

DATA FOR THE GEOECOLOGY OF SOLUTION KARST DOLINES, WITH PARTICULAR ATTENTION TO CLIMATIC, SOIL AND BIOGENIC ENVIRONMENT

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Summary: The appearance and spatial distribution of the solution dolines of the temperate karsts are closely related to the climatic conditions of the temperate zone and its ecological characteristics. The basis of the classical geomorphological classification of dolines was the characteristic geological condition and the resulting form. Doline formation is shaped by the processes of complex geoeological factors (rock, climate, water, soil, vegetation). Dolines are vulnerable spots in karst areas. The environmental load originating from anthropogenic utilization endangers the natural course of corrosion and the quality of the non-renewable resources of karsts as well as karst ecosystem services, therefore, a complex assessment is necessary for revealing the changes. The study investigates the affect of some important geoeological parameters on the development of solution dolines.

Key words: karst dolines, geoeology, climate, soil, biogenic environment of dolines

1. INTRODUCTION

The specific morphology and phenomena of karsts were observed by the ancient thinkers of the pre-Christian period, and from the 16th century on, natural scientists interpreted the phenomena of limestone mountains as karst phenomena (Pfeffer 2010). In Slovenia, Valvasor wrote about the characteristic closed depressions of karsts in the 17th century (Kranjc 2013). Haquett (1778) already referred to karst dolines as “kessel”. In the 19th century, the study of karsts became common among geographers and geologists. This era was also designated the appearance of the term “karst rock” on the geological map of the Istrian peninsula, and researchers considered karst dolines to be the consequences of weathering (Prestwitz 1854).

In the late 19th century, Cvijic (1893) was the first to define karsts in his work “Das Karstphaenomen” and characterized the micro-karren, dolines, uvalas and poljes of karst areas. The literature considered the period between 1888 and 1927 to be “the golden age of studies in the Dinaric Karst” (Ford 2015). The scientific research of karsts began with the work of Cvijic. In this period, most researchers described dolines based on their external morphology, and their formation was explained by a dissolution process (Gortani 1908, Lugeon and Jérémime 1911). Karst morphological research made a long way during this period. The study of the interaction of karstic and non-karstic rocks, the interpretation of hydrogeographic conditions, the tracing of dissolution processes to climate and different environmental factors provided a significant opportunity for modern karst morphology (Grund 1904, Katzer 1909, Terzaghi 1913). Comparing previous theories, Cramer (1939)

created a genetic-based doline system in which he distinguished solution dolines and collapse dolines.

Lehmann O (1931) and Lehmann H (1954) considered solution dolines to be the characteristic form of temperate climatic areas. The International Karst Commission, established in 1953, prioritized the climate-specific assessment of karsts. In the 1950s, most researchers studied the location of karst water level, interpreted the chemical processes of karst dissolution, and mixing corrosion (Bögli 1960). In addition to the analysis of climatic conditions, the topic on the role of biogenic carbon dioxide in corrosion was also raised. The vegetation covering the surface and the humus-rich soil significantly modify the amount of the carbon dioxide content of soil air that is dissolved in groundwater, and thus the intensity of karst corrosion. The enrichment of the carbon dioxide content of soil air, in addition to temperature and precipitation, depends on the local vegetation, soil organisms, soil properties, and soil diffusion capacity. The study of the chemical properties of corrosion came to the fore (Priesnitz 1968, Bakalovicz 1977, Trudgill 1977). Maximovich (1963) described suffusion dolines of covered and uncovered karsts. Groschopf and Kobler (1974) found that the shapes are similar due to climatic effects and ecological conditions even under different geological conditions.

Representatives of the dynamic karst morphological trend (Haserodt 1965, Sweeting 1972) also pointed out early that the factors causing karstification are more complex than those formulated by classical geomorphological trends. Dolines were also considered diagnostic forms of karsts, which are natural closed depressions, usually circular in shape, a few meters to 1000 m in diameter, and a few meters to some 10 m in depth (Gams 1974, 2000, Sauro 2005, Ford and Williams 2007). In the genetic understanding, we distinguish solution (corrosive), collapse (gravitational), clayey sediment-overburdened (suffusion) and subsidence dolines. Expanding the range of the previously listed types, Williams (2004) wrote about soil dropout, buried and caprock dolines. Later, Sauro (2012) defined a specific type of dolines that deepens into cave fill as an intersection doline.

The geocological study of karsts has become more and more highlighted for a few decades. Geoecology is a holistic frontier science between geography and biological ecology that studies the formation, development and changes of different landscape types under natural and anthropogenic influences in space and time. The material and visual appearance of the changed landscape expresses the characteristics and state of the long-term development of the area. Thus, geoecology presents the landscape formed as a result of the changes, regardless of whether it has retained its original values or has been significantly transformed by human intervention. Dolines are the ecotopes of karst landscapes, where it is possible to study the specific environmental conditions in a complex way.

Previous morphological studies of karst depressions were refined by morphometric analyses (La Valle 1967, Williams 1972, Bárány and Mezősi 1978, Bárány Kevei and Mezősi 1991, Castiglioni 1991, Sustercic 1994, Hoyk 1999, Péntek and Veress 2007). In the 2000s, these morphometric assessments contributed to a better understanding of doline development, as well as to the exploration of different environmental effects and ecological conditions (Telbisz et al. 2009, Mix and Kúfman 2011, Basso et al. 2013, Ramsey 2015). Data that can be generated by remote sensing are also gaining more and more significance in karst research. In combination with field measurements, accurate topographic models can be generated from large-scale aerial photographs using digital photogrammetry, which allow the accurate determination of corrosion surfaces (including dolines) (Zboray and Keveiné Bárány 2004, 2005, Zboray 2007).

In recent decades, the exploration of karst areas using GIS and the creation of databases have become more and more popular (Gao and Alexander 2003, Siska and Kemmerly 2007, Telbisz et al. 2007, Lipmann et al. 2008, Kobal et al. 2014). These data help predict the occurrence of geohazards (Bruno et al. 2008). Nowadays, the frequent collapse of dolines has aroused the interest of researchers (Galve et al. 2009, Gutierrez et al. 2014, Siska et al. 2016). Human interventions (e.g. urban development, agriculture, quarrying, road construction, etc.) significantly disrupt the activities of the natural geoecological environment of karsts.

The data of morphometric parameters collected in the studied dolines of the Mecsek, Bükk and Aggtelek mountains proved that the sediments filling the dolines, the elongation of the dolines and the accumulation of clay reduce the corrosion of the doline bottom, while the corrosion of the doline slopes is accelerated by the same processes. Simultaneously with the growth of dolines, the asymmetry of dolines increases due to geoecological factors (Bárány Kevei et al. 2015)

The ecosystem services of karsts, the different socio-economic characteristics, and the significant differences in the spatial pattern of karsts form an important part of contemporary karst research. Dolines are also prime sites for the study of the geodiversity of karsts and, thus, of the correlations between ecosystem services and geodiversity (Corenblit et al. 2011, Kiss et al. 2011, Goldscheider 2012, Keveiné Bárány and Kiss 2018). As dolines are typical representatives of the aesthetic values of karsts, their research in this direction still offers a lot of opportunities for researchers.

The present study highlights the typical trends of changes in the effects of microclimatic, soil, and biogenic (primarily vegetation) factors that create spatial imbalances in the functioning of degradation processes in dolines.

2. GEOECOLOGICAL INTERPRETATION OF DOLINES

The geoecological system of karsts is a complex system (Bárány Kevei 1998ab, Daoxian 2001, Venhua and Jianhua 2015, Phillips 2016). The geoecological system of dolines (as a local subsystem of karsts) is a structural and dynamic system in which the abiogenic elements are rocks, water, soil, macro- and microclimate, while the biogenic elements are micro- and macroflora, and man. The operation of the system is ensured by the interaction of abiogenic and biogenic factors, as well as the flow of matter and energy generated during the interaction. Its structure is determined by the three-dimensional arrangement of the elements. Its specificity is its vulnerability and the rapid course of processes (Bárány Kevei 2016). In the geoecological sense, dolines are “hot spots” in karst areas, where geoecological factors and processes (rock type, topography, microclimate, soil processes, plant species and human activity) change the dissolving effect of infiltrating water, which also causes the rate of development of surface and subsurface forms change.

2.1 The role of climate in shaping the geoecological character

Climate is a morphogenetic factor in the process of karst rock degradation, an eco-factor that ensures the dynamism of the karst system (Jakucs and Bárány Kevei 1984). Changes in rainwater affect the solution process and hydrological system of karsts. Under the influence of the macroclimate in the karsts, the specific microclimate spaces of the

dolines, the spatial and temporal differences of energy intake cause significant differences in the geocological processes of the karsts (Keveiné Bárány 2009). Climate change is a much more significant stress factor in karsts than in non-karst areas (Meixian et al. 2016). Extreme meteorological events in recent decades have also affected the geocological state of dolines as a result of global climate change.

Since the middle of the last century, researchers have been studying the microclimate processes of karsts (Schmidt 1930, Bacsó and Zólyomi 1934, Reicher 1936, Lauscher 1937, Horvát 1953, Geiger 1961, Sauberer and Dirmhirn 1954, Wagner 1964, Yoshino 1984, Bárány Kevei 1967, 1985).

In the microclimate of dolines (Bárány Kevei 1999), the exposure effect occurs in the solar irradiance period (but the amount of energy per surface unit is also modified by the slope incline). The steep and north-facing slope has a larger radiation deficit than the south-facing northern slope. The daily amount of radiation is the highest both in January and July on the south-facing slope. From sunrise to 9 a.m., the east-facing slope receives more radiation than the south-facing slope, and, in the afternoon, the west-facing slope is in a more favorable radiation position. In the north-west section, the same amount of radiation reaches both slopes, but in the daily course, the east-facing slope receives stronger radiation in the morning, while more energy arrives on the west-facing slope in the afternoon.

Examining the amount of energy per surface unit of the northern and southern slopes of a Bükk doline without forest (the positive with of the sun was 25° the average extincio was 3.1), we determined the amount of energy per surface unit every hour, with full knowledge of the slope angles. Obviously, there was a big difference between the amount of energy received concerning the northern and the southern slopes. While the temperature rise on the valley floor, where the doline is located, is 10°C an hour between 5 a.m. and 6 a.m., most of the doline is still in self-shade. Solar irradiance in the doline starts on the north-facing slope first, when the position of the sun is still low, therefore the radiation surplus is not significant. Then the east-facing slope begins to warm up with a significant excess of radiation. On a clear summer day, between 8 a.m. and 9 a.m., the global radiation on the eastern slope is 2.688 MJm^{-2} , in the same period it is 1.570 MJm^{-2} on the western exposure and 1.896 MJm^{-2} on the bottom of the doline. After a short isothermal state, from 7 a.m., the nocturnal inverse thermal stratification is replaced by the straight thermal stratification characteristic of the irradiation type. At the same time, the temperature maximum is transferred from the east-facing slope to the south-facing slope, where the temperature excess of the south-facing slope is $4\text{--}5^\circ\text{C}$ from sunrise to 8 a.m. On the east-facing slope, the culmination maximum occurs as early as 10 a.m., while it occurs on the south-facing slope around midday. On the east-facing slope, air humidity does not follow the expected temperature changes, because air humidity increases on this slope between 6 and 11 o'clock in the morning due to the evaporation of dew (the intensive transpiration of vegetation also begins), while the drying of dew draws away heat. There is a significant difference in the amount of global radiation between the northern and southern slopes. South-facing slopes receive approximately 18% more radiation during the day than north-facing slopes (Whiteman et al. 2004).

A specific microclimate phenomenon is the process of the formation of a cold air-pool (cold air lake) filling dolines at night (Petkovsek and Rakovec 1983, Maki and Harayama 1988, Bárány Kevei 1999, Clements et al. 2003, Whiteman et al. 2004, Keveiné Bárány 2011, Litschmann et al. 2012, Caputa 2016, Ogrin et al. 2018, Vilović et al. 2019, Quintero-Ruiz et al. 2019). Studying the strong cooling down of the early self-shaded slopes

at the bottom of the depressions, it was found that due to the horizon limitation diffuse radiation is reflected from the adjacent surfaces on the shaded (Caputa and Woykowski, 2015), which plays a decisive role in the formation of minimum temperatures. Colder air accumulated at the bottom of depressions locally buffers the effects of climate change, so these small areas can act as micro-refugia for cold-tolerant species (Bátori et al. 2009, 2014, 2019, Maclean et al. 2015).

Although the microclimate of dolines is characteristic on summer days, it is also worth examining the temperature course of a winter day (Fig 1). The graph shows the daily temperature course at the bottom of a Bükk doline (17 March). The daily amplitude on the doline bottom was in the negative temperature range with -22.8°C (during the summer measurement this amplitude usually exceeded 25°C at the bottom of the Bükk dolines). Both winter and summer temperature maxima and minima show very extreme values.

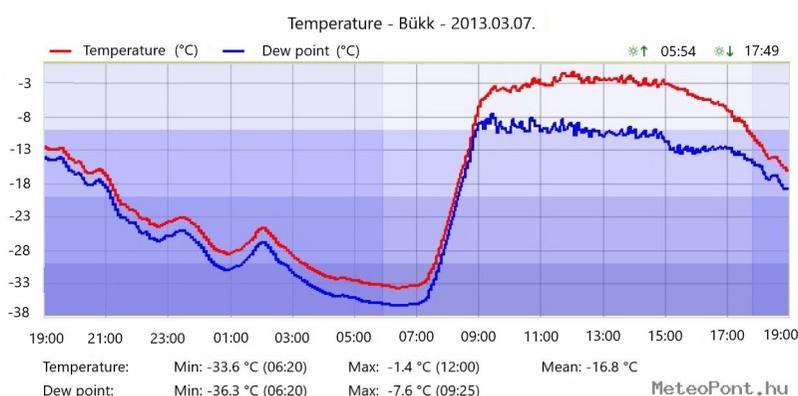


Fig. 1 Daily air temperature (top red line) and dew point (bottom, blue line) in winter in a Bükk doline (Kerékgyártó 2016)

The course of soil temperature in dolines is less studied than air temperature, despite the fact that it is important for biogenic processes (vegetation root respiration, bacterial activity). Soil temperature amplitudes (at soil depths of 2, 5, 10, 20 and 30 cm) show a remarkably large difference between soil temperature minima and maxima within a few 10 meters (Fig. 2). The size of the soil amplitudes of the southern and western slopes is much greater than those of the northern and eastern slopes when the sample comes from near the surface (the amplitude is three times bigger on the eastern slope than on the southern slope). The southern and western slopes have lower daily temperature fluctuations, air temperature and humidity are lower, and snow cover periods also last longer. The microclimate characteristics of the slopes with different exposures differ significantly, which changes the quality of soil processes too (Wagner 1964, Bárány Kevei 1999).

As climate, soil and vegetation in karsts affect the corrosion process in an integrated geocological relationship; the topic is still at the forefront of international and national research. Either factor changes, it affects the other two factors and vice versa. The soils redeposited on slopes of different inclines and accumulate at the bottom of the doline. This weakly acidic or acidic soils may also amplify or reduce the intensity of degradation processes.

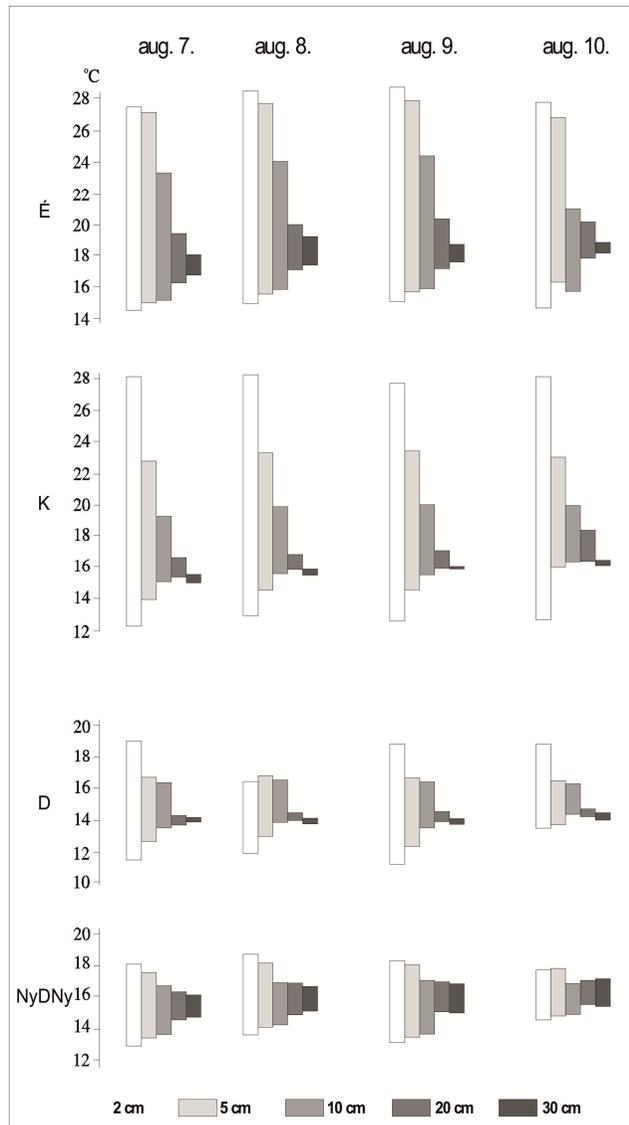


Fig. 2 Differences in soil temperature amplitudes on the slopes of the doline (Bükk Mountains) (on 4 August days) É = northern slope; K = eastern slope; D = southern slope; NyDNy = west-south-western slope (Wagner 1964, Bárány Kevei 1999).

2.2 The geoecological role of doline soils

The near-surface water-permeable, transitional epikarst zone, of which the soil is an important part, plays an important role in karst development (Jones et al. 2004, Williams 2008, Bakalowicz 2014, Móga et al. 2017, Phillips 2018). The importance of the role of biogenic CO₂ in karst corrosion (rock dissolution) was raised early (Jakucs 1971, 1980, Trudgill 1977, 1986, Zábó 1986, Bárány Kevei and Zábó 1986, Ford and Williams 1989).

The CO₂ content of soil air (with a concentration ranging from 0.1 to 10%) plays a dominant role in the solution processes of karsts. This CO₂ comes from the root respiration of higher vegetation and the decomposition of organic matter (Kuzyakov 2006). At the same time, the soil is the indicator sphere of the geo-ecosystem of karsts (Bárány Kevei 1992), it indicates and balances the unfavorable effects coming from outside to a certain extent. In Hungary, the study of karst soils has become more important in the last few decades (Zámbó 1986, Bárány Kevei 1987, 1998a, 1998b, Zámbó and Telbisz 1999, Barta et al. 2009), which is increasingly justified by various environmental loads nowadays.

Soil plays a very important and central role in the complex interaction with the climate and vegetation in terms of changes in the karst system (Keveiné Bárány 2009) (Fig. 3).

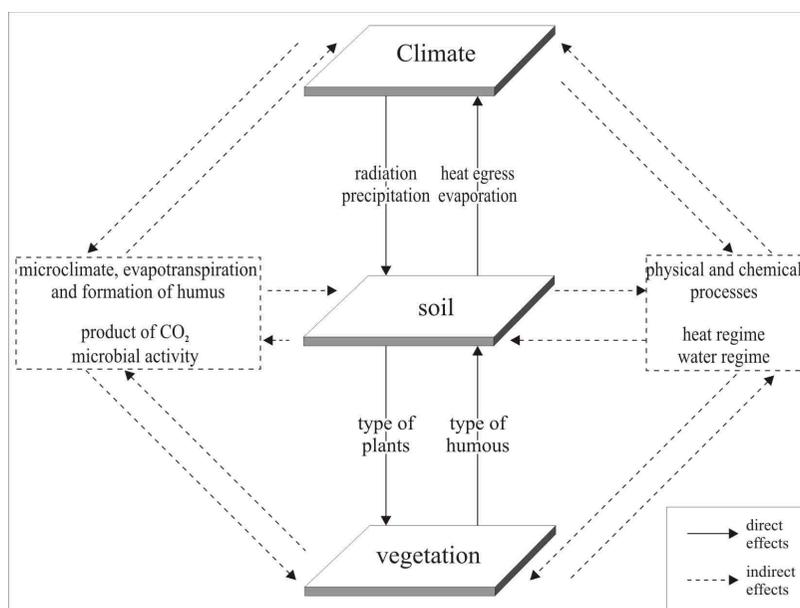


Fig. 3 Interaction within the climate-soil-vegetation systems of karsts

The studied karsts are characterized by the occurrence dark or black rendzina of shallow depths (some 10 cm), mixed with rock debris, with levels A and C. According to the international WRB system (World Soil Reference Base System), these are black rendzina (Mollic Rendzic Leptosol, Humic, Eutric) soils (Barta et al. 2009), but brown rendzina (Leptic Phaeozem) and red clayey rendzina soils (Leptic Luvisol, Humic, Hypereutric, Clayic, Chromic) indicating forest soil dynamics also occur. The red clayey rendzina was formed as a result of previous warm-season soil formation, and now occurs mostly in a redeposited state at the bottom of the dolines. In Hungarian karst areas Luvisols also occur.

2.2.1 Physical and chemical properties of doline soils

The physical properties of soils (structure and fabric) determine the air, water and heat management of the soil, they have an effect on the chemical properties, but they also play a significant role in soil biological processes. Karst soils are not classified very well; the dominant fraction is loam, clayey loam, with a smaller proportion of clay. In the soils of the

dolines located in Aggtelek and Bükk, loam occurs in the largest percentage. Clay accumulates at the deeper levels (50 cm) in larger quantities, and clay can become impermeable at the deepest points of the dolines. In such cases, the corrosion may shift towards the edge of the dolines, and the dolines start widening instead of deepening (Zámbó 1986). An increase in the proportion of sand results in faster water drainage, which facilitates the entry of possible external pollutants into cave passages and karst water.

The pH of soils plays an important role in karstic dissolution (Zseni and Keveiné Bárány 2001). The pH of soils formed on limestone is generally not acidic which is in accordance with the properties of the bedrock. However, its acidification tendency can be inferred from the increase in the difference between the aqueous and potassium chloride soil solution (ΔpH). The value of ΔpH is normal at 0.2-0.5, while values approaching 1.0 indicate acidification. The acidification tendency of the soils of Hungarian dolines has increased since the early 1980s. In the dolines of all three areas (Bükk, Aggtelek, and Mecsek mountains) the difference between the two pH values exceeds the limit at which acidification can be expected. Interestingly, not only are there significant differences in space (on different slopes or at different surface cover), but there is also an increase in the difference between the two pH values over time. In 1982, the ΔpH value was 0.2-0.6, after 5-6 years it was between 0.3-1.3, but it was mostly above 0.7. In the 2000s, this value ranged from 0.47 to 1.16 (Table 1).

Table 1 Average pH values on the three test areas
(The table shows the average of 288 soil samples from 2000)

Location of dolines	pH H ₂ O	pH KCL	pH H ₂ O - KCL
Bükk A	6.40	5.93	0.47
Bükk B	6.50	5.45	1.04
Bükk C	6.60	5.54	1.06
<i>Average</i>	<i>6.50</i>	<i>5.64</i>	<i>0.86</i>
Aggtelek A	5.35	4.36	0.99
Aggtelek B	6.13	5.49	0.64
<i>Average</i>	<i>5.74</i>	<i>4.93</i>	<i>0.81</i>
Mecsek A	5.48	4.33	1.16
Mecsek B	6.04	5.16	0.88
Mecsek C	5.83	4.67	1.15
<i>Average</i>	<i>5.78</i>	<i>4.72</i>	<i>1.06</i>

The pH values of the soils of Aggtelek, Bükk and Mecsek indicate acidic, weakly acidic and neutral pH in absolute values (Bárány 1980, Bárány Kevei 1987b). The soils of Mecsek and Aggtelek are slightly more acidic than those of Bükk. The pH values according to the slopes of the dolines were examined. It can be clearly seen that the pH values are different on the doline slopes with different exposures as well as at the bottom and on edge of the doline. On the southern slope, the values approach a neutral pH, in other places weakly acidic or acidic pH values are typical. Due to the one-way subsidence in the dolines, the soils in the three study areas are acidic or weakly acidic based on hundreds of measured data. Acidious leaching water also dissolves most of the contaminants and delivers them into the system. Although the buffering capacity of soils decreases due to the low lime content, the high organic matter content compensates for the lack of calcium carbonate (Zámbó and Telbisz 1999).

2.2.2 Heavy metal contamination in doline soils

Heavy metals are present in the soil in bound and bioavailable forms and play a role in the changes of soil conditions. When analyzing the heavy metals retention capacity of a soil, the “total” (acid-soluble content) metal content and the potential metal content plants can take up (bioavailable content) should also be considered. As metals can enter the water leaking through the soil, from there into the karst water, they deteriorate the quality of karst water, and, thus, the supply of drinking water to the population of the given area is endangered. It can also be a problem if there are a lot of heavy metals that can be taken up by plants (Bárány Kevei and Mezösi 1999, Zseni et al. 2003, Kaszala and Bárány Kevei 2015, Kalinovic et al. 2019), because if animals eat heavy metal-polluted grass or other plants during grazing, it can lead to serious health problems. The metal retention of soils is affected by the interaction of different metals, as well as by the pH and the organic matter content of soils also affects the mobility of metals. Low pH (in acidic soils) causes most of the heavy metals to get mobilized.

The heavy metal load of the soils of the Aggtelek and Bükk dolines (Zseni 2003, Bárány-Kevei et al. 2006, Kaszala and Bárány Kevei 2004) is higher in several places than expected. Aggtelek has higher Co and Cr contents (up to 27 and 87 ppm), lower Cd contents, and higher Cd contents (nearly 10 ppm in some places) can be found in Bükk samples (Cd is mobilized at neutral near pH, while most metals are mobilized at pH 5.5). Ni contamination is only high in some places (1.5 times the limit value). The Aggtelek and Bükk karsts are exposed to higher heavy metal load than the Western Mecsek karst. It is probable that the Aggtelek and Bükk mountains received environmental loads from the Sajóvölgy chemical industrial area (e.g. ore concentrator) and from the nearby Slovak industrial area. The buffering effect of soils is also manifested in the reduction of heavy metal mobility in karstic soils.

2.3 The role of biogenic processes in the evolution of geoecological features

Among the biogenic processes, the production of CO₂ by microbial processes (decomposition of organic matter) and higher vegetation (root respiration) in karsts is important. Both represent a true ecological order of magnitude for rock dissolution.

2.3.1 Microbial activity in doline soils

One gram of soil is home to billions of bacteria and millions of microfungi (bacteria, *Actinomyces* or “ray fungi”, microbial fungi). The pH value of soils influences soil life, i.e. the activity of microbial life (Bárány Kevei and Mezösi 1978, Kevei and Zámbo 1986, Darabos 1999, Gaozhong et al. 2019). In recent years, more and more microbiological studies have contributed to the understanding and assessment of the diversity of bacterial populations in karst soils (Knáb et al. 2012, 2018). More than two-thirds of the CO₂ produced in soil is released through the decomposition of organic matter in these microbial populations. More intensive CO₂ production takes place in the upper 20-30 cm of soil. The amount of soil microbes present in forest soils ranges to 15-20 million, while they are present in significantly smaller numbers in soils under herbaceous vegetation. Examining the relationships among soil temperature, soil moisture and the amount of bacteria, bacteria count in the dolines near the surface was found to correlate significantly with soil temperature, while it correlated strongly with soil moisture in the deeper soil layer (below 30 cm). The amount of carbon

dioxide produced by microbes is thus a real ecological. Under Hungarian climatic conditions, temperature ranging from 22.2 to 24.6 °C and the calculated 14-25% dry weight percent of soil moisture in karst areas give the optimum range for microbial activity, where microbial activity develops favourably (Bárány and Mezösi 1978).

Since soil bacteria largely prefer a neutral or slightly basic environment, acidic pH adversely affects the bacterial activity of the soil. In summer, the microbial activity in the soils is intensive, therefore the decomposition of organic matter increases in summer, but in winter it decreases (Kevei and Zábó 1986). In addition to soil reactivity (pH), favorable soil moisture and soil temperature are also important conditions for bacterial activity. The amount of carbon dioxide produced by microbes is thus a true ecological magnitude. It can also be stated that significant microbial activity is strong in the upper layer of the soil, while the number of microbes and activity decreases significantly in the lower layer. This fact confirms our hypothesis that processes determining soil dynamics occur in the topsoil layer, while at greater soil depths only material and energy flows take place. Interference with the system can cause significant changes in the topsoil layer. Biological processes also affect the chemical properties of the soil through the decomposition of humic substances, so it is desirable to maintain a natural bacterial population.

2.3.2 The geoecological role of vegetation in dolines

The composition of the vegetation on limestone surfaces is studied by international and national researchers in several directions (Brancelj 2006, Corenblit 2011, Efe 2014, Ramsey 2015, Phillips 2016, Meixian et al. 2016). In Hungary, Bacsó and Zólyomi (1939) were the first who addressed the interaction between karstification and vegetation, they were followed by Jakucs P (1956). Nowadays, the study of vegetation has come to the fore by examining the extreme microclimate of dolines (Bárány Kevei 1992, Bárány Kevei and Horváth 1996, Bárány Kevei 2011, Bátori et al. 2009, 2014, 2019, Vojtkó et al. 2018, Öztürk and Savran 2020). The type of original associations has already changed in many areas due to anthropogenic influence (Bárány Kevei and Horváth 2005).

Our detailed plant survey showed that only a fraction of the plant species found in dolines can be located in all exposures; there are species that occur only on one slope. We can find the highest percentage of species on the southern and western slopes, and they can be found on these slopes only (these species are the most slope-sensitive ones). The differences between the slopes are characteristically outlined in both the grassy and forested dolines.

At the bottom of the doline, we found 6 species that can only be found in an open doline: *Urtica dioica*, *Rumex confertus*, *Potentilla recta*, *Waldsteinia geoides*, *Dactylis glomerata*). On the southern slope, 7 species occurred only there (*Vicia sepium*, *Origanum vulgare*, *Aegopodium podagra*, *Galega officinalis*, *Crataegus oxycantha*). Only 3 such species appeared on the eastern slope (*Anthyllis vulneraria*, *Euphorbia cyparassion*, *Aconitum variegatum*). On the western slope, however, we found 10 species that did not occur on other slopes (*Valeriana officinalis*, *Cerinth minor*, *Sedum maximum*, at the bottom of the rock slope *Dafne mezerum*, *Rhanus catharticus*, *Euonymus verrucosus*, *Carpinus betulus*, *Cornus sanguinea*, *Pyrus ochras*, *Sambucus nigra*. On the northern slope, *Nardus stricta* was the only species that did not appear on any other slope. It can also be stated that the dominance of the western and southern slopes is significant in relation to hygrophitic species. Exposure differentiation is well-identifiable in the composition of the vegetation, which is in line with the indicators of previous microclimate and soil ecological processes.

On the slopes of the dolines, the distribution of plant species according to the nature conservation value also shows a significant difference.

On the northern slope (where the irradiated energy is highest, soil moisture is low) there is a lack of protected and edaphic, edaphic accompanying species, only tolerant to disturbance species were found. The highest numbers of protected species were found on the southern slope, the number of protected and edaphic accompanying species is almost the same on the western and eastern slopes, but tolerant to disturbance and weed species also appear here.

The natural vegetation in Hungarian karstlands is mainly mixed deciduous forest. The specialty of karst areas regarding forest management is their high vulnerability. Besides the pollution issues of increasing importance forest management in Hungarian karst areas had to face special challenges throughout its history. The most important of these are the shallow karst soils characterised by an extreme water balance, which affects species composition and quality. The forests with the most extreme conditions (e.g. the steep southern slopes) got legal protection very early in the interests of erosion protection (Tanács et al. 2007).

Positive biological feedback is from the aspect of global atmospheric processes, the carbon fixation ability of different types of karstic forests (Bárányi Kevei and Kiss 2016). According to the vegetation mapping, on the study area in Aggtelek (Tanács et al. 2010) is characterized by thermophilous oak forests, beech forests, beech-sessile oak forests, linden scree forests, ash scree forests, aspen forests, and birch forests. The calculated carbon fixation ability of the different types of forests with the help of a model based on tree stands structural data. The tendencies found in the study area reflect the habitat differences of the karstic region having varying relief.

A further research question related to the issue of doline vegetation is how the afforestation of dolines affects different ecosystem services. In this case, afforestation is a natural succession process, however, in some places, land management for nature conservation purposes prevents afforestation by grazing and mowing (in order to maintain grassland associations). Another research question can also be related to the study of how different land cover patterns affect the discharge of karst springs and watercourses, and how the quality of drinking water and the provision of drinking water supply can be linked to heavy metal pollution, both in qualitative and quantitative ways.

Our previous studies showed that microclimate, soil and vegetation, being the most important ecological factors, contribute significantly to the formation of doline asymmetry. In the present study, we wanted to confirm this finding with additional morphometric data. The comparative assessment also shows that different types of dolines develop on genetically identical types of karsts, and that their morphological development is at different stages.

3. CONCLUSION

Very important features of karst areas include the three-dimensional affect surface, vulnerability and the fast development of processes. The present study sought to point out which parameters (without claiming completeness) are well representative of the complexity of the system and draw attention to the geoecological scientific study of karst dolines. A change in any factor of the system affects the entire system. The magnitude of the changes is significantly influenced by the interaction of the climate-soil-vegetation system.

The specific extreme microclimate on the slopes and bases of the dolines differentiates the composition and processes of soils and biogenic factors (vegetation, microbial decomposition). The soil compensates for extreme effects to a certain extent (soil acidification, heavy metal pollution), but it changes the geoecological conditions in the long run. The intensity of karstic corrosion also changes in the dolines, and this processes of change contribute to the formation of the asymmetric shape.

The different socio-economic uses of karsts and the significant differences in the spatial pattern of the land use of karsts call attention to the need for the more precise exploration and research of these phenomena, on the one hand, and to the greater consideration of ecosystem services in land use and land development, on the other.

REFERENCES

- Bacsó N, Zólyomi B (1934) Mikroklíma és növényzet a Bükkfennsík. [Microclimate and vegetation on the Bükk Plateau (in Hungarian)] *Időjárás* 38:177-196
- Bakalowicz M (2014) The epikarst, the skin of karst. *Epikarst Karst Waters Inst Spec Publ* 9:16-22
- Barta K, Tanács E, Samu A, Keveiné Bárány I (2009) Hazai rendzinák megfeleltetése a WBR nemzetközi talajosztályozási rendszerben. [Correspondance of Hungarian rendzinas to the international soil classification system WBR. (in Hungarian)] *Agrokém Talajtan* 58:7-18
- Basso A, Bruno E, Parise M, Pepe M (2013) Morphometric analysis of sinkholes in a karst coastal area of southern Apulia (Italy). *Environ Earth Sci Springer*:1-12
- Bárány I (1967) Der Einfluss des Niveauunterschiedes und der Exposition auf die Lufttemperatur in einer Doline im Bükk-Gebirge. *Acta Climatol* 7:85-109
- Bárány I (1980): Some data about the physical and chemical properties of the soil of karst dolines. *Acta Geogr* 20:37-49
- Bárány I (1985) Ökologische Untersuchung der Karstdolinen unter besonderer Berücksichtigung des Mikroklimas. *Acta Geogr* 25:109-130
- Bárány Kevei I (1987) Tendencies to change in the compositions of the karstic soil and the vegetation in the dolines in the Hungarian Bükk Mountain. *Endins* 13:87-992
- Bárány Kevei I (1992) Karst soil as indicators of karst development in Hungarian karsts. *Z Geomorphol* 85:101-110
- Bárány Kevei I (1998a) Geoecological system of karsts *Acta Carsolog* 27:13-25
- Bárány Kevei I (1998b) The geo-ecology of three Hungarian karsts. *Cave Karst Sci* 25:113-117
- Bárány Kevei I (1999) Microclimate of Karstic Dolines. *Acta Climatol* 32-33:19-27
- Bárány Kevei I (2011) Changes in the vegetation of dolines in Aggtelek and Bükk Mountains. *Acta Climatol* 44-45:25-30
- Bárány Kevei I (2016) Vulnerability and autorestoration capacities of karst geocoecosystems. *Z Geomorphol* 60:235-255
- Bárány Kevei I, Horváth A (1996) Survey of the interaction between soil and vegetation in a karstecological system (at Aggtelek Hungary). *Acta Geogr* 35:81-87
- Bárány Kevei I, Horváth A (2005) Typical association and habitat types in the Aggtelek Karst Area. *International Atlas of Karst Phenomena (Cartography: Beck R)*. *Z Geomorphol* 139:18
- Bárány Kevei I, Kiss M (2016) Biogeomorphological feedback in karst areas. *Landsc Environ* 10:101-108
- Bárány Kevei I, Kiss M, Nelis S (2015) Néhány további adat a hazai karszdolinák aszimmetriájának kialakulásához. [Some additional data for the development of the asymmetry of hungarian karst dolines (in Hungarian)] *Karsztfeljlődés* 20:125-144
- Bárány I, Mezősi G (1978) Adatok a karsztos dolinák talajökológiai viszonyaihoz. [Data for the soil ecological condition in karst dolines (in Hungarian)] *Földrajzi Értesítő* 27:65-73
- Bárány I, Mezősi G (1991) Further morphometrical data from some important Hungarian karst areas. In: *Proc Int Conf Environ Chang in Karst Areas IGU-UIS* 13:137-142
- Bárány Kevei I, Mezősi G (1999) The relationships between soil chemistry and the heavy metal content of vegetation on karsts. In: Bárány Kevei I, Gunn J (eds) *Essays in the Ecology and Conservation of Karst*. 47-53

- Bárány Kevei I, Zseni A, Hoyk E, Kaszala R (2006) Investigations of heavy metal pollution in the karst regions of Hungary. In: Halasi-Kun GJ (ed) Sustainable development in Central Europe. Pollution and water resources. Columbia Univ Sem Proc 36:181-191
- Barta K, Tanács E, Samu A, Bárány Kevei I (2009) Hazai rendzinák megfeleltetése a WRB nemzetközi talajosztályozási rendszerben. [Classification of Hungarian rendzina soils in conformity with the international World Soil Reference Base System (WRB) (in Hungarian)] *Agrokem Talajtan* 58:7-18
- Bátori Z, Csiki J, Erdős L, Motschauser T, Török P, Körmöczi L (2009) Vegetation of dolines in Mecsek Mountains (South Hungary) in relation to the local plant communities. *Acta Carsolog* 38:237-252
- Bátori Z, Gallé R, Erdős L, Körmöczi L (2011) Ecological conditions, flora and vegetation of a large doline in the Mecsek Mountains (South Hungary) *Acta Croat* 70:147-155
- Bátori Z, Lengyel A, Maróti M, Körmöczi L, Tölgyesi Cs, Bíró A, Tóth M, Kincses Z (2014) Microclimate-vegetation relationships in natural habitat islands: species preservation and conservation perspectives. *Időjárás* 118:257-281
- Bátori Z, Vojtkó A, Maák IE, Lőrinczi G, Farkas T, Kántor N, Tanács E, Kiss PJ, Juhász O, Módra G, Tölgyesi Cs, Erdős L, Aguilon DJ, Keppel G (2019) Karst dolines provide diverse microhabitats for different functional groups in multiple phyla. *Sci Rep* 9:7176
- Bögli A (1960) Kalklösung und Karrenbildung. *Internationale Beiträge zu Karstmorphologie. Z Geomorphol* 2:4-21
- Brancelj A (2006) The epikarst habitat in Slovenia and the description of a new species, *J Nat Hist* 40:403-413
- Bruno E, Calcaterra D, Parise M (2008) Development and morphometry of sinkholes in coastal plains of Apulia, southern Italy: Preliminary sinkhole susceptibility assessment. *Eng Geol* 99:198-209
- Caputa Z (2016) The impact of solar radiation on the temperature of the exposed rocks of the karst canyon (the Kraków-Częstochowa Upland, Poland). *Bulletin of Geography. Phys Geogr S* 10:19-30
- Caputa Z, Wojtkowski J (2015) Structure of radiation balance in diverse types of relief. *Ann Warsaw Univ Life Sci*, 47:343-354
- Castiglioni B (1991) Some morphometric and environmental aspects of dolines in Berici Hills (Vicenza, Italy). *Proc Int Conf Environ Chang in Karst Areas IGU-UIS* 13:143-155
- Clements CB, Whiteman CD, Horel JD (2003) Cold-airpool structure and evolution in a mountain basin: Peter Sinks, Utah. *J Appl Meteor* 42:752-768
- Corenblit D, Baas ACW, Bornette G, Delmotte S, Francis RA, Gurnell A, Julien F, Naiman RJ, Steiger J (2011) Feedbacks between geomorphology and biota controlling Earth surface processes and landforms. *Earth Sci Rev* 106:307-331
- Cramer H (1941) Die Systematik der Karstdolinen. *Neues Jahrb Geol P-A, Beilage-Band, Abst. B* 85:293-382
- Cvijic J (1893) Das Karstphänomen. *Geogr Abhandl* 5:217-329
- Darabos G (1999) Karst corrosion - specifically regarding the role of the soil-microorganisms. In: Bárány Kevei I, Gunn J (eds) *Essays in the Ecology and Conservation of Karst*. 54-59
- Daoxian Y (2001) On the karst ecosystem. *Acta Geol Sin Engl* 75:336-339
- Efe R (2014) Ecological properties of vegetation formations on karst terrains in the Central Taurus Mountains (Southern Turkey). *Proc Soc Behav Sci* 120:673-679
- Ford DC (2015) The science of caves and karst: From the beginning of the Geological Society of America to ca. 1960. In: Feinberg J, Gao Y, Alexander EC (eds) *Caves and Karst across time*. 1-18
- Ford DC, Williams PW (1989) *Karst Geomorphology and Hydrology*. Chapman and Hall, London
- Ford DC, Williams PW (2007) *Karst Hydrogeology and Geomorphology*. Wiley and Sons Ltd, Chichester
- Galve JPF, Gutiérrez P, Lucha J, Bonachea J, Remondo A, Cendrero M, Gutiérrez M, Gimeno J, Pardo G (2009) Sinkholes in the salt-bearing evaporite karst of the Ebro River valley upstream of Zaragoza city (NE Spain): Geomorphological mapping and analysis as a basis for risk management. *Geomorphology* 108:145-158
- Gams I (1974) *K ekologiji vrtac*. [Towards an ecology of gardens (in Slovenian)] IX. Kongres Geografa Jugoslavija. S.R. Bosnia Hercegovina, Sarajevo. 151-159
- Gams I (2000) Doline morphogenetical processes from global and local viewpoints. *Acta Carsolog* 29:123-13
- Gao Y, Alexander C (2003) Mathematical model for a map of relative sinkhole risk in Fillmore County Minnesota. In 9th Multidisciplin Conf on Sinkholes and the Engineering and Environ Impacts of Karst. 439-449
- Gaozhong P, Yanna L, Lina D, Longwu Z, Kechao Hg, Danjuan Z, Ling M, Guangping X (2019) Profiling the bacterial diversity in a typical karst Tiankeng of China. *Biomol* 9:1-18
- Geiger R (1965) *The climate near the ground*. Harvard University Press, Cambridge
- Goldscheider N (2012) A holistic approach to groundwater protection and ecosystem services in karst terrains. *Aqua Mundi* 3:117-124
- Gortani M (1908) *Appunti per una classificazione delle doline*. *Mondo Sotterraneo* 6:115-116

- Groschopf P, Kobler HU (1974) Beobachtungen und Entstehung von Dolinen und Karstwannen auf der Swaebischen Alb und Oberen Neckar. *Mitteil Verb Deutsch Höhlen- und Karstforscher* 20:57-63
- Grund A (1904) Die Karsthydrogeographie Studien aus Westbosnien. *Geogr Abhandlungen* 7:103-200
- Gutierrez F, Parise M, De Waele J, Jourde H (2014) A review on natural and human-induced geohazards and impacts in karst. *Earth Sci Rev* 138:61-88
- Haserodt K (1965) Untersuchungen zu Höhlen zu Altersgliederung der Karstformen in den nördlichen Kalkalpen. *Münchener Geographische Hefte* 27
- Haquet B (1778) *Oryctographia Carniolica oder Physicalische Erdbeschreibung des Hezogtums Krain, Ostrien und zum Teil Benachbarten Laender*. Gottlob und Breitkopf, Leipzig
- Horvat I (1953) Die Vegetation der Karstdolinen. *Geografski Glasnik* 14-15:1-25
- Hoyk E (1999) Investigations of the vegetation and soil in the dolinas of Mecsek Mountains South Hungary. *Acta Carsolog* 28:105-114
- Jakucs L (1971) Karsztok morfogenetikája. A karsztfelődés varienciái. [Morphogenetics of karsts. Variations in karst development (in Hungarian)] *Akadémiai Kiadó, Budapest*
- Jakucs L (1980) Karszt biológiai produktum. [Karst biological product (in Hungarian)] *Földrajzi Közlemények* 28:331-339
- Jakucs L, Bárány I (1984) Ecological factors playing part in karst denudation dynamism for different geographical zones. In: Godard A, Rapp (eds) *Process et Mesure de l'Érosion*. Éditions du CNRS, Paris
- Jakucs P (1956) Karrosodás és növényzet. [Karst formation and vegetation (in Hungarian)] *Földrajzi Közlemények* 4:214-249
- Jones WK, Culver DC, Herman JS (2004) *Epikarst*. Karst Waters Institute, Leesburg
- Kalinovic JV, Serbula SM, Radojevic AA, Milosavljevic JS, Kalinovic TS, Steharnik M (2019) Assessment of As, Cd, Cu, Fe, Pb and Zn concentration in soil and parts of Rosa spp sampled in extremely polluted environment. *Environ Monit Assess* 19:1-15
- Kaszala R, Bárány-Kevei I (2004) Heavy metal content of soils in the karstic area of North Hungary. In: Calabrese EJ, Kostecki PT, Dragan J (eds) *Contaminated Soils, Sediments and Water*. Science in the Real World. Springer
- Kaszala R, Bárány Kevei I (2015) Heavy metal concentrations in the soils and vegetation of the Béke-cave watershed (Aggtelek-karst). *Landsc Environ* 9:51-58
- Katzer AF (1909) *Karst und Karsthydrography*. Kajan, Sarajevo
- Kemmerly PR (1982) Spatial analysis of karstdepression population: cluesto genesis. *Geol Soc Am Bull* 93:1078-1086
- Kemmerly PR (2007) Modelling doline populations with logistic growth functions. *Earth Surf Proc Land* 3:355-362
- Kerékygártó R (2016) Töbrök titkai a Bükkben. [The secrets of dolines in the Bükk mountains (in Hungarian)] In: "Met-Ész" Conf, 22 Oct 2019, Hungarian Meteorological Service, Budapest
- Kevei I, Zámbo L (1986) Study of the relationship between bacteria activity in karstic soils and corrosion. *Annales Univ Scientiarum Budapestinensis de Rolando Eötvös Nominatae* 20-21:325-333
- Keveiné Bárány I (1985) A karsztdolinák talajainak és növényzetének sajátosságai. [Characteristics of the soils and vegetation of karst dolines (in Hungarian)] *Földrajzi Értesítő* 34:195-207
- Keveiné Bárány I (2009) A karsztok ökológiai rendszere: Szerkezet, működés, környezeti hatások a rendszerben [Ecological system of karsts: Structure, activity, environmental effects in the system (in Hungarian)] *Földrajzi tanulmányok, JATEPress, Szeged*
- Keveiné Bárány I (2011) Néhány adat a bükki töbrök mikroklímájához. [Some data for the microclimate of Bükk dolines (in Hungarian)] *Geotudományok: A Miskolci Egyetem Közleménye: A Sorozat, Bányászat* 82:171-176
- Keveiné Bárány I (2018) Karsztdolinákról másképpen (Geoökológiai értelmezés). [From karst dolinas otherwise (Geoecological interpretation) (in Hungarian)] *Karsztfelődés* 23:163-185
- Keveiné Bárány I, Kiss M (2018) A karsztok ökoszisztéma-szolgáltatásai integrált geográfiai megközelítésben. [Karst ecosystem services in an integrated geographic approach] (in Hungarian)] In: Pap N, Szalai G (eds) *Táj geográfus ecsettel. (Landscape with geographer brush) (in Hungarian)]* 31-44
- Keveiné Bárány I, Mezősi G (1978) Adatok a karsztos dolinák talajökológiai viszonyaihoz [Data for the soil ecological condition in karst dolines (in Hungarian)]. *Földrajzi Értesítő* 27:65-73
- Kiss M, Tanács E, Bárány Kevei I (2011a) Ecosystem services in Hungarian karst areas. *Acta Climatol* 44-45:41-49
- Kiss M, Tanács E, Keveiné Bárány I (2011b) Karsztos erdők szénmegkötésével kapcsolatos számítások egy erdőrezervátum adatai alapján. [Related to carbon binding in karst forests calculation based on forest reserve (in Hungarian)] *Karsztfelődés* 16:157-166

- Knáb M, Szili-Kovács T, Kiss K, Palatinszky M, Márialigeti K, Móga J, Borsodi AK (2012) Comparison of soil microbial communities from two distinct karst areas in Hungary. *Acta Microbiol Imm H* 59:91-105
- Knáb M, Szili-Kovács T, Márialigeti K, Móga J, Borsodi AK (2018) Bacterial diversity in soils of different Hungarian karst areas. *Acta Microbiol Imm H* 1:1-20
- Kobal M, Bertoneclic JI, Pirotti F, Kutnar L (2014) Lidar processing for defining sinkhole characteristics under dense forest cover: a case study in the Dinaric Mountains. *Int Arch Photogramm Remote Sens Spatial Inf Sci* 15:113-118
- Kranjc A (2013) Klassifikation of Closed Depressions in Carbonate Karst In: Shroder J, Frumkin A (eds) *Treatise on Geomorphology*. Academic Press, San Diego, CA, USA. 104-111
- Kuzakov Y (2006) Sources of CO₂ efflux from soil and review of partitioning methods. *Soil Biol Biochem* 38:425-448
- Lauscher F (1937) Grundlagen des Strahlungsklimas der Lunzer Kleinklimastationen. Beihefte zu den Jahrbüchern der Zentralanstalt für Meteorologie und Geodynamik 4:1-24
- La Valle P (1968) Karstdepression morphology in South Central Kentucky. *Geografiska Annaler Ser A Phys Geogr* 50:94-108
- Lehmann H, Roglic J, Rathjens C, Lasserre G, Harrassowitz H, Corbel J, Birot P (1954) Das Karstphänomen in den verschiedenen Klimazonen. *Erdkunde* 8:1-112
- Lehmann O (1931) Über die Karstdolinen. *Mitt Geogr Ethnogr Ges* 31:43-71
- Lippmann L, Kis K, Móga J (2008) Az Abaliget-orfűi Karszt karsztos felszínformáinak vizsgálata térinformatikai módszerekkel. [Investigation of the karst surface forms of the Abaliget-Orfű Karst by GIS methods (in Hungarian)] *Karsztfejlődés* 13:151-166
- Litschmann T, Roznovsky J, Streda T, Stredova H, Hebelka J (2012) Temperature and humidity conditions of Macocha Abyss. *Contrib Geophys Geodesy* 42:227-242
- Lugeon M, Jérémin E (1911) Les bassins fermés des Alpes suisses. Univ de Lausanne, Lausanne
- Maclean IMD, Hopkins JJ, Bennie J, Lawson CR, Wilson RJ (2015) Microclimates buffer the responses of plant communities to climate change. *Glob Ecol Biogeogr* 24:1340-1350
- Maki M, Harimaya T (1988) The effect of advection and accumulation of downslope cold air on nocturnal cooling in basins. *J Meteor Soc Japan*, 66:581-597
- Maximovich GA (1963) Principles of the study of karst. Permskoe knish izdat, Moscow
- Meixian Liu, Xianli Xu, Dingbao Wang, Alexander YS, Ke-Lin W (2016) Karst catchments exhibited higher degradation stress from climate change than the non-karst catchments in southwest China: An ecohydrological perspective. *J Hydrol* 535:173-180
- Mix C, Küfman C (2011) Dolinenengese und ihre Steuerfaktoren in einem subalpinen Karstökosystem der Nördlichen Kalkalpen Plateau Zahmer Kauser (Österreich). *Z Geomorphol* 56:141-163
- Michevc A, Mihevc R (2021) Morphological characteristics and distribution of dolines in Slovenia, study of LIDAR-based doline map of Slovenia. *Acta Carsologica* 50:11-36
- Móga J, Strat D, Iván V, Mari L, Kiss K, Szabó M, Borsodi A, Csüllög G (2017) Changes of the karst landscape and epikarst system in the area of the Tapolca karst terrains, North-West Balaton Highlands, Hungary. *Forum Geogr* 16:12-25
- Móga J, Kiss K, Borsodi A, Szabó M, Strat D, Bódai B (2018) The analyze of relationship between microclimate and microbial carbon-dioxide production in the soils of the Tapolca and Gömör-Tornai karst terrains, Hungary. *Forum Geogr* 17:31-43
- Ogrin M, Nikolić G, Ogrin D, Trobec T (2018) An investigation of winter minimum temperatures in the mountains of Montenegro: A case study from the karst depression of Valoviti Do and selected mountain stations of northern Montenegro. *Geogr Pannonica* 22:241-252
- Öztürk MZ, Savran A (2020) An oasis in the Central Anatolian steppe: the ecology of a collapse doline. *Acta Biologica Turcica* 33:100-113
- Palmquist R (1979) Geologic controls on doline characteristics in mantled karst. *Z Geomorphol* 32:76-90
- Petkovsek Z, Rakovec J (1983) Modelling of cool pool dissipation. *Razprave Papers (Ljubljana)* 27:53-63
- Pfeffer KH (2010) *Karst Entstehung-Phaenomene-Nutzung*. Studienbücher der Geographie Borntraeger Science Publishers, Stuttgart
- Péntek K, Veress M (2007) A morphometric classification of solution dolines. *Z Geomorphol* 51:19-30
- Phillips JD (2016) Biogeomorphology and contingent ecosystem engineering in karst landscapes. *Prog Phys Geog* 37:1-24
- Phillips DJ (2018) Self-limited biogeomorphic ecosystem engineering in epikarst soils. *Phys Geogr* 39:304-328
- Prestwich J (1854) Swallow holes on the Chalk hills near Canterbury. *Quart J Geol Soc* 10:222-224
- Priesnitz K (1968) Über die Vergleichkeit von Lösungsformen auf Chlorid-Sulfat- und Karbonatgestein Überlagerungen zu Fragen der Nomenklature und Methodik der Karstmorphologie. *Geol Rundsch* 58:427-438

- Quintero-Ruiz JR, Yáñez-Espinosa L, Flores J, Fortanelli J, De-Nova A, Reyes-Hernandez H, Rodas-Ortiz JP (2019) Analysis of the soil and microclimate relationship in two dolines of Carso Huasteco, Mexico. *J Nat Res Dev* 9:25-33
- Ramos J, Gracia JS, Ortiz S, Gonzales-Chávez JL, Iturbe R (2018) Water quality in aguadas within a protected karstic rain forest: The role of the vegetation-soil-water interactions. *Ecol Eng* 21:2-11
- Ramsey LC (2015) Morphometry and basic ecological characteristics of dolines in unlogged temperate rainforest karstlandscapes of Northern Vancouver Island, British Columbia, Canada. PhD dissertation. University Nova Gorica, Slovenia
- Reicher M (1936) Naechtlicher Kaltluftfluss an Hindernissen. *Bioklim B* 3:152-163
- Sauberer F, Dirmhirn J (1954) Über die Entstehung der extremen Temperaturminima in der Dolina Gstettner-Alm. *Arch Meteor Geophys Bioklim B5*:307-326
- Sauro U (2005) Closed depressions. In: Culver DC, White WB (eds), *Encyclopedia of Caves*. Elsevier, Amsterdam 108-127
- Sauro U (2012) Landforms of mountainous karst in the middle latitudes: reflections, trends and research problems. *Acta Carsolog* 42:5-16
- Schmidt W (1930) Die tiefsten Minimum Temperaturen in Mitteleuropa. *Die Naturwissenschaften* 18:367-369
- Siska PP, Kemmerly PR (2007) Doline feature database (DFD) development and assessment of hazards using a co-regionalization model. *Pap Appl Geogr Conf* 31:34-42
- Siska P, Goovaerts P, I-Kuai H (2016) Evaluating susceptibility of karst dolines (sinkholes) for collapse in Sango, Tennessee, USA. *Prog Phys Geogr* 40:579-597
- Sustercic F (1994) Classic dolines of classical sites. *Acta Carsolog* 23:123-156
- Sweeting M (1972) Karst landforms. Columbia University Press. New York
- Telbisz T, Mari L, Kohán B, Calic J (2007) A szerbiai Mirochegység többreinektérinformatikai és GPS-es terepi vizsgálata. [GIS and GPS field investigation of the dolines of the Miroc Mountain in Serbia (in Hungarian)] *Karsztfejlődés* 12:71-90
- Telbisz T, Dragusica H, Nagy B (2009) Doline Morphometric Analysis and Karst Morphology of Biokovo Mt (Croatia) based on field observations and digital terrain analysis. *Croat Geogr Bull* 71:2-22
- Terzaghi K (1913) Beitrag zur Hydrographie und Morphologie des kroatischen Karstes. *Mitteil Jb Ungar Geol Reichsanst* 20:256-369
- Trudgill ST (1977) The role of a soil cover in limestone weathering, Cockpit Country, Jamaica. *Proc of the 7th Int Speleol Congress, Sheffield, England*. 401-404
- Trudgill ST (1986) Limestone weathering under a soil cover and the evolution of limestone pavements, Malham District north Yorkshire UK. *New directions in karst. Proc of the Anglo-French Karst Symposium*. 461-471
- Vojtkó A (2018) A fás vegetáció jellegzetességei az Alsó-hegy (Gömör-Tornai-karszt) karsztfennsíkján. [Characteristics of woody vegetation on the karst plateau of the Alsó-hegy (Gömör-Tornai karst (in Hungarian)] *Botanikai Közlemények* 105:97-108
- Wagner R (1964) Lufttemperaturmessungen in einer Doline des Bükk-Gebirges. *Z Angew Meteorol* 5:192-199
- Wenhua Li, Jianhua C (2015) Karst ecosystem: An ecosystem on carbonate rocks. *J Res Ecol* 6:197-198
- Whiteman CD, Haiden T, Pospichal B, Eisenbach S, Steinacker R (2004) Minimum temperatures, diurnal temperature ranges, and temperature inversions in limestone sinkholes of different sizes and shapes. *J Appl Meteorol* 43:1224-1236
- Williams PW (1972) Morphometric analysis of polygonal karst in New Guinea. *Geol Soc Am Bull* 83:761-796
- Williams PW (2004) Dolines. In: Gunn J (ed) *Encyclopedia of caves and karst science*. Routledge, London
- Williams PW (2008) The role of the epikarst in karst and cave hydrogeology: a review. *Int J Speleol* 37:1-10
- Yoshino MM (1984) Thermal belt and cold air drainage on the mountain slope and cold air lake in the basin at quiet, clear night. *Geo Journal* 8:235-250
- Zámbó L (1986) A talajhatás jelentősége a karszt korróziós fejlődésében [Significance of soil influence in karst corrosion development (in Hungarian)] PhD Dissertation, Budapest
- Zámbó L, Telbisz T (1999) The influence of the soil zone on karst corrosion and karren development. In: Bárány-Kevei I, Gunn J (eds) *Essays in the Ecology and Conservation of Karst*. Szeged, Budapest, Miskolc
- Zámbó L, Telbisz T (2000) A mikrobiális befolyásoltású karsztkorrózió vizsgálata magyarországi karsztok talajaiból származó kismintákon. [Investigation of microbially affected karst corrosion on small samples from Hungarian karst soils (in Hungarian)] *Karsztfejlődés* 5:11-39
- Zboray Z (2007) Az erdő növekedésének vizsgálata térinformatikai és fotogrammetriai módszerekkel karsztos mintaterületen. [Investigation of forest growth by GIS and photogrammetric methods in a karst sample area (in Hungarian)] *Tájékológiai Lapok* 5:287-293
- Zboray Z, Keveiné Bárány I (2004) Domborzatértékelés a Bükk-fennsíkon légifelvételek felhasználásával. [Relief evaluation in the Bükk Plateau based on aerial imagery (in Hungarian)] *Karsztfejlődés* 9:207-213

- Zboray Z, Keveiné Bárány I (2005) A dolinák korróziós felszínének meghatározása digitális domborzatmodell alapján. [Defining the corrosion surface of dolines by means of a digital elevation model (in Hungarian)]. *Karsztfejlődés* 10:221-228
- Zseni A (2003) Karsztos mintaterületek talajainak kicserélhető kationtartalma és nehézfém terhelése. [Interchangeable cation content and heavy metal contamination of soils in karstic sample areas (in Hungarian)]. *Karsztfejlődés* 8:273-295
- Zseni A, Keveiné Bárány I (2001) Talajtulajdonságok változása és jellemzői a dolinákban. [Changes in soil properties and characteristics in the dolines (in Hungarian)] *Földrajzi Konferencia Szeged*
- Zseni A, Goldi H, Bárány Kevei I (2003) Limestone pavements in Great Britain and the role of soil cover evolution. *Acta Carsologica* 32:57-67