).

The dominant groundwater flow direction in the Dumre plateau is towards the Thana artificial lake located in the southern edge (Figs. 16 and 17A). Discharge occurs through small and large springs commonly arranged along the lake shores, and subaquatic springs.

Small springs (Fig. 17A, C) discharge through the caprock deposits. Discharges of individual small springs vary from <0.1 to ~1.0 l/s, but along the spring lines at ~200 to 400 m the total discharge can reach 10 to 30 l/s.

Large springs (Fig. 17C, D) emanate from caprock consisting of cemented but fissured and karstified carbonate blocks of a total thickness 20–40 m. The springs appear and disappear according to the fluctuation of the Thana Lake level, the yearly amplitude of which is 8 to 10 m (Fig. 17B).

Subaquatic springs flow into Thana Lake and two of them, shown in Figure 17A, are easily visible; one is at a distance of 4–5 m from a large shoreline spring, and the other one effuses several hundred metres away from the shore. Their discharge is thought to be highly variable. The observed large variability of the shoreline springs' discharge reflects the seasonal variation of the rains, but is also influenced by the conduit nature of permeability of the gypsum-caprock aquifer.

The quality of surface and groundwater of the Dumre gypsum plateau has not been greatly studied. Table 2 show the results of four chemical analyses, from three springs and Black Lake (Table 2). Microcomponents that have concentrations smaller than the sensitivity of the analyses (Be^{2+}, Fe^{2+},

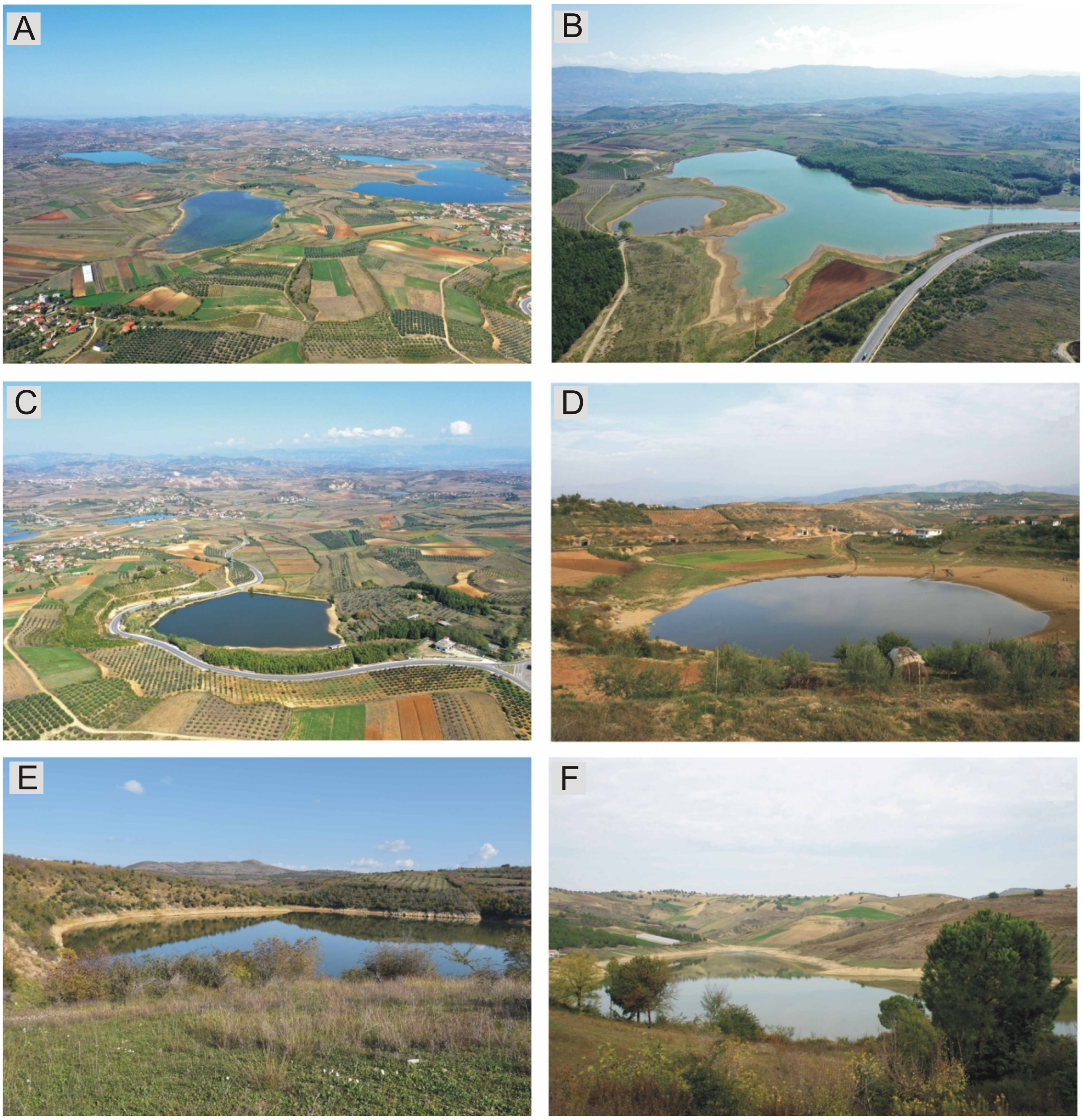

Fig. 14. Some examples of natural lakes that occupy karst depressions within the Dumre area

A–**C** – bird's eye view by drone; **D**–**F** – landscape view (picture E is Black Lake)
(photos by: A–C – A. Klimchouk, D, F – V. Andreychouk, E – R. Eftimi)

Mn^{2+}, Ag^{+}, $Zn^{2,}$ Cu^{2+}, Ni^{2+}, Co^{2+}, Pb^{2+}, Hg^{2+}, Se^{2+}, Sb^{3+}, Al^{3+}, Cr^{3+}, V^{5+}, Zr^{4+}, As^{3+}, Tl^{4+}, W^{6+}, Br^{-}, I^{-}, and CO_3^{2-}) are not included in the table**.**

Up to some 25 years ago, anthropogenic pressure has not been significant in the study area; even the water of Belsh Lake was used for drinking (Parise et al., 2008). The development of tourism and the intensification of agriculture has resulted in heavy pollution by anthropogenic liquid wastes, herbicides, and pesticides (Cane et al., 2010). Nevertheless, the total dissolved solids (TDS) in the water of most of the lakes is <300 mg/dm^3 (Cane et al., 2010). The only exception is Black Lake, located near Thana Lake and at the same elevation. The Black Lake water represents a mixture of atmospheric precipitation and the Dumre area groundwater draining into it, resulting in TDS values reaching 1700 mg/l (Table 2).

The water of small springs draining from the caprock of the plateau are weakly mineralised; the TDS values are ~300–400 mg/l and the hydrochemical facies is mostly HCO_3-Ca. Small springs are usually used for village water supply. The water quality of the springs flowing into Thana Lake is quite different: the water conductivity varies from 1900 to 3400 µS/cm and the water chemical type is SO_4-Ca, but with increased concentration of Cl ions (200–250 mg/l) and Na ions (140–150 mg/l). This shows that the rock mass hosting the

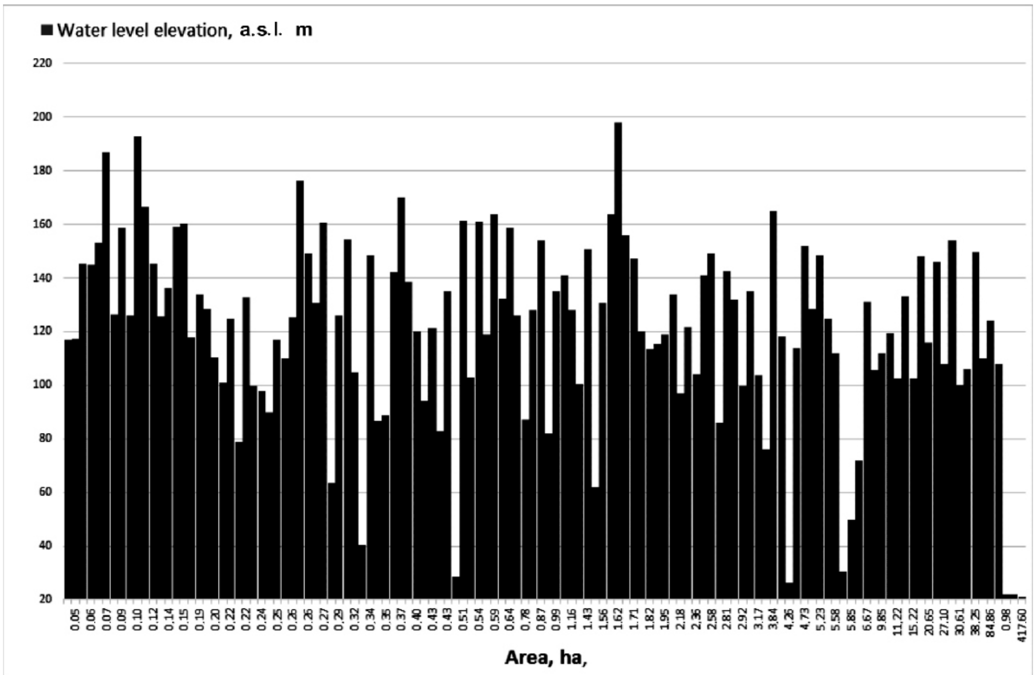

Fig. 15. Water table levels in the lakes of the Dumre area in relation to their surface

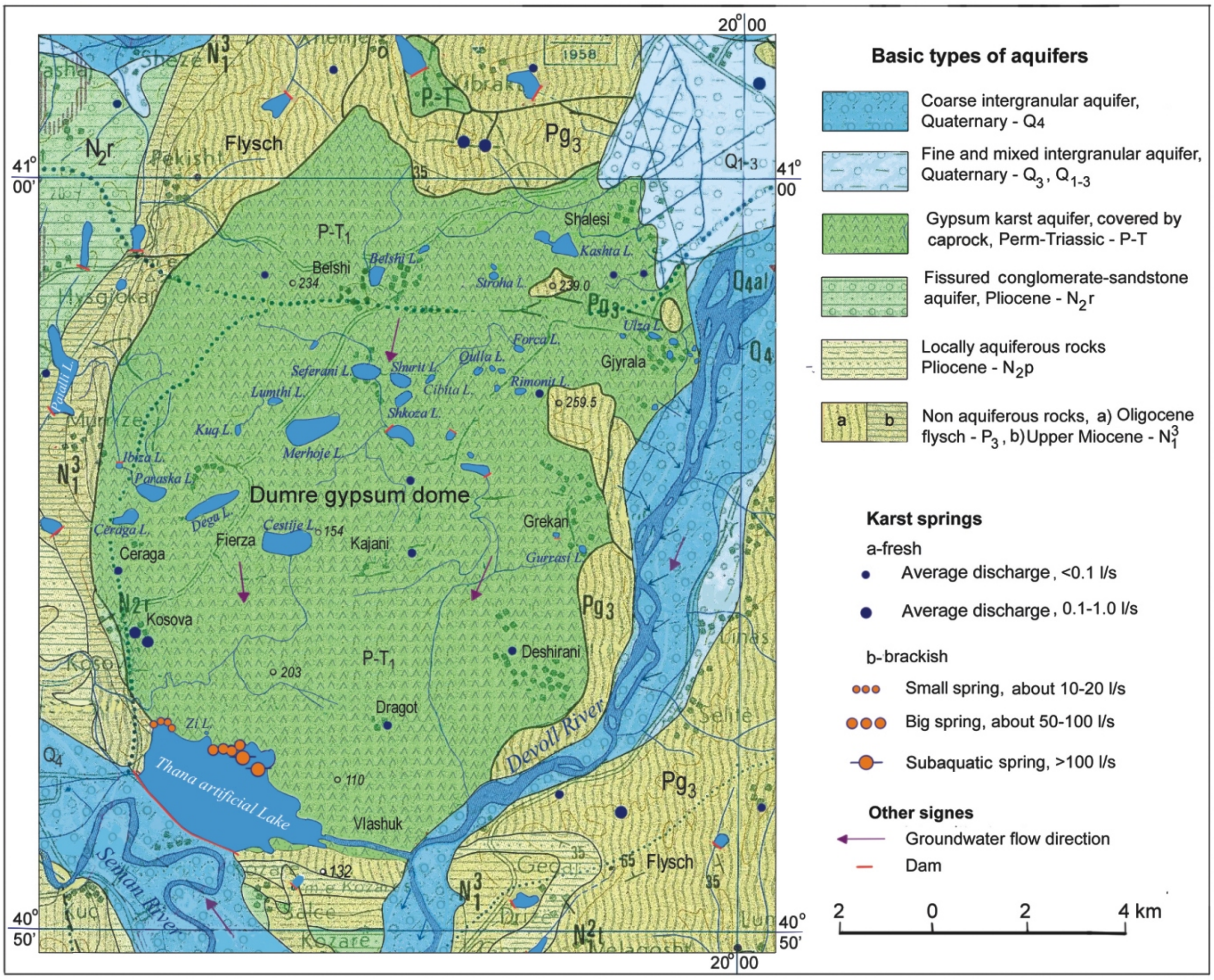

Fig. 16. Hydrogeological map of the Dumre gypsum dome (Eftimi et al., 1985)

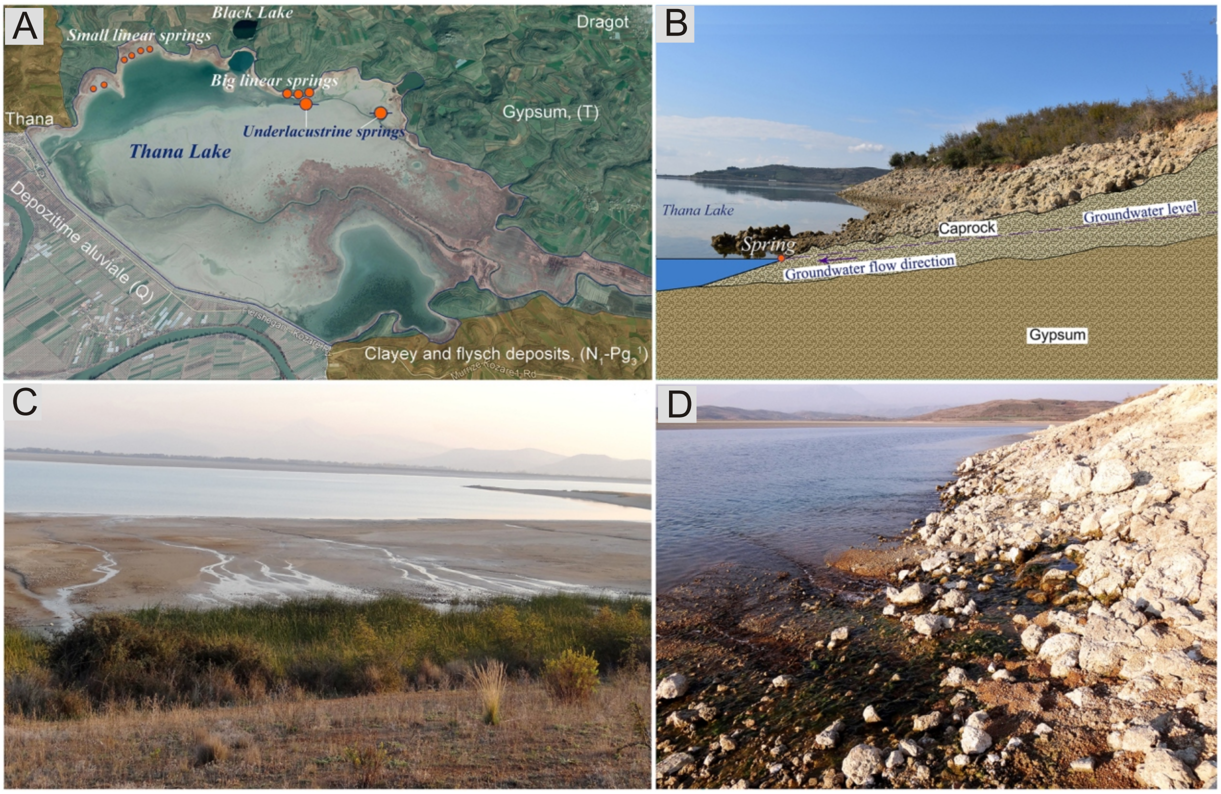

Fig. 17. Springs discharging from the Dumre gypsum plateau in the Thana artificial lake

A – location of springs; **B** – the principal discharge scheme of large springs; **C** – the area of small linearly arranged springs; **D** – a large spring, a part of a linear series of springs (photos by R. Eftimi)

Dumre aquifer contains dispersed NaCl or salt bodies. Solution of NaCl salt is thought to cause the formation of karstic porosity in the upper gypsum layers in the boundary zone with the caprock. The temperature of the springs is 15–16°C, which is equal to the average yearly air temperature of the study area. This demonstrates the shallow circulation of the groundwater of the Dumre area.

DISCUSSION

WATER CIRCULATION AND CHEMICAL DENUDATION

Of key importance for understanding the mechanism(s) of karst development in the study area is the determination of the nature and specificity of the water cycle, with particular emphasis on the water-rock interaction. So far, the lack of specialised research and specific data in this area does not allow the construction of quantitative or qualitative models of water circulation. Therefore, the considerations presented below are preliminary.

The study area is fed almost exclusively by meteoric waters. From the east and south, the area is limited by river valleys that set local erosion bases, and from the north and west by hill ranges rather than by depressions, the orientation of which excludes significant amounts of surface water inflow. No permanent river flows into the study area from these sides. Due to these circumstances, the recharge in the area is entirely autogenic.

Due to a large number of closed depressions, an substantial part of the precipitation water is stored in lakes. The fractions of evaporation, abstraction, and infiltration can be only approximately estimated at this stage of study.

An important feature of the Dumre area is the different elevation of the water table between individual lakes (Table 1). At the same time, the difference in elevation reaches several tens of metres or even 100–160 m. It is obvious that the elevation of the water table in the lakes correlates with the general inclination of the relief towards the south, as illustrated by the hypothetical profile in Figure 18. However, it commonly happens, and seems to be a rule, that even in lakes adjacent to each other the difference in elevation is significant (Qirjazi, 2019). This is particularly evident in the case of a “cluster” of a dozen lakes in the eastern part of the area that form a fairly compact spatial group, in which levels of the water table differ by several tens of metres. This clearly indicates that the water levels in the lakes do not directly correspond to the water table within the karst aquifer, but point to the large diversity of local conditions of water accumulation in the depressions, and its retention therein.

The only reason of this, as well as for the occurrence of the lakes within the karst area, above the karst aquifer, may be the presence of effective isolation of the water body by a clayey layer in the lake bottoms. As noted earlier, the caprock mass, comprising much residual dispersed material, may by source of clays accumulating in the lake bottoms. The other source could be clayey material which has been supplied from the flysch hills (ranges) surrounding the Dumre area. Whichever it was, the weak permeable layer in the lake bottoms effectively isolates

Table 2

Hydrochemical parameters of underground (1–3) and surface (Black Lake) waters from the southern part of the Dumre area

Parameter, component	Unit	Sample no. 1	Sample no. 2	Sample no. 3	Black Lake
Sampling date	–	13.11.2020	13.12.2020	13.12.2020	09.05.2019
Analysed	–	15.01.2021	15.01.2021	15.01.2021	23.05.2019
Temperature	°C	15.7	15.7	15.7	12.5
pH	–-	6.78	6.78	6.84	7.49
Eh	mV	167	164	161	163
Total dissolved solids (TDS)	mg/dm^3	2636.2	2626.5	2622.0	1735.4
Mineralisation M	mg/dm^3	2824.8	2812.2	2809.2	1907.9
Total hardness (Ho)	mg $CaCO_3$/l	1819.0	1825.0	1792.4	1041.4
Carbonate hardness (Hw)	mg $CaCO_3$/l	309.2	304.4	306.8	282.8
Non-carbonate hardness (Hn)	mval/l	30.20	30.41	29.71	15.17
EC (25)	µS/cm	3410	3410	3420	2300
H_2SiO_3	mg/dm^3	21.09	21.33	21.09	2.34
SiO_2	mg/dm^3	16.23	16.41	16.22	1.80
Na^+	mg/dm^3	148.9	151.0	150.7	139.9
K^+	mg/dm^3	3.15	3.17	3.00	4.25
Li^+	mg/dm^3	0.051	0.050	0.051	0.043
Ca^{2+}	mg/dm^3	612.9	613.9	602.0	333.6
Mg^{2+}	mg/dm^3	70.42	71.25	70.55	50.80
Sr^{2+}	mg/dm^3	9.16	9.20	9.05	6.214
Fe^{2+}	mg/dm^3	<0.01	<0.01	<0.01	<0.005
Total cations	mg/dm^3	844.7	848.7	835.5	535.3
Cl^-	mg/dm^3	247.3	244.7	245.3	193.0
Br^-	mg/dm^3	<0.1	<0.1	<0.1	<0.2
I^-	mg/dm^3	<0.01	<0.01	<0.01	<0.2
SO_4^{2-}	mg/dm^3	1313.0	1304.0	1311	829.0
HCO_3^{2-}	mg/dm^3	377.2	371.4	374.3	345.0
CO_3^{2-}	mg/dm^3	<0.5	<0.5	<0.5	<0.5
NO_3^-	mg/dm^3	21.17	21.57	21.26	1.50
PO_4^{3-}	mg/dm^3	0.0277	0.0134	0.0115	<0.02
BO_3^{3-}	mg/dm^3	0.29	0.27	0.28	1.07
HBO_2	mg/dm^3	0.22	0.20	0.21	0.79
Total anions	mg/dm^3	1958.8	1942.0	1952.4	1369.5
Total analysis	mg/dm^3	2803.5	2790.7	2728.9	1904.8
Hydrochemical type	–	SO_4-Ca	SO_4-Ca	SO_4-Ca	SO_4-Ca-Na

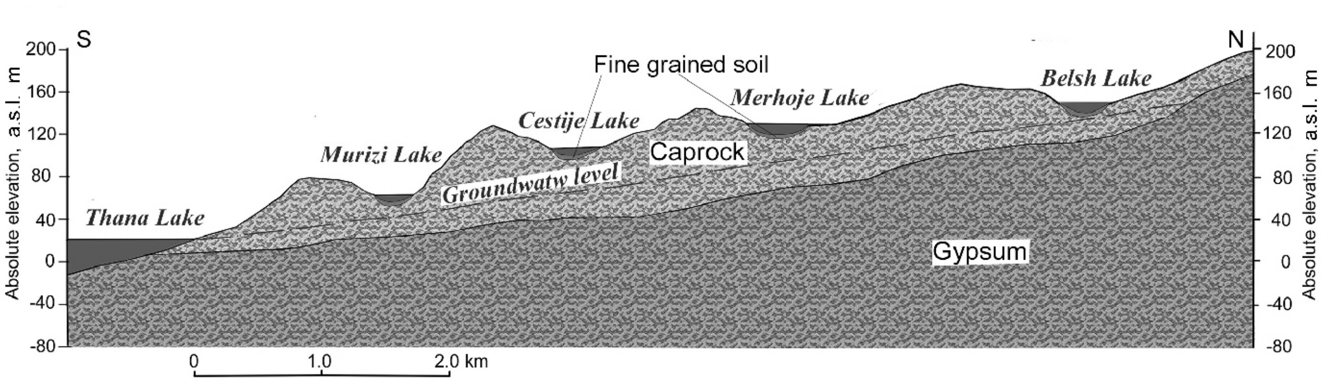

Fig. 18. Hypothetical profile illustrating the diversity of water tables in the lakes and showing the level of groundwater inclined towards the south

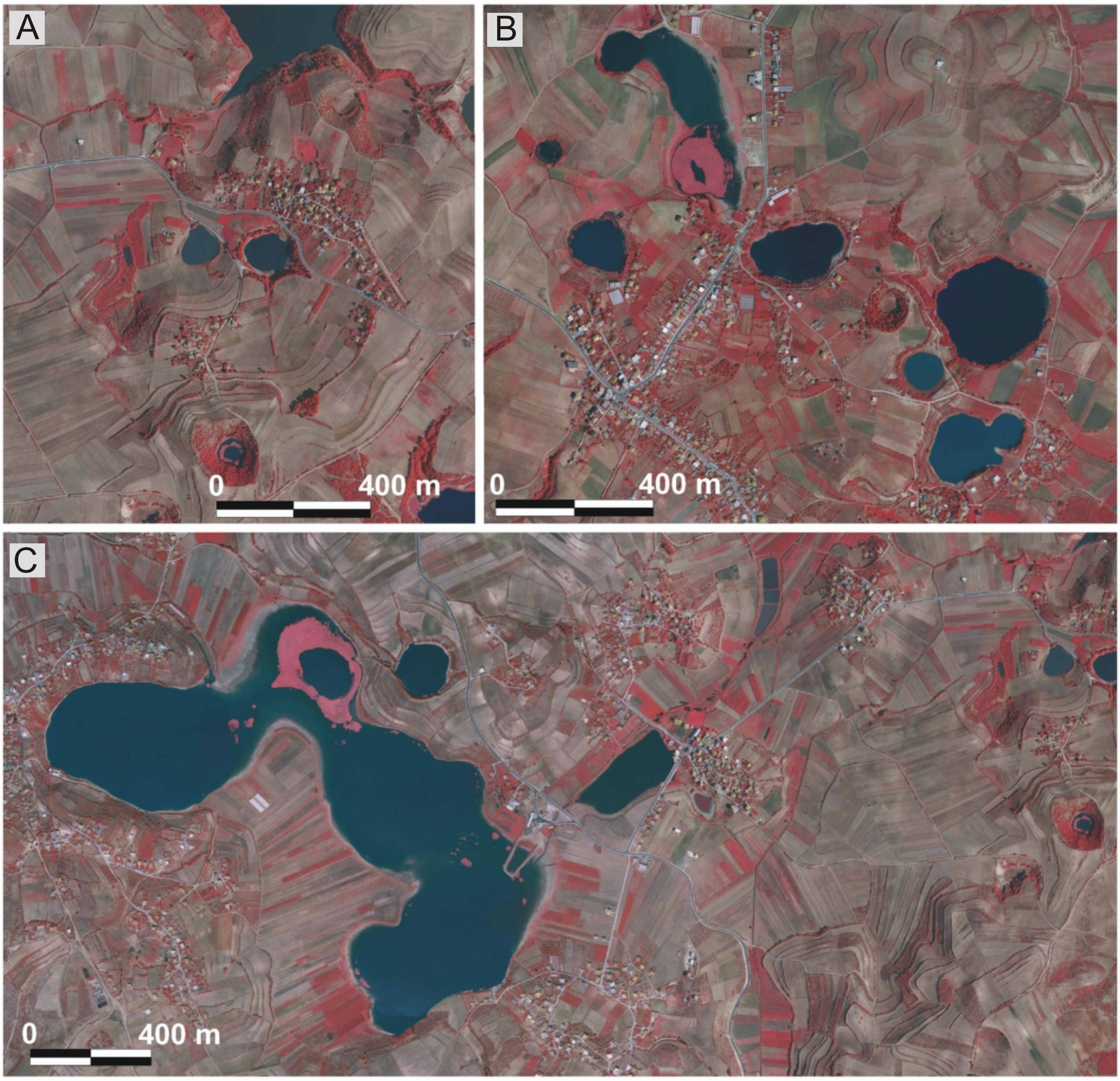

Fig. 19. The lakes in the central part of the Dumre area on the orthophotomap

A, **B** – relatively small lakes occupying sinkholes and large solution dolines; **C** – an example of larger lakes occupying the bottoms of karst depressions

them from the gypsum substrate, leaving them perched above the groundwater table (Fig. 18).

Nevertheless, there are lakes, mainly in the extreme south of the area, the lowest situated and adjacent to the artificial reservoir, which are undoubtedly directly associated with the karst aquifer in the gypsum. The fact that they reflect the surface of karst waters is indicated by their geomorphological (steep banks) and hydrological conditions (they correlate with the water table in the Thana reservoir), as well as by the high sulphate ion content (Table 2). Blake Lake, located a short distance from the shoreline of the reservoir, is the best example of such a lake (Fig. 17A).

The water balance and chemical denudation within the Dumre area can be accessed in the following way. As allogenic surface flow is missing, the water balance can be defined as:

P (precipitation) = effective infiltration (I_{ef}) + evapotranspiration (E)

Applying the Turc method (Turc, 1954; Bonacci, 1999), the components of the balance are:

P = 1054 mm/year (equal to 179.18 x 10^6 m^3/year, or 5.69 m^3/s);

I_{ef} = 586 mm/year (equal to 99.62 x 10^6 m^3/year, or 3.16 m^3/s);

E = 468 mm/year (equal to 79.56 x 10^6 m^3/year, or 2.53 m^3/s).

As defined by balance investigations (Vogli, 1980), about one third of the infiltrated precipitation, ranging to 33.20 x 10^6 m^3/year (or 1.02 m^3/s), goes to recharge the lakes of the gypsum plateau. The rest of the effective infiltration comprises the total groundwater resources for the entire Dumre area, estimated at) 67.42 x 10^6m ^{3}/year (or 2.14 m^3/s. Supposing that the total discharge of all non-subaqueous mainly fresh springs is 0.3 m^3/s, the total discharge of the subaqueous springs (known and unknown) is estimated at 57.96 x 10^6 m^3/year (or 1.84 m^3/s).

Based on the results of the chemical analyses the mean dissolved gypsum is 1.9 g/l and mean dissolved NaCl is 0.4 g/l. The mean flow rate of the subaqueous springs is calculated at 1.84 m^3/s. The density of gypsum is 2.3, and that of rock salt is 2.17 (Chiesi et al., 2010), thus the total volume of dissolved gypsum per year is 47.420 and 10.680 m^3 for salt. These values allow one to quantify the total volume of dissolved material released by the subaqueous springs in one year: 58.100 m^3. This would correspond to a cubic volume of 38.7 m along each side.

MORPHOGENESIS AND EVOLUTION OF KARST FORMS

The landscape development of the Dumre area is complex. During its evolution under continental conditions since the Pliocene, morphogenetic factors have changed. There is no doubt, however, that a leading role was played by karst processes, although their participation in shaping the landscape may have been different at different stages.

The contemporary characteristics of the landscape, i.e. low hypsometry, moderate denivelations, dominance of large elements – both convex (hills) and concave (depressions) – the monadnock character of gypsum outcrops, the flattened bottoms of major depressions, the lack of active ponors in the valleys of the rivers and streams, and the presence of a large number of lakes, collectively point to its mature character. Due to a significant degree of cover of the gypsum substrate by residual weathering material, as well as the resulting isolation of the karstic substrate from the direct impact of precipitation and surface waters, the dissolution processes currently occur almost exclusively at depth, in the karst aquifer zone within the gypsum. These result in the formation of cavities, which are revealed from time to time in the form of small sinkholes in caprock deposits and in the bottoms of old depressions. By contrast, widely understood erosive processes play a dominant role in shaping the landscape. In the surface zone, karst processes *per se* take place only within the outlier gypsum hills.

The most characteristic elements of the landscape are depressions of various types and sizes, often filled with water and forming lakes (Fig. 19). The basins of all the lakes are of karst origin, and the larger the lake, the more complex has been its history. The formation of the smallest and probably the youngest lakes can be clearly explained by collapse/subsidence processes. Such a genesis is indicated by their round shape, considerable depth and steep banks. In the formation of larger lakes, the processes of slow dissolution of the gypsum substrate may have been important, if not decisive. As for the basins of the large lakes in extensive depressions, these have a complex and multi-stage genesis, in which various processes and factors participated at various stages of development. At the beginning, the leading factors were dissolution, ground subsidence, and collapse of the roofs of the forming karst cavities, with subsequent evolutionary merging of adjacent dolines, erosional shaping, and accumulation of inwashed material. Significant numbers of depressions within the study area; their closed character in most cases, a large surface of weathered hill slopes, and the lack of larger rivers draining the area mean that there is a progressive accumulation of inwashed residual material within the area, mainly in the depressions. This results in a gradual rise of their bottoms, a decrease in the relative depths of the valleys, and an increase in the thickness of the insoluble cover over the gypsum substrate.

These factors are currently conducive to the retention of rainwater within the area and the formation of lakes, and partly also to the revival of the river network degraded by karst. Over time, these trends would lead to a decrease in the depth but an increase in the size of the lakes, their merging and overflow into other catchments, thus forming new watercourses.

Nevertheless, at any given stage, significant resources of surface water accumulated in the lakes facilitate rational land cultivation, primarily for agriculture. As for groundwater, regardless of the considerable resources, the quality of karst water (too high mineralization) significantly limits the possibilities of their use.

CONCLUSIONS

The Dumre area of Central Albania is distinguished by a specific geomorphological landscape, whose main features include low altitudes, a mosaic character, irregularity, and the presence of a large number of lakes. These features are a consequence of the development of karst related to the presence of a tectonically conditioned “stock” of Triassic evaporites. Gypsum karstification has been ongoing since the Pliocene and the present-day geomorphological character of the area points to an advanced, mature stage of karst evolution. The widespread prevalence of large depressions, a significant number of which are filled with water (lakes), the occasional presence of gypsum hills in the form of monadnocks, a thick “coating” of residual deposits largely isolating the karstic gypsum substrate from the influence of precipitation and surface waters, the intermittent nature of a degraded river network, and others signs indicate that karst is mature in the area.

This study reveals the conditions of the development of the gypsum karst in the area and determines its main features and spatial peculiarities. However, the study is preliminary in nature, to attract researchers’ attention to an extremely interesting region, detailed study of which can provide valuable information not only regarding karst science but also for regional geology, hydrology, hydrogeology, and geomorphology. The principal tasks for further research include:

- determination of the thickness and structure of the caprock through geophysical studies according to a selected grid of profiles;
- inventory of karst forms and their classification according to size, shape, water level, origin, and economic utilisation;
- detailed field studies within gypsum monadnocks – determination of the degree and character of their karstification, organization of monitoring elements (benchmarks, markers, mini-meteorological stations, etc.);
- formulation of the water balance for the entire area in the annual and seasonal cycles, as well as for selected elements (catchments, depressions);
- monitoring of karst springs in order to determine the amount of chemical denudation and its seasonal variations;
- detailed studies of the lakes, including pollution of their waters.

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