

Article

Climate Change, Anthropogenic Pressure, and Sustainable Development of Karst Geosystems (A Case Study of the Brestnitsa Karst Geosystem in Northern Bulgaria)

Peter Nojarov ^{1,*} , Petar Stefanov ² , Dilyana Stefanova ²  and Georgi Jelev ³ 

- ¹ Climate, Atmosphere and Water Research Institute, Bulgarian Academy of Sciences, Akad. G. Bonchev Str., Bl.30, 1113 Sofia, Bulgaria
- ² National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Akad. G. Bonchev Str., Bl.3, 1113 Sofia, Bulgaria
- ³ Space Research and Technology Institute, Bulgarian Academy of Sciences, Akad. G. Bonchev Str., Bl.1, 1113 Sofia, Bulgaria
- * Correspondence: pnojarov@abv.bg

Abstract: This study examines climate change, anthropogenic impacts, and their relationship with the sustainable development of the Brestnitsa karst geosystem. It is representative of the karst in Bulgaria, which is developed on a quarter of its territory. The geosystem approach was used to reveal the interrelationships in a typical karst territory. The data were collected from more than 10 years of integrated monitoring of the geosystem, including continuous instrumental monitoring in the show cave Saeva Dupka, which is part of the geosystem. Various data from other sources were also used, such as satellite observations (a digital terrain model, land cover, and satellite images and products), ground data, and climate reanalyses. A spatial analysis of the karst geosystem in the context of climate change and sustainable development was conducted using a complex of remote sensing methods, geographic information systems, and statistical methods. The main results include the state and trends in the climate of the area, changes and trends in the speleoclimate and gas composition of the air in the Saeva Dupka cave, and changes in land use in the territory of the geosystem. Conclusions about the connections between climate change, current karstogenesis, and the carbon cycle in the geosystem, as well as the response of the geosystem to the consequences of the combined impact of climate change and human activities, have been made. All these impacts on the karst geosystem have been assessed in order to make adequate management decisions to guarantee its sustainable development in the future.

Keywords: karst; karst geosystems; Brestnitsa karst geosystem; show cave Saeva Dupka; Integrated Monitoring of Karst Systems (MIKS); speleoclimate; anthropogenic pressure; global changes; sustainable development



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1. Introduction

“Earth’s climate should be seen as the basis for the coevolution (related development) of nature and society, synthesized in the theory of sustainable development”

T. Nikolov, 2011, p. 294

Humanity’s main concerns about the balance of natural systems today focus most strongly on issues related to climate change. Growing industry, intensive agriculture, large-scale deforestation, transport, and a number of other human activities are the cause for the acceleration of natural climate fluctuations and activation of dangerous trends [1]. The growing release into the atmosphere of greenhouse gases and aerosol particles not only pollutes the air we breathe but also disturbs the Earth’s energy balance. However, it

should be borne in mind that natural factors play the main role in climatic cyclicity, which is typical for our planet and has left clear traces in geological annals. These factors are:

- external: solar radiation and changes in the orbital parameters of the Earth during its movement around the Sun;
- internal: atmospheric circulation, geophysical and tectonic fluctuations in the Earth's crust, and the type of the Earth's surface.

Their combination over time causes climatic fluctuations, and the impacts of human activities are superimposed on them. Karst is a natural phenomenon with wide occurrence (15–20% of the Earth's land area) and the lives of millions of people are directly or indirectly connected to it [2]. A distinctive feature of karst territories is that they are one of the most sensitive to both natural and anthropogenic impacts and they can be considered among the most vulnerable in the world [3,4]. This causes a number of problems in their sustainable development due to intensifying global and climate changes [5–7]. Especially considering that the specifics of karst in the 21st century continue to be “terra incognita” (poorly known) both for the general public and for governing institutions [3,8]. This makes karst research more and more relevant. It is interdisciplinary and requires good synchronization and an appropriate methodological approach. The geosystem approach is the most effective [9–13] because all elements of the karst geosystem are equivalent (equal) and studies focus on the interactions between elements that determine system properties. Knowledge of these properties is particularly important for clarifying trends and predicting expected changes in terms of planning certain activities in karst territories, especially those due to active global changes.

The main system-forming role in the karst is played by the circulation of waters and related karst processes [12]. They organize the environment in a certain way, forming territorially uniform and functionally complete formations—karst geosystems. They show spatial, functional, dynamic, and genetic subordination of interconnected and interacting elements. The contact and interpenetration between them take place at a great depth (well-defined vertical structure). Therefore, the structure of the karst geosystem comprises two main subsystems—the surface and underground (cave). The material–energy interactions between the surface and underground subsystems are the basis for the functioning and dynamics of the karst geosystem. Its main system features are [10,12]:

- Volumetric in space and metachronous in time dynamic structure with two main parts/subsystems: the surface and underground. The material–energy interactions between them are the basis of the functioning and dynamics of the karst geosystem.
- Structural complexity (a necessary condition for the stability/sustainability of the system)—it is much greater in karst due to the intra-system surface–subsurface connections/interactions.
- Paradynamic and paragenetic relations between the surface and underground parts—positive feedback (mutually stimulating);
- Delay in the response of the underground subsystem to events on the surface, and vice versa—asynchrony of changes in the structural subsystems (relative dynamic autonomy);
- Buffer mechanism (additional condition for sustainability) between surface and underground subsystems in relation to external impacts (redistribution of destructive processes), resulting in azonality;
- High structural permeability between the subsystems, and in general—highly manifested vulnerability;
- High general resource potential—both on the surface and underground.

These features define karst geosystems as one of the most complex in the global system [11,12], the most dynamic, and the most ecologically sensitive [14]. Therefore, they are susceptible to an increased risk, which requires protection of both subsystems—surface and underground. Because of their specificity, another problem must be addressed—the frequent disagreement of the boundaries of the surface and underground subsystems, i.e., disagreement of the boundaries of the surface catchment area and the underground hydrogeological basin. The functioning of the karst geosystem is assessed mainly through the parameters of the flows of matter and energy at its inlets and outlets. Most often, karst geosystems refer to the “gray box” conceptual model—caves make part of their internal structure accessible and some of the interactions can be studied “in situ” [12,15].

Karst geosystems also have a “memory”—they store enormous amounts of information in the karstolites (speleothems) of the caves. Extraction of this information enables both paleogeographical reconstructions and the development of forecast models about the results of global changes [16–19].

There is no doubt that the identification of global changes affecting the karst and related problems on regional and local scales is a relevant and responsible task. This is also valid for Bulgaria, where karst covers over 1/4 of its territory [20] and there are over 7000 caves, of which 15 are tourist attractions. The Bulgarian karst is unique in its diversity, which makes it a kind of natural laboratory for experimenting with the geosystem approach, successfully applied since the end of the 20th century. For this purpose, model karst geosystems representative of the main karst types were selected [21]. One of these geosystems is Brestnitsa, which is the object of this study. It is distinguished by a complex structure and a wide range of different impacts on both the surface and underground subsystems, which makes the Brestnitsa karst geosystem highly vulnerable. The applied geosystems approach aims, through a developed original methodology, to analyze the degree of impact of one of the most active global changes (climatic) on modern karstogenesis and on the carbon cycle in the geosystem. Its response to the combined effects of climate change and human activity, causing land use changes in the karst area, is also investigated. The results have been evaluated with the aim of making adequate management decisions to guarantee the sustainable development of the karst geosystem.

2. Object of This Study

The Brestnitsa karst geosystem (BKG) is located in northern Bulgaria and has an area of 62.570 km². It is bounded by the valleys of the rivers Vit (east) and its left tributary Voneshtitsa river (south) and Batulska river (northwest), and its right tributary Yablanishki dol (west) and Brestnishki dol—a right tributary of the Panega river (northeast) (Figure 1). The relief is dominated by hills (200–600 m above sea level), comprising 96.7%.

The boundaries of the BKG are lithologically and tectonostructurally predetermined. Karstogenesis takes place in micro-grained organogenic (reef) limestones (brJ₃^t-K₁^{bs}) with thicknesses between 200 and 450 m and a very high carbonate content—97–99% [22,23]. In tectonostructural terms, the geosystem is in a flat spread fold structure with a northern vergence, which includes the Batul and Assen anticlines [24]. It is part of the pre-Balkan block step [25], formed between the Miesian continental plate (to the north) and the Stara planina longitudinal fault-flexure strip (to the south).

The summit part of the Assen anticline (Lednishki rut) is split by the Garvanishki fault with a subparallel (east–west) direction [26]. The northern (Brestnishki) block has sunk along it by about 140 m, forming an Eopleistocene graben [22,23]. Several more morphologically pronounced faults contributed to the tectonic block rearrangement of the relief of the geosystem. The tectonic activation is associated with intense cracking of the limestones, especially in the summit parts of anticlines. This has favored and guided the development of the karst.

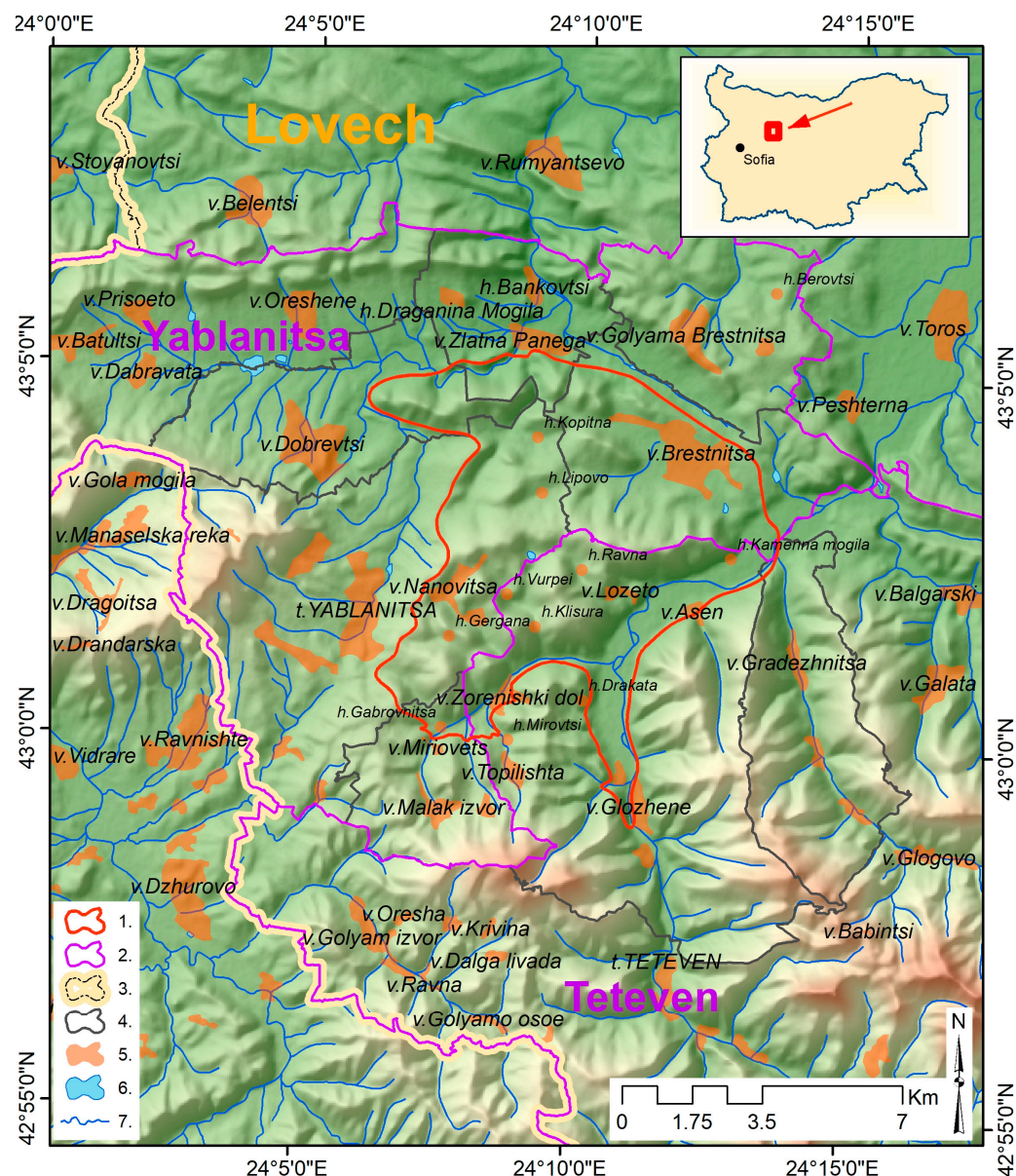


Figure 1. Location of the Breznitsa karst geosystem in Bulgaria (the little red square on the top right small figure). Borders: 1. geosystem, 2. districts, 3. municipalities, 4. Settlements 5. settlement's land use area (SLUA); 6. Lakes and swamps; 7. Rivers.

A complete karst morphological complex of the nested type is formed in the relief of the BKG. It comprises karrens and karrenfelds, sinkholes, valogs, uvals, blind and dry karst valleys, karst gorges, residual heights (hums), rock ridges, karst niches and caves (including abyss), and karst polje (Figure 2). The term “valog” is typical for the karst in the central part of the Balkan Peninsula. It designates a rounded trough-like surface karst form, most often formed by the merging of adjacent dolines or in a dry karst valley around zones of sinking waters. In terms of dimensions, the valog is transitional between the doline and uvala. The terminology of the remaining karst forms is consistent with The UIS Cave and Karst Glossary [27].

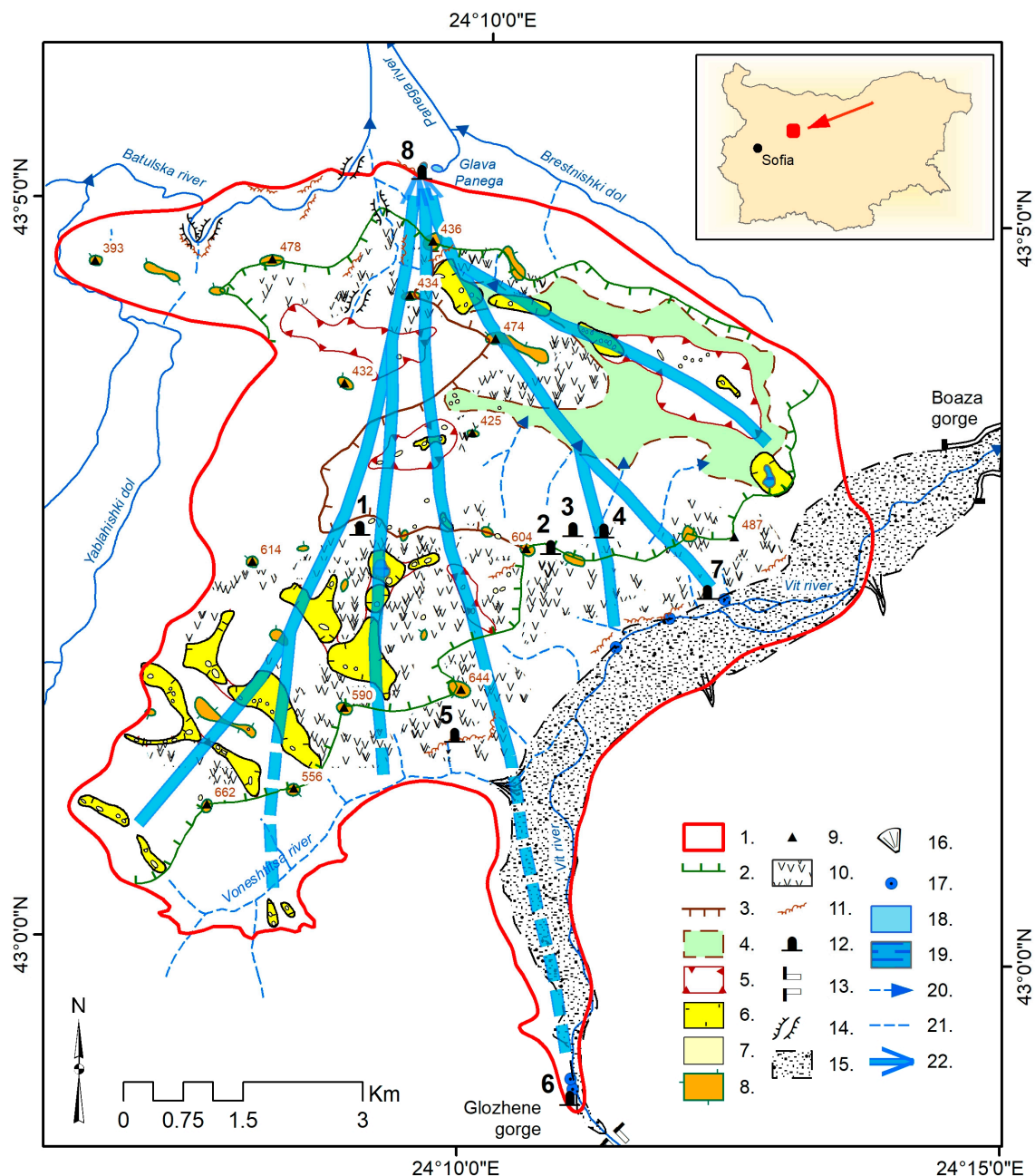


Figure 2. Karst forms in the Breznitsa geosystem. (the little red square on the top right small figure shows the location of the geosystem in Bulgaria) 1. Geosystem boundary; 2. Boundary of the non-drainage area; 3. Boundary of karst polje; 4. Bottom of karst polje; 5. Border of uvala; 6. Valog; 7. Doline; 8. Hum; 9. Peak with elevation; 10. Karrenfeld; 11. Rock wreath; 12. Cave (numbers indicate the entrances to: 1. Bezdanniyat pchelin; 2. Golyamata Ledenitsa; 3. Ledenishka yama; 4. Saeva Dupka cave; 5. Draganchovitsa; 6. Planinets; 7. Partisan cave; 8. Upper and Lower cave); 13. Entrance/exit of gorge; 14. Entrance and exit of karst canyon; 15. Alluvial riverbed; 16. River drift cone; 17. Sinkhole; 18. Karst lake; 19. Karst swamp; 20. Blind karst valley; 21. Dry karst valley; 22. Direction of movement of underground karst waters.

The predominant karst type is subsoil karst. The intense and long-lasting karstification is the cause for the development of classic karst uvals—a total of eight. The largest one is near the village of Breznitsa (embedded in the karst polje). It is 2650 m long, 870 m wide, and up to 10–20 m deep (area of 1.464 km²). The most typical, however, are the uvals that dissect Yablanishko bardo. They are highly elongated (up to 3000 m with a width of up to

750 m) and are up to 40 m deep. They are oriented to the south towards the Voneshtitsa river valley, which was the base level during their formation. A large uvala is also formed near the Koritna quarter (1750/500 m and a depth of 20 m). Between the uvals, especially along the Yablanishko bardo, residual heights (hums) with a relative height of 100–150 to 200–220 m are formed. A total of 13 valogs and more than 50 dolines are embedded in the uvals. Another seven valogs are formed as independent forms, comprising a number of dolines. Typical karrenfelds are developed on the slopes of the uvals and residual heights, and often on the slopes of the valogs. There are entrances to the abyss and abyssal caves at the bottom of some of the dolines. Red weathering clay (terra rossa) is deposited at the bottom of the large negative surface forms, which in the Bretnitsa karst polje is up to 10 m thick [22]. The silting of sinkholes is the cause for the formation of a karst swamp in the uvala near the Varpey quarter with a diameter of approx. 500 m and a depth of 8 m. A karst swamp (Great swamp) is formed in the valog in the southeastern part of the Bretnitsa karst polje, which is the most typical for Bulgaria. It has an area of 15.820 km², of which 5.362 km² is a leveled floor. In addition to the uvala, the polje also comprises five valogs and over 30 dolines. Some of the dolines are leveled with bulldozers and included in the cultivated lands. The Bretnitsa polje, like other classical karst poljes, is vulnerable to flooding during prolonged and heavy rainfall. Such a case was recorded in 1893, when for 12 days, almost half of the polje was flooded and swamped [28]. Filling of dolines and sinkholes with water has been observed during heavy rainfall in subsequent years, but without spillage in the polje.

In the northwestern part of the BKG, the Batulska river formed a karst gorge 2.5 km long and 40–60 m deep. A karst gorge 2 km long and 150 m deep was also formed north of the Koritna quarter. However, it has no permanent river flow.

Over 50 caves are known in the BKG. The abyss and abyssal caves predominate. Among them, the deepest are the Partisan cave (−118 m), Bezdannia pchelin (−105 m), Draganchovitsa (−72 m), Golyamata and Malkata Ledenitsa (−63 and −40 m, respectively), and Planinets (−45 m) (Figure 2). Bezdannia pchelin and the two Ledenitsas are formed in the Garvanishka fault zone. The popular show cave, Saeva Dupka [15], was also developed in this area.

In addition to the surface morphological complex that is the entrance to the BKG, its structure also comprises a complex subsystem of underground cavities and channels that form the underground subsystem. Complex connections exist between precipitation, surface runoff, and underground water within the boundaries of the BKG, and hydrogeological zones typical for the karst are formed [23,29,30]. It is characteristic of the geosystem that it is formed as a combination of allogenic and autogenic types of karst (according to L. Jakucs [31]). The replenishment of the karst aquifer occurs in two ways:

- Inflow of waters from the Vit river (direct and through the alluvial terrace) in the section between the gorges near the villages in the Glozhene and Boaza areas. Three sinkhole zones are located in the riverbed (Figure 2). The indicator experiments conducted in 1947 and 1955 prove that the sinking river waters, after 12 days, flow into the karst spring Glava Panega [23], which is the start of the Panega river, a right tributary of the Iskar river. The spring is of the Vauclusian type and its location is predetermined by the Bretnista fault in the contact zone of limestones with marls (sK₁^{bs-b}) [24]. Given that the straight-line distance between the sinkholes and the spring is approx. 7 km, this long period of underground flow is indicative of the complex underground karst subsystem. An assumption of a connection between the sinking waters of the Vit river and the Glava Panega spring was made as early as 1887 [28]. During the dry months at the end of summer and autumn, the river water completely sinks and the Vit river dries up.
- Infiltration of rainwater through the entire exposed area of the limestones. An extensive non-drainage basin (36.544 km²) has been formed within the BKG, which covers 58.41% of the area of the geosystem.

During periods of low river water, the bifurcation of the waters of the Vit river changes into piracy, and through the Glava Panega spring, Vit waters are “stolen” by the Iskar river. This phenomenon also has a paleogeographical aspect—it is assumed that before the formation of the antecedent gorge in Boaza area, the Vit river flowed to the northwest and drained into the Iskar river.

The average annual run-off of the Vit river at the “entrance” of the geosystem (near the village of Glozhene) is $8.43 \text{ m}^3/\text{s}$ [30]. According to previous research, it was established that 2.64 to $1.2 \text{ m}^3/\text{s}$ of this water sinks. In summer and autumn, when the flow of the river is below $1 \text{ m}^3/\text{s}$, it dries up. The karst spring Glava Panega has the highest flow (average 3765 l/s) of all concentrated springs in Bulgaria [30]. The measured maximum flow rate is $35,700 \text{ l/s}$ (January 1971), and the minimum is 580 l/s (December 1970). Glava Panega springs in a picturesque karst lake (Siniloto) with a depth of 5 to 11.5 m . In the southwestern rocky ridge above the lake, two spring caves (Upper and Lower Cave) are formed, which mark old spring levels. Scuba diving studies conducted in the lake discovered an underwater rock opening (the Big Crack) in its western part, through which in 1992, a Bulgarian speleologist scuba diver overcame 230 m of horizontal underwater galleries and reached a critical depth of 52 m [32]. The volume of this large and complex underground system can be assessed by the described case of the temporary drying up of the Glava Panega spring in 1867 for 8 h [28].

In order to drain, the water from the lake pierced two griffins in the eastern slope at a depth of 7 and 5 m , over which a rock bridge was formed. At the beginning of the 18th century, the waters flowing through them were dammed and a second artificial lake (Lower) with a depth of up to 7 m was created. It is used as the main source of water from the Glava Panega spring. Under the waters of Lower Lake, three warm (22°C) springs (Topla voda) with a total flow rate of 3 l/s are located, which have been popular since ancient times [30]. Their waters most likely move along their own channels and do not mix with the waters of Glava Panega. The most recent studies suggest that there was hydrothermal activity and mixing of karst and deep mineral waters in the Brestnitsa fault zone [33].

The main research object of the underground subsystem of the BKG is the show cave Saeva Dupka. It is representative of the underground karst of the geosystem, and its status and electrification make it possible to conduct continuous instrumental monitoring. In addition, the cave has very high year-round attendance and it is an example of the impact of tourism on the sustainable development of karst territories.

The entrance to Saeva Dupka cave ($4.2/4.5 \text{ m}$) is 500 m above sea level on a rocky ridge on the northern slope of the Lednishki rat (Figure 3). The cave is subhorizontal with a length of 230 m and a height difference between the highest part (Cosmos hall) and the lowest accessible part (the bottom of Srutishteto hall) of 20 m (height difference relative to the cave entrance at $+3 \text{ m}$ and -17 m , respectively). There are four cave halls. The total area of the cave is 3020 m^2 , and the volume is $28,800 \text{ m}^3$. Saeva Dupka is formed in the epikarst of the vadose zone of the Brestnitsa geosystem and is about 200 – 250 m above the water-saturated (phreatic) zone. The cave has no constant water flow, but rainwater actively infiltrates it through numerous cracks in the rock arch, the thickness of which varies from 5 – 12 to 20 – 30 m . A typical karst relief is formed on the surface above Saeva Dupka, comprising karrens, valogs, and dolines. Weathered clay material (terra rossa) from older stages of relief formation [22,34] penetrated into the cave through them, forming two large alluvial cones in the Concert hall. There is also an alluvial cone in the Stack hall—the doline above this hall is active and visibly growing in recent years, and through the sinking waters, it continues to periodically supply the alluvial cone with clay material.

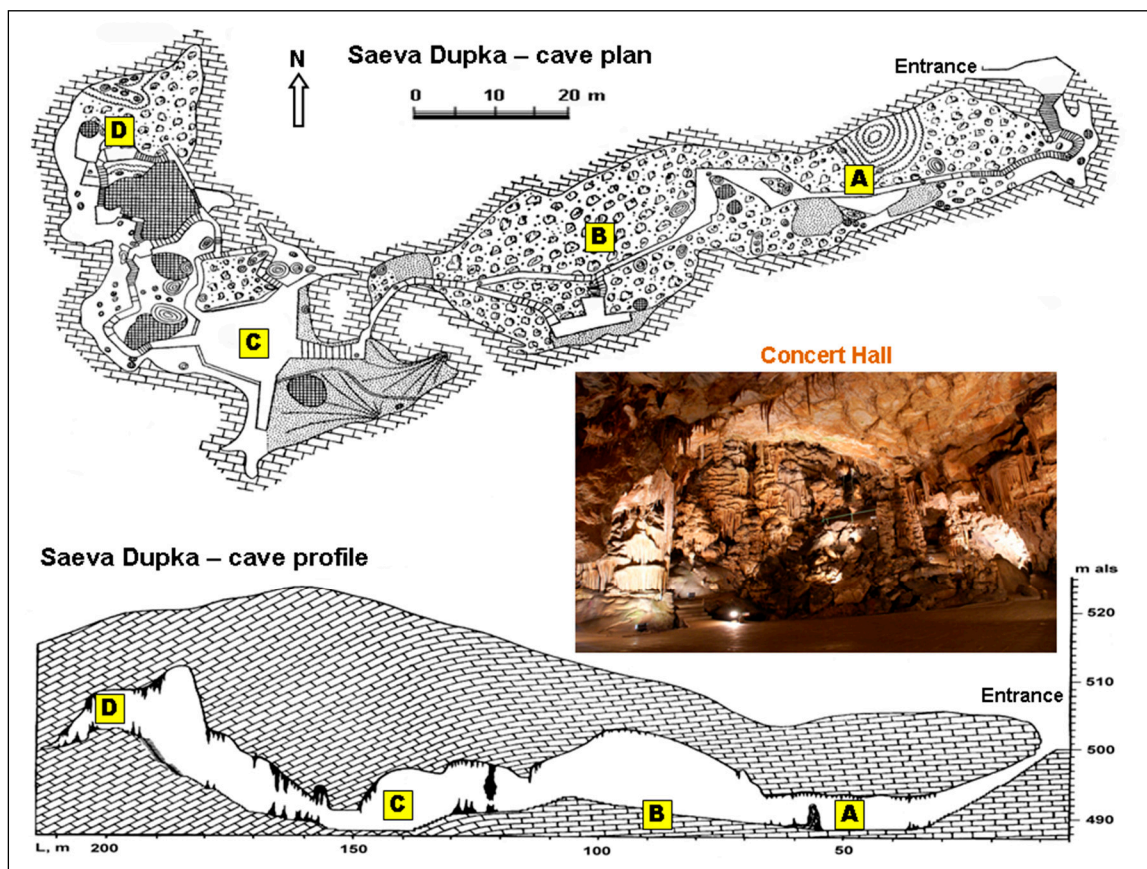


Figure 3. Plan and longitudinal profile of Saeva Dupka cave (by V. Popov, 1969 [34]). Halls in the cave: A. Stack, B. Collapse, C. Concert, D. Cosmos. Photo: P. Stefanov.

The terrain above the cave is covered with humus-carbonate soils (Rendzic Leptosols, LPk) with a thickness of 0.2–0.5 m and locally up to 1–1.2 m in the channels of subsoil karrens. The vegetation consists of shrub-tree derivatives with a predominance of eastern hornbeam (*Carpineta orientalis*) and red hornbeam (*Carpinus orientalis*). Single old oak trees (*Quercus*) have also been preserved, testifying to human-destroyed native tree communities.

3. Methods and Data

The present study is based on an original methodological platform—the ProKARSTerra paradigm [21]. It was developed by the Experimental Laboratory of Karstology (ELK) at the National Institute of Geophysics, Geodesy, and Geography—Bulgarian Academy of Sciences (NIGGG-BAS). The platform is consistent with the systemic nature of karst and global changes and combines three important factors for the sustainable development of karst territories (Figure 4):

- scientific research (main highlights: system analysis, integrated monitoring, and karst cadastre);
- efficient and environmentally friendly management of the karst territories and business with karst resources;
- innovative education and training for and through the karst, for which a specialized educational strategy, ProKARSTerra-Edu, has been developed.

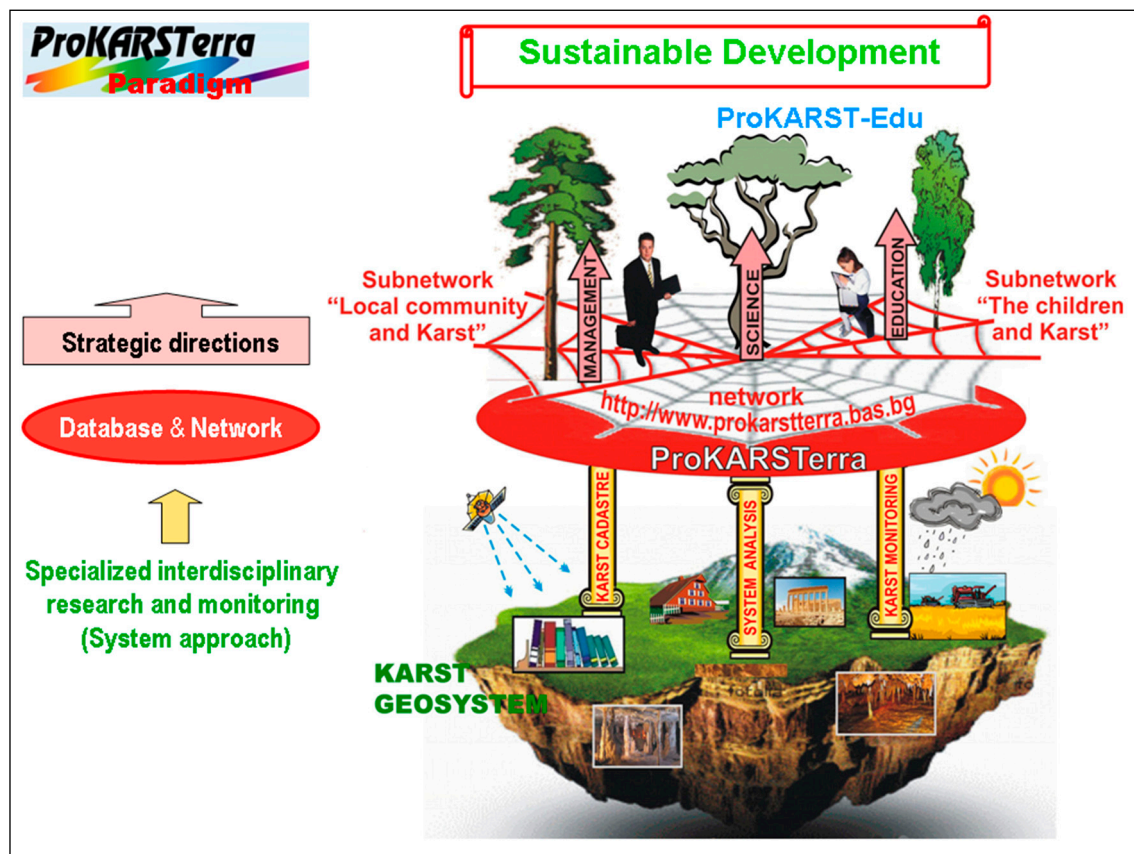


Figure 4. Theoretical-methodological platform ProKARSTerra.

The ProKARSTerra paradigm has been successfully implemented in a scientific network of model karst geosystems of ELK [21], representative of the different types of karst in Bulgaria. One of them is the BKG, in which integrated monitoring has been carried out since 2011. The Integrated Monitoring of Karst Systems (MIKS) is a continuous process of monitoring and recording the parameters determining the state of the geosystem. It also provides objective information about reactions to impacts—both anthropogenic and from various extreme natural phenomena and changes of a global nature. Due to the specificity of the underground part of the karst geosystems, Speleo-MIKS-integrated monitoring of a cave karst system [15] was also developed within MIKS. It covers almost all indicators of the cave environment that can be observed and measured. They are carried out both through expedition trips (in different months and seasons and after extreme situations) and continuously through instruments (including automatic stations and monitoring networks).

Given the specificity of the karst, MIKS in the BKG is concentrated in two main directions:

- Monitoring (hydrometric and hydrochemical) of the water cycle. This is achieved through expedition trips, which have been carried out once every 1–1.5 months since 2010. The objects of the monitoring are surface waters in the recharge zone (precipitation, soil, river, and swamps) and spring karst waters in the discharge zone. Karst groundwater in the transit zone (infiltration/droplet, condensation, cave ice, and cave lakes) is measured and sampled at seven representative points in Saeva Dupka cave. Due to the specificity of the karst waters and the instability of the carbonate balance, the hydrochemical analyses of the water samples are performed “in situ” in the cave and at its entrance with an MP-type field laboratory [35]. This methodology is also used in the analyses of the waters of the Vit river (at the sinkholes), of the Nanovitsa karst swamp, of the soil waters above Saeva Dupka cave, and at Glava Panega spring. If contamination is suspected, water samples are taken and

analyzed in certified laboratories. Lysimeters are constructed to collect soil water and are installed in 2 soil horizons of the Rendzic Leptosol. Simplified versions of condensatometers that collect condensation water have been installed at 2 points in Saeva Dupka. Due to problems with their protection from contamination (dust from visitors and splashes from dripping cave water), the aggressiveness of condensation water, which has an important and still neglected role in speleogenesis, is determined in the cave experimentally [10]. Precipitation (rain and snow) in the area of Saeva Dupka is subject to periodic (seasonal) monitoring. It is collected outdoors under the shrub-tree vegetation and is analyzed “in situ”.

- Carbon cycle monitoring (CO₂ concentration, ppm). This covers atmospheric air, soil air (above Saeva Dupka cave), and cave air (along the longitudinal profile of Saeva Dupka cave), as well as the content of free CO₂ in the waters of the water cycle. Measurements of CO₂ in the air are taken through expedition trips with a periodicity of 1–1.5 months and are carried out with a VAISALA Hand-Held carbon dioxide meter GM70. Since 2011 in the Concert hall and since 2018 in the Stack hall of Saeva Dupka cave, continuous instrumental monitoring of CO₂ has been carried out with GMP222 probes with a range of 1–10,000 ppm. Free CO₂ in the waters is determined by “in situ” titration using the field hydrochemical laboratory mentioned above.

Given the complex system of factors that influence karstogenesis, including current global changes, MIKS considers other elements of the environment and anthropogenic impacts. They may have direct and indirect impacts on both the water cycle and the carbon cycle in the BKG. For this purpose, the following tasks are carried out:

- Meteorological measurements. They are located above the entrance to Saeva Dupka cave. They have been carried out since 2017 with the VAISALA WTW520 automatic weather station with a measurement frequency of 10 min. Precipitation data are supplemented by data from a standard rain gauge installed in 2010 in the village of Brestnitsa. Available data from the National Institute of Meteorology and Hydrology's Lovech weather station are also used.
- Speleometeorological measurements (temperature and relative humidity of cave air, temperatures of cave waters and sediments, and atmospheric pressure). They are carried out during expedition trips at 14 points along the longitudinal profile of Saeva Dupka cave with portable instruments (Assman's aspiration psychrometer with an accuracy of 0.1–0.2 °C and electronic thermometers with metal probes with an accuracy of 0.1 °C). Periodic temperature measurements are carried out in the soil above Saeva Dupka cave. Since 2018, 2 automatic weather stations (WTW535 Weather Transmitter Series (VAISALA)) have been installed in the Stack and Concert cave halls.
- Radiological monitoring (bulk activity/concentration of radon-222 and activity of radiocarbon, ¹⁴C). This is concentrated within the boundaries of the Saeva Dupka cave system and has 3 objectives: the role of natural radiation processes in the cave atmosphere; connection between radon activity and tectono-seismic activity; and radiation protection of visitors and workers in Saeva Dupka cave [15]. Radiological monitoring is carried out in partnership with the Department of Radiation Dosimetry, Nuclear Physics Institute—Czech Academy of Sciences.
- Monitoring of current seismo-tectonic activity. The object of the monitoring is Saeva Dupka cave, which is a natural rock cavity developed in a fault zone and very suitable for this type of measurement. The monitoring is conducted with a TM-71 3D dilatometer installed in 2012 in an open tectonic crack in the Concert hall. Saeva Dupka cave is included in the international network EU TecNet [36].
- Socio-economic monitoring (SEM). This is carried out according to an experimentally developed original methodology for karst territories. In the BKG, it comprises an inventory of the socio-economic infrastructure and monitoring of visitors in Saeva Dupka cave, which has been carried out with an automatic counter since 2019.

MIKS in the BKG is conducted with professional periodically calibrated instrumentation. Instrumental monitoring in the local communication network configured in 2018 in Saeva Dupka cave has a measurement frequency of 10 min. The data are transmitted to a receiving server located in the cave office. It has a continuous connection with ELK, where the processing, storage, analysis, visualization, and management of the databases [15] take place. Such an information system structure allows quick feedback in order to control and adjust the measuring instruments in the cave.

Data from The European Center for Medium-Range Weather Forecasts (ECMWF) and ERA5-Land reanalysis (Copernicus Climate Change Service (C3S), 2017 [37]) were used to reveal the trends in climatic elements in the BKG. The resolution of these data is $0.1 \times 0.1^\circ$ (9×9 km). At this resolution, the geosystem region falls within the boundaries of a total of 4 gridcells, with coordinates of their center being 43° N, 24.1° E; 43° N, 24.2° E; 43.1° N, 24.1° E; 43.1° N, 24.2° E. Accordingly, all values were averaged over these 4 gridcells. The temporal resolution of the data is monthly and the study period is 1979–2022. The climatic elements that are important for the changes in BKG climate are as follows: air temperature at 2 m above the surface, precipitation, evaporation, specific humidity, u-wind at 10 m above the surface, v-wind at 10 m above the surface, and the difference between precipitation and evaporation, which indicates the amount of water remaining in a given territory.

The wind rose is calculated based on the frequency of winds from 8 directions. The actual wind direction at 10 m above the surface level for each month is calculated by simple trigonometric equations using u-wind and v-wind data. U-wind represents the projection of the wind vector on the ordinate and v-wind is the projection of the wind vector on the abscissa. A positive value of u-wind indicates wind from the west, and a negative value indicates wind from the east. A positive value of v-wind indicates wind from the south, and a negative value indicates wind from the north.

Climate change data are processed using statistical methods [38]. The level of statistical significance for all calculations is $p < 0.05$. The trend analysis was performed by means of linear regression. The linear regression represents the relationship between the independent variable (time) and the dependent variable (e.g., air temperature, precipitation, evaporation, specific humidity, etc.) through a linear equation based on the measured values. Spearman's rank correlation was used in order to reveal the relationships between the different climatic elements and the concentration of carbon dioxide in the cave. The correlation coefficients were calculated using the residuals (calculated based on linear regression for each month of the year) of the relevant variables. Calculating the residuals separately for each month removes seasonality, which is typical for most of the climatic elements.

Identification of the main economic activities and bearers of anthropogenic pressure in the BKG is achieved through selected indicators, supported by statistical and other information. They represent the current state of the socio-economic system, which has a direct effect on the karst geosystem. The spatial distribution and quantitative characteristics of the land cover and land use (LC/LU) classes were analyzed using geographic information systems (GISs). A GIS database (KARST.gdb) with a set of reference vector and raster layers has been created. CORINE Land Cover (CLC) from the Copernicus program [39], which contains vector layers for 1990, 2000, 2006, 2012, and 2018, and CORINE Land Cover Change (LCC) for the periods 1990–2000, 2000–2006, 2006–2012, and 2012–2018 were used. The restitution (the return of agricultural land) began in Bulgaria after the political changes in 1989, which caused serious changes in the organization of agriculture. The data were processed within the boundaries of the BKG and organized in summary tables (Pivot tables) in MS Excel. The analyses were performed at level 1 and level 3 of Corine, land cover (Table 1).

Table 1. Nomenclature “Corine, land cover”, Levels 1–3.

Level 1	Level 2	Level 3
1 Artificial surfaces	11 Urban fabric	112 Discontinuous urban fabric
	12 Industrial, commercial, and transport units	121 Industrial or commercial units
	13 Mine, dump, and construction sites	131 Mineral extraction sites 133 Construction sites
2 Agricultural areas	21 Arable land	211 Non-irrigated arable land
	22 Permanent crops	222 Fruit trees and berry plantations
	23 Pastures	231 Pastures
	24 Heterogeneous agricultural areas	242 Complex cultivation patterns 243 Land principally occupied by agriculture, with significant areas of natural vegetation
3 Forest and semi natural areas	31 Forests	311 Broad-leaved forest 313 Mixed forest
		321 Natural grasslands
	32 Scrub and/or herbaceous vegetation associations	324 Transitional woodland–shrub

4. Results and Discussion

The results of our research on the trends in the most actively ongoing global changes and their impact on current karstogenesis in the BKG will be presented in a summarized form. Before that, a brief overview of the stages in the evolution of the geosystem will be made in order to clarify the extent of current changes in the background of cyclical fluctuations reflected in the geological record.

4.1. Stages in the Karstogenesis of the BKG

Drilling studies in the region of the geosystem confirm the great depth of karst processes—up to 250 m [22,23]. The initial stage of karstification is considered to be the young Pliocene (approx. 3 million years ago), when a denudation surface was formed on the limestones [22]. The erosion-corrosion net has been developing along the prevailing 65–80° and 140–175° cracks, directed towards the forming valley of the Voneshchitsa river. During the Quaternary, the region was subjected to differentiated cyclic tectonic movements, also marked by a series of river terraces on the slopes of the Vit, Panega, and Batulska rivers. At the beginning of the Quaternary, the already karstified northern tectonic block (Brestnishki) went down along the Garvanishki fault. This is the reason why its system of underground karst caverns and channels fell below the erosion base (drowned karst). This explains why boreholes here reveal karstification of the limestones at a much greater depth than the groundwater level. The boreholes also pass through channels and caverns filled with residual clay and calcite, indicating subsiding karstification. Continuing karst processes have been gradually transforming the Brestnishki block, and in the middle of the Quaternary, it had a closed karst polje already. This is evidenced by the old Quaternary terraces along its eastern border, which are 32–35 m higher than the bottom of the karst polje [22]. During the Quaternary, the formation of the antecedent gorge of the Vit river began in the locality of Boaza, which caused the reorientation of the Vit river from a tributary of the Iskar river to a tributary of the Danube river.

The full range of floodplain river terraces has been preserved along the left valley slope of the Vit river [22]. They mark the main stages in the development of the karst in the BKG during the Quaternary (the last 2.588 million years): Pliopleistocene—seventh terrace (105–120 m relative height), Eopleistocene—sixth and fifth terraces (80–85 and 55–65 m), Mesopleistocene—fourth and third terraces (35–45 and 25–30 m), and Neopleistocene—

second and first terraces (15–20 and 8–12 m) [40]. The high (4 m) and low (2 m) flood terraces that form the wide riverbed of the Vit river are of Holocene age (11,700 years). The entrances to two of the karst abysses are at the river terraces: Partisan cave is at the third river terrace, i.e., it began to form during the Mesopleistocene, and Planinets abyss is at the high Holocene floodplain terrace. These facts show that the subsidence of the Vit river began no later than the Mesopleistocene, with the oldest sinkholes near the Kamenna Mogila quarter, and the youngest near the village of Glozhene. This is also consistent with regressive erosion during the formation of the Vit valley.

The karstogenesis in the BKG took place along with numerous cyclic climate variations, typical of the Pliocene and Quaternary [1]. Regardless of climatic variations, higher than current temperatures prevailed during the Pliocene and there were correspondingly more active corrosion processes in the limestones, as evidenced by the weathered materials in the karst forms—red clays (“terra rossa”). For the last 2.5 million years (Quaternary), more than 80 glacial episodes have been recorded, during which air temperatures were 5–7 °C lower than current ones. In the interglacial episodes, the trend is opposite—higher temperatures than current ones. This climatically determined cyclicity in karst development is marked in the rich palette of speleothems in the caves of the geosystem. Unfortunately, they have not yet been subjected to dating for the purposes of paleogeographical reconstructions. The available weather databases and the 14-year integrated monitoring of the karstogenesis in the BKG make it possible to track and assess the impact of current climate changes.

4.2. State and Trends in Current Climate Change in the BKG Region

4.2.1. Climate Change Affecting the Surface Subsystem of the BKG

Figure 5 shows the intra-annual course of some climatic elements in the BKG for the period 1979–2022. The average annual air temperature is 10.6 °C, with a minimum in January (−1.1 °C) and a maximum in July and August (21.3 °C). In Saeva Dupka cave, the average temperature varies between 9 and 11 °C. Precipitation in the BKG region has a main maximum in May and a secondary maximum in December. The main minimum is in November, and the secondary minimum is in January. Evaporation is greatest in June (greatest negative value), which is due to the still abundant precipitation in the area and relatively high air temperature in that month. Evaporation is lowest in January due to low air temperatures and less precipitation. An important element of the climate in the BKG is the difference between precipitation and evaporation, which shows how much precipitation water is involved in karstogenesis. This difference has positive values in the period from October to May with a maximum in December. This means that in this part of the year, the area has a water surplus that can accumulate in the soil and rock cracks and drain through the vadose zone, including through the epikarst, as drip water into the caves. Negative values are observed from June to September with a maximum in July. These are the months in which there is a moisture deficit and the BKG loses its water supply. Similar results for the climate of the studied area were obtained, but in this older period, the maximum and minimum air temperatures were lower compared to the current values.

Figure 6 shows the BKG’s wind rose for the period 1979–2022. Panel “b” shows the winter wind rose (January, February, and March), and panel “c” shows the summer wind rose (July, August, and September). The winter and summer months are one month late compared to the traditional presentation of these seasons because in Saeva Dupka cave and generally in the underground parts of the geosystem, it was established that the processes are delayed in time [11]. On an annual basis (panel “a”), the frequency of winds from the southwest is highest (about 40% of the cases). The next highest are south (about 20%) and north (just under 15%). An important indicator is the frequency of winds from different directions in the two opposite seasons—winter and summer. Panel “b” shows that in winter, the southwest direction sharply prevails, making up about 55% of the cases. It is followed by the south direction with about 18% of the cases. In summer (panel “c”), the picture is different. The most frequent wind is from the north, making up about 30% of the cases. The next highest are south (about 22% of cases) and southwest (about 20% of cases).

The main conclusion is that during most of the year (winter, spring, and autumn), winds from the southwest prevail in the studied area. Only in summer does the transport from the north increase, which is related to the intra-annual course of the position of the main baric centers that affect the territory of Bulgaria [41]. Considering that the main potential source of industrial air pollution—the cement plant in Zlatna Panega—is located in the northern periphery of the BKG, the geosystem is threatened by air pollution mainly in summer.

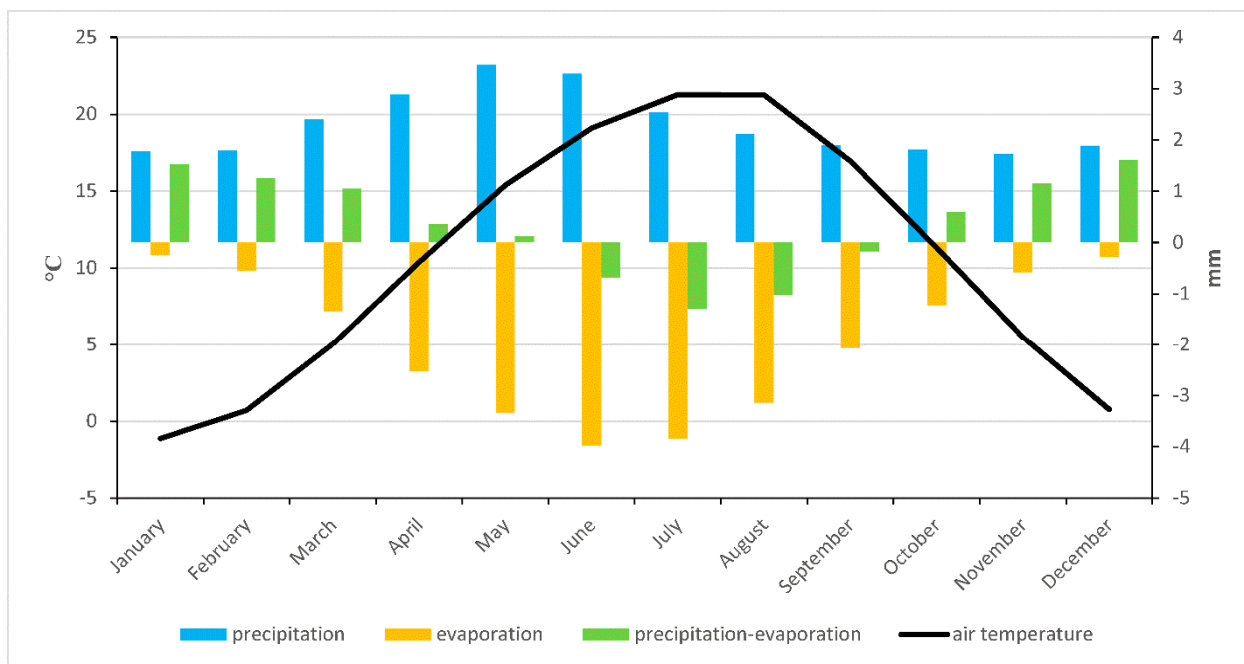


Figure 5. Intra-annual course of air temperature (°C, left vertical axis), precipitation (mm, right vertical axis), evaporation (mm, right vertical axis), and the difference between precipitation and evaporation (mm, right vertical axis) in the Brestnitsa karst geosystem for the period 1979–2022.

Figure 7 shows the emissions of three main air pollutants emitted by the cement plant in Zlatna Panega for the period 2001–2023. The plant is located on the northern border of the BKG. In this sense, the predominant transport of air masses from the north in summer (Figure 6c) can have a significant negative impact on the BKG. Figure 7 shows a decreasing trend of all three air pollutants because of the measures taken by the management of the plant. This means that air pollution (especially in summer) in the BKG has also decreased in recent years, which is a favorable trend for the population and all nature-related economic activities in the area.

The trends in the different climatic elements in the BKG for the period 1979–2022 are shown in Table 2. Those climatic elements that are related to the carbon cycle in the geosystem are selected according to the table in Section 4.4. The air temperature has a statistically significant positive trend in the average annual values. The increase is over 0.4 °C per decade. Most of the months of the year also show statistically significant positive trends. The period from May to August is characterized by positive trends, which are mainly due to the great height of the sun above the horizon and the correspondingly greater amounts of radiation that the Earth's surface receives in summer. There are also significant positive trends in February and November, which are a result of changes in atmospheric circulation.

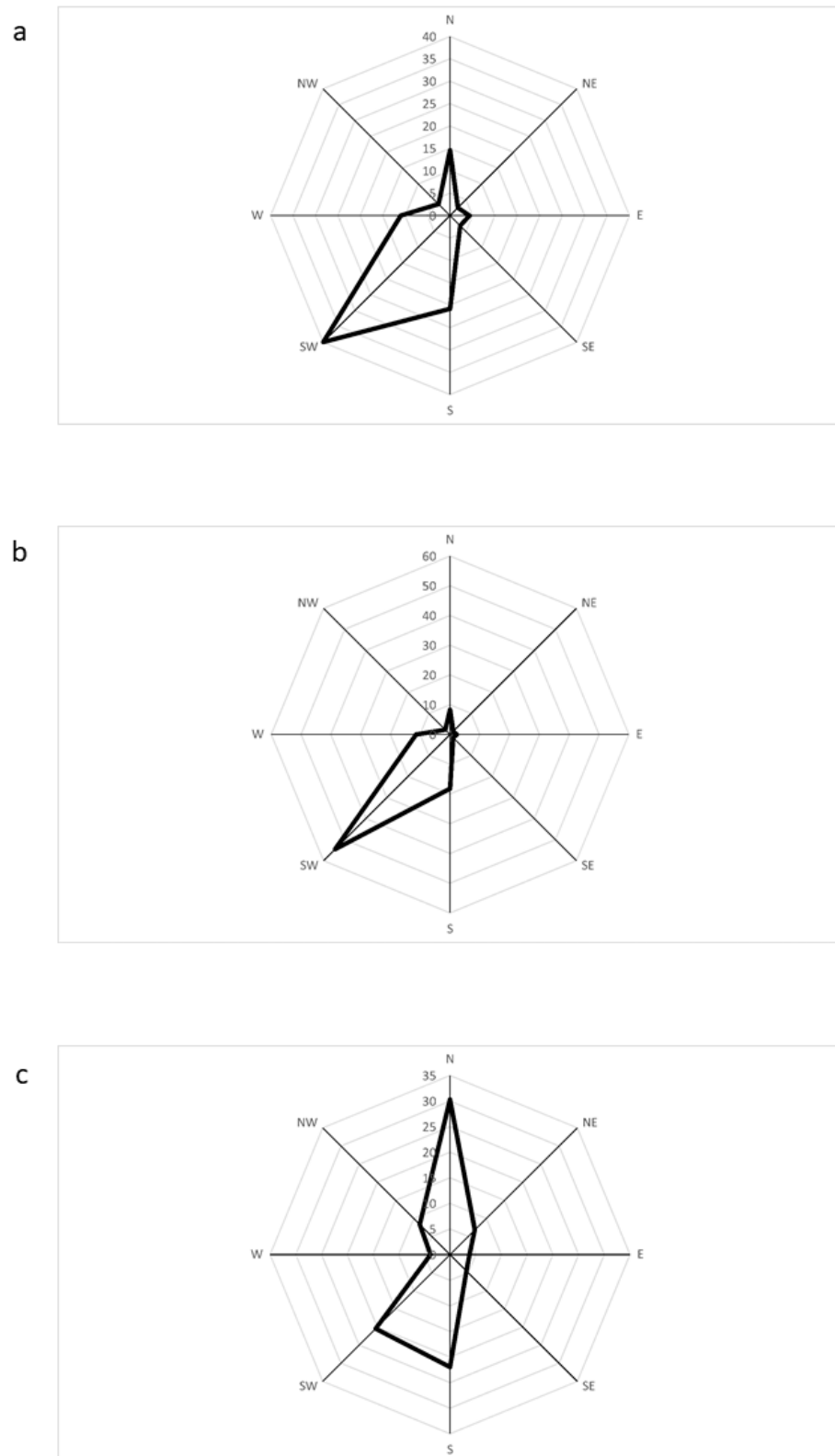


Figure 6. Wind frequency (%) in the Brestnitsa karst geosystem for the period 1979–2022 from eight directions. For: (a) the entire year; (b) winter (January, February, and March); and (c) summer (July, August, and September).

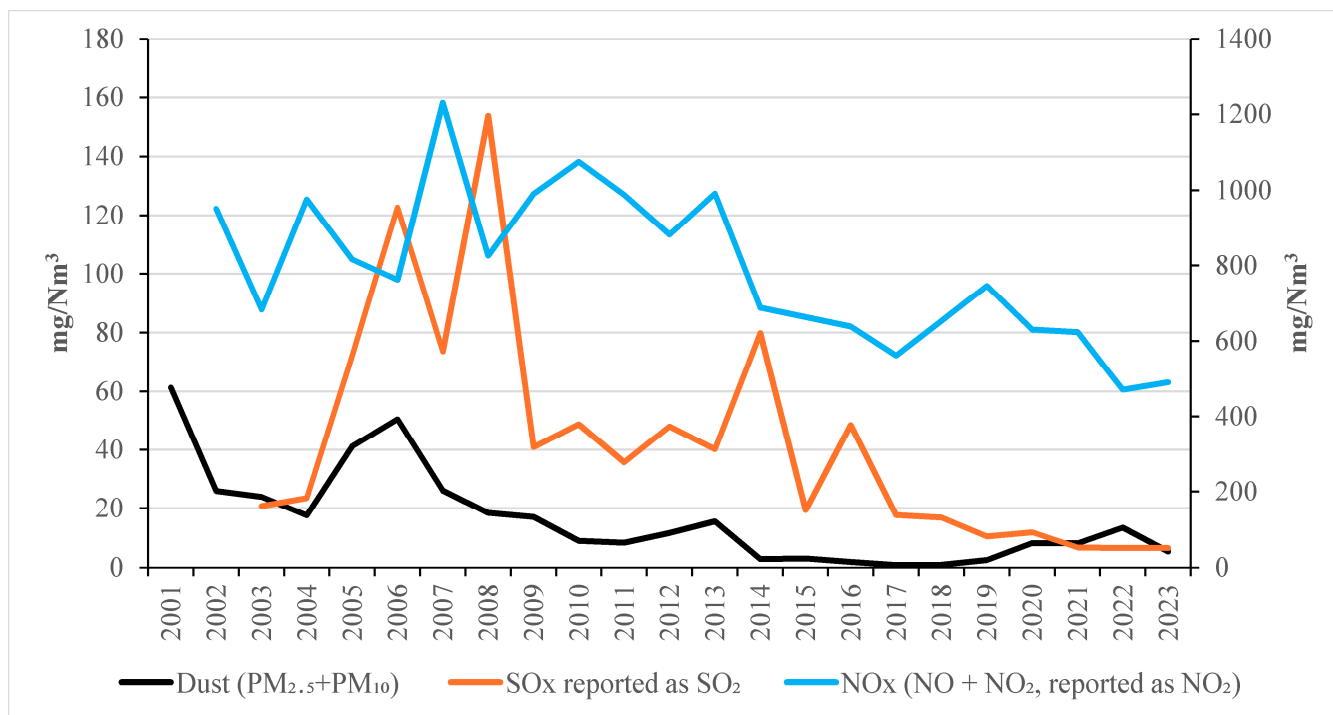


Figure 7. Emissions of three main air pollutants—dust (mg/Nm³, left vertical axis), SOx (mg/Nm³, left vertical axis), and NOx (mg/Nm³, right vertical axis)—from the cement plant in Zlatna Panega for the period 2001–2023.

Table 2. Trends in the different climate elements in the Brestnitsa karst geosystem for the period 1979–2022. Statistically significant values are shown in bold font.

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Air temperature outside (°C)	0.0279	0.078	0.0297	0.0328	0.0340	0.0371	0.0606	0.073	0.0246	0.0114	0.077	0.0373	0.0436
Precipitation (mm)	0.0152	0.0107	0.0116	−0.00519	−0.01889	−0.000829	−0.00994	−0.03106	0.0168	0.0246	−0.01860	0.00295	−0.000228
Evaporation (mm)	−0.001809	−0.00641	−0.00662	−0.00746	−0.00955	−0.006761	−0.004109	−0.000006	0.0089	0.00013	−0.002486	−0.001100	−0.003112
Precipitation–evaporation (mm)	0.0134	0.00425	0.00501	−0.01265	−0.02845	−0.00759	−0.01405	−0.03112	0.0257	0.0247	−0.02109	0.00185	−0.003340
Specific humidity (kg*kg ^{−1})	0.000005	0.000017	0.000002	0.000005	0.000005	0.000021	0.000018	0.000011	−0.000008	0.000006	0.000026	0.000009	0.000010

A statistically significant positive trend is observed in precipitation only in October. In the remaining months, the trends are different and not statistically significant. Average annual values of evaporation increase significantly. Significant positive trends in evaporation are observed in the months of February, April, May, and June. This is due to the good water supply in the study area and rising air temperatures that stimulate evaporation. It decreases significantly only in September, which is due to the low water reserves in the soil cover and the insignificant increase in air temperature. The precipitation–evaporation difference has a statistically significant positive trend in October, which is due to the significant increase in precipitation and insignificant changes in air temperature. This means that during this month, the water reserves in BKG increase, but mainly in the soil cover. There is also a certain increase in the flow rate of Glava Panega spring, which is due to the episodic increased amount of sinking water from the Vit river. In the next month (November), however, there is a statistically significant decrease in this indicator, which cancels the trend from the previous month. In general, there are no significant changes in the water reserves in the studied territory, which are due to climatic factors. The specific humidity increases significantly both as an annual average value and in some specific months—February, June,

and November. These positive trends are due to the positive trends in air temperature, as warmer air can hold more water vapor. At the beginning of the vegetation period, which is the most important for the accumulation of CO₂ in the soil and for the activation of karst processes in the epikarst, positive trends in temperature do not correspond to positive trends in humidity (precipitation–evaporation).

The prevailing consensus in climate science is that the anthropogenic influence on the atmosphere has been prominent in recent decades and the observed trends (the increase in air temperature and changes to atmospheric circulation) in climate elements are due to this factor. Thus, the trends presented here are likely due to human activity, which is a destabilizing factor in terms of the sustainable development of the geosystem.

4.2.2. Climate Change Affecting the Underground Subsystem of the BKG

The results of long-term research in Saeva dupka cave—representative of the underground karst in the BKG—were used. Integrated monitoring, which was organized in the cave system of Saeva Dupka cave (Speleo-MIKS “Saeva Dupka”), has revealed the clearly expressed seasonal dynamics of the ventilation regime, the parameters of the speleoclimate, and the gas composition of the air. Through these, it has also revealed the current speleogenesis. This dynamic, which is directly dependent on the morphology of the cave (Figure 3), has established three speleoclimatic zones [15]: an entrance zone with an external part (entrance area) and an internal part (vestibule), a transitional zone (Stack hall and Collapse hall), and an inner zone, which includes the Concert hall and the higher Cosmos hall with a relatively constant temperature. The entrance zone has the largest annual amplitudes of climatic elements (temperature fluctuations in its two parts from −1.0 to 23.2 °C and from 1.9 to 12.2 °C, respectively). The lowest temperatures were measured at the bottom of Collapse hall, between 6.2 °C in the cold period and 10 °C in the warm period, and the highest year-round temperature is maintained in Cosmos hall between 10.3 °C and 11.5 °C. The relative humidity in the cave is constantly high (average of 98%), and during the warm period of the year (May–June to September–October), active condensation occurs on the cave walls and ceiling.

The ventilation processes in Saeva Dupka cave have two clearly manifested periods—active continuous “winter” ventilation (during the cold half of the year from the beginning of November to the end of March) and static “summer rest” (without ventilation) during the warm half of the year (from the beginning of June to the middle of September). The mechanism that drives the ventilation is the difference in the temperature/density of air in the outside atmosphere and in the first hall (Stack) of the cave. The threshold temperature is 9–9.5 °C in spring and 10–10.5 °C in autumn. Between the two periods in the ventilation regime of the cave, there are transitional stages of “on” and “off” of the natural “fan”, when the temperature of the outside air varies around the temperature of the cave air of the entrance and transitional speleoclimatic zones. The transitional stage is longer in spring (from the beginning of April to the end of May) and much shorter in autumn (lasting about a month in the period from the middle of September to the beginning of November). During the transitional stages, active ventilation phases occur, lasting from hours (at night and early morning) to several days (depending on atmospheric circulation).

A shift of the seasons and a delay in the diurnal and seasonal fluctuations of the speleoclimatic parameters were detected in the cave. This phenomenon is related to the thermal inertia of the karst massif (during the cold season) and the time required for its warming by external atmospheric air and water (during the warm season) [15]. An essential role is played by the ventilation regime of the cave. Cave air temperature extremes are delayed compared to those of the outside atmosphere by 1–2 months. Moreover, the temperature amplitude between extremes in the cave is much smaller compared to that in the outer atmosphere, by up to 2–2.5 times for the entrance speleoclimatic zone, 6–7 times for the transitional zone, and more than 10 times for the inner zone.

The status of the cave (show cave) is the reason why it is subjected to active anthropogenic pressure. The automatic weather stations in Saeva Dupka cave have registered the thermal effect of the visitors. It is highest in the period of low ventilation, which coincides with the most active summer–autumn tourist season. According to data from the automated visitor monitoring for the period June–October 2019 (the year before the COVID-19 pandemic), the cave was visited by 30,500 people, which is 60.3% of the total number of visitors for the year (50,500). During the daily visits (from 300 to 650 people) in this period, a temporary increase in the temperature of the cave air in the Concert hall of 0.4–0.6 °C was recorded. In the Stack hall, which is in the transitional speleoclimatic zone, this increase was 0.1–0.3 °C [15]. A thermal effect, although much weaker, is also exerted by the lighting fixtures in Saeva Dupka cave, which were in a busy mode of use during this period. The temperature in the cave was restored to its initial values during the night.

The combination of speleoclimatic changes and anthropogenic pressure in Saeva Dupka has a particularly strong impact on the gas composition of the cave air. Particularly sensitive is the concentration of carbon dioxide (CO₂), which is the main factor for the karstogenesis. The annual variation of CO₂ concentration is from 400 to 18,000 ppm [15]. Concentrations above 1% are registered after 2017 (Figure 8) and remain permanently above this value from the second half of July to the first half of October, i.e., during the most active tourist season. Given the specific cave morphology, this heavy gas fills the entire cave and, regardless of its elevation (+3/−17 m), no vertical stratification in CO₂ concentration has been established. During the entire monitoring period, a very rapid “blowing” of CO₂ from the cave atmosphere was observed during the first active ventilation processes in autumn (October and less often in September or November). This “plateau” of high CO₂ concentration in the cave formed during the summer–autumn season literally disappears in hours.

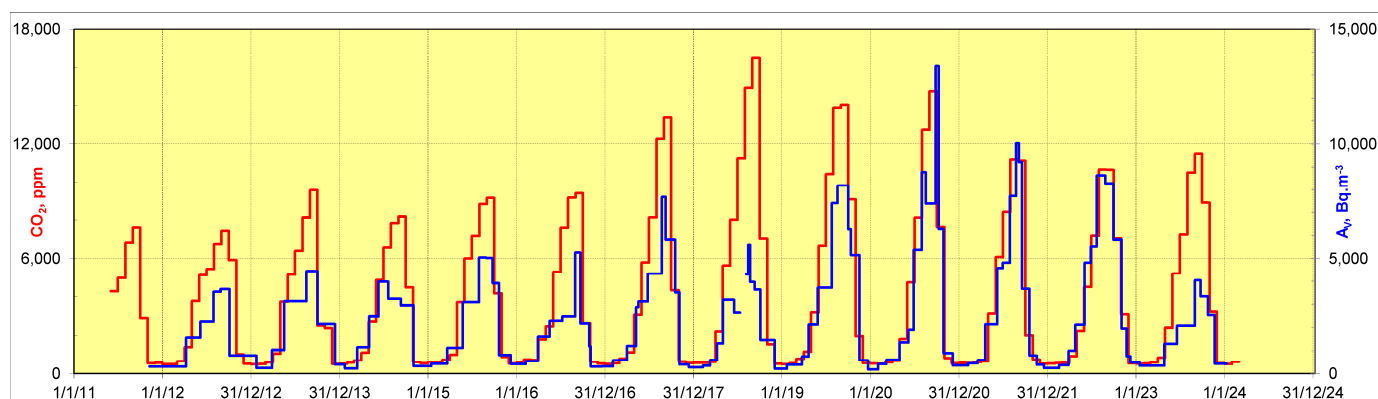


Figure 8. Annual variations of concentrations of CO₂ (red line, left vertical axis) and radon-222 (blue line, right vertical axis) in the Concert hall of Saeva Dupka cave for the period 2011–2023.

A very well-manifested seasonal shift in the regime of the cave’s CO₂ concentration was found during the monitoring period. The minimum (400–600 ppm) is from mid-November to mid-March. At the end of April, the concentration of CO₂ permanently remains above 1000 ppm, and in May it quickly begins to rise and exceeds 5000 ppm. From the end of July to the middle of October, the “plateau” of maximum values (over 10,000 ppm) is formed. The results of the expedition field measurements above Saeva Dupka cave confirm the working hypothesis that the main source of CO₂ in the cave is soil vegetation cover [15]. CO₂ is formed there most actively during the vegetation period. Between late spring and mid-summer (May–July), values of 6000–17,000 ppm CO₂ were measured in the soil above Concert hall. However, given the ventilation regime, the maximum CO₂ concentration in the cave occurs in late summer and early autumn (August–October).

The monitoring has revealed the role of the breathing of tourists as the second main source of CO₂ in the cave [15]. This was registered during the cold half of the year, when,

due to active ventilation, the background CO₂ value was below 500–600 ppm. When there are more visitors (over 150–200 per day) during the winter holidays, the concentration of CO₂ in the Concert hall (with a volume of approx. 10,000 m³) rises to 1400 ppm. Within 2 to 3 days, it returns to its typical seasonal values, which is due to the active ventilation processes. Human breathing has a particularly large share in the concentration of CO₂ in June–October. This is the period without ventilation in the cave, and the visitors number over 30,000 people.

A very strong correlation between the CO₂ and radon (Rn-222) regimes in Saeva Dupka cave was also found (Figure 8). The concentration of Rn-222 in the air of the cave can be within a very wide range—from 112 to 8780 Bq.m³. The maximum values are in the months of August–October, and the minimum are in December–March [15,42]. The difference between the two ventilation periods in the cave is over 7000 Bq/m³, and during the “summer rest”, it varies by 1500 to 2000 Bq/m³ on average.

Monitoring in Saeva Dupka cave proved the presence of fossil carbon released during the dissolution of carbonate rocks and the subsequent deposition of fresh calcite in the cave. The Suess effect (dilution of ¹⁴C radiocarbon content with emissions of fossil carbon occurring because of calcite speleolithogenesis) provides additional information about the features and intensity of current karst processes. The intra-annual amplitude in radiocarbon activity ($\Delta^{14}\text{C}$) is related to the well-expressed seasonal dynamics in the ventilation processes in Saeva Dupka cave [15].

The high concentrations of CO₂ and radon-222 found in the cave air, especially during the most active tourist season, create serious health risks for cave visitors and especially for cave tour guides. Recommendations for solving this problem are listed in Section 4.4.

4.3. Anthropogenic Pressure and Changes in Land Use in the Territory of the Geosystem

Continuous human activity, typical for the karst territory of the geosystem, leads to transformation of karst types and to structural–functional changes in karst geosystems [11,12]. Conversely, these changes in turn affect, sometimes unexpectedly, economic activity and the social environment in karst territories. That is why the identification of anthropogenic pressure, consideration of real and potential problems and threats, and corresponding minimization of different risks are steps in the right direction for the sustainable development of the karst territory. The main sources of anthropogenic pressure in the BKG are various economic activities: agriculture, animal husbandry, forestry, extraction of construction/aggregate materials (limestone and marl quarries), industrial production (cement and clinker), construction of water supply and sewage systems and road infrastructure, creation of landfills (some of them are illegal), and tourism [8,43].

The BKG is sparsely populated. As of 2023, 1961 people live on its territory, including 1083 people in the village of Brestnitsa and 878 people in the village of Glozhene. Another 20 people can be added to this population, living in the Nanovitsa and Gabrovitsa quarters. The demographic crisis in Bulgaria and the depopulation trends of small settlements have directly affected the territory of the geosystem. For the period 1990–2023, the total population decline in the geosystem was 21.7%. However, opposite trends are observed during this period in the villages of Brestnitsa and Glozhene—an increase in the population in the village of Brestnitsa due to the mass settlement of Roma and a decrease in the population of the village of Glozhene (Figure 9A). This has also changed the ethnic composition. In the village of Brestnitsa, about 40% (in 2011) of the population is now Roma and, for the most part, it is poorly educated. However, a positive tendency for the demographic structure is the high share of the population below working age in the village of Brestnitsa (Figure 9B), as well as the remaining high share of the population of working age in both settlements. The small population size is favorable for the inhabited karst territory. However, at the same time, the ethnic composition and low level of education of the local population are reasons for not knowing the specifics of the karst, and this poses serious risks for land use in the BKG.

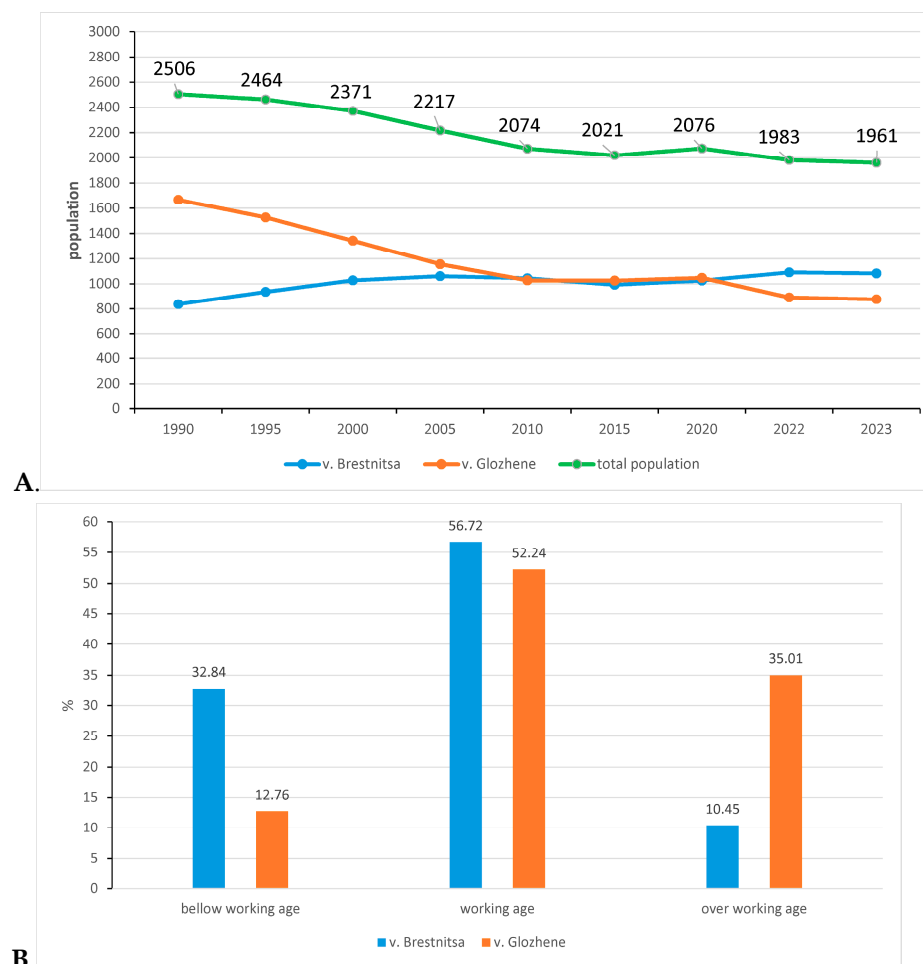


Figure 9. Dynamics of the population and age structure in the villages of Breznitsa and Glozhene: (A). Population dynamics for the period 1990–2023 (number); (B). Age structure for the year 2021 (%). Source: National Statistical Institute—Bulgaria.

A source of local anthropogenic pressure and of potential negative impacts on the karst geosystem is the agriculture developing there. Due to the karst's terrain, arable land in the BKG is limited in area and it is mostly on the bottoms and the gentle slopes of the uvals and dolines, as well as in the karst polje. The socio-economic changes in Bulgaria in the field of agriculture that have occurred over the last 30–35 years and the depopulation of the small settlements (quarters) in the geosystem that began in 1956 are the reasons that most of the limited-area and difficult-to-maintain arable lands have been abandoned and have become overgrown with shrub and tree vegetation. This limits the erosion processes and increases the carbon dioxide content in the soil—the natural karstogenesis is restored.

Current agricultural production in the geosystem is concentrated mainly in Breznitsa karst polje. It is carried out both by local users of agricultural land and by external lessees and tenants. The cultivated crops are wheat, corn, oats, barley, sunflower, etc. Potatoes are traditionally produced. Fruit growing (plums) has been developed on considerably small areas, but in recent years, it has been declining. The European subsidies for direct payments are an incentive for farmers to increase the size of agricultural areas with cereals. That is why it is important to ensure that the economic benefits are not at the expense of ecological balance in the system.

Animal husbandry is poorly developed in the territories of the villages of Breznitsa and Glozhene. The number of livestock farms and the number of animals (cattle, goats, sheep, and pigs) in them show a downward trend. An exception is observed in sheep, which are growing in absolute number on the background of a decreasing number of livestock breeding sites (Figure 10). Regardless of the fact that animal husbandry is poorly

represented, it is a significant polluter of groundwater given the specifics of the karst territory in which it is practiced. These are still unsolved problems from the point of view of the sustainable development of the geosystem. Therefore, it is necessary to implement a number of regulations related to both the habitat of the animals and the hygiene norms at the animal breeding sites [8].

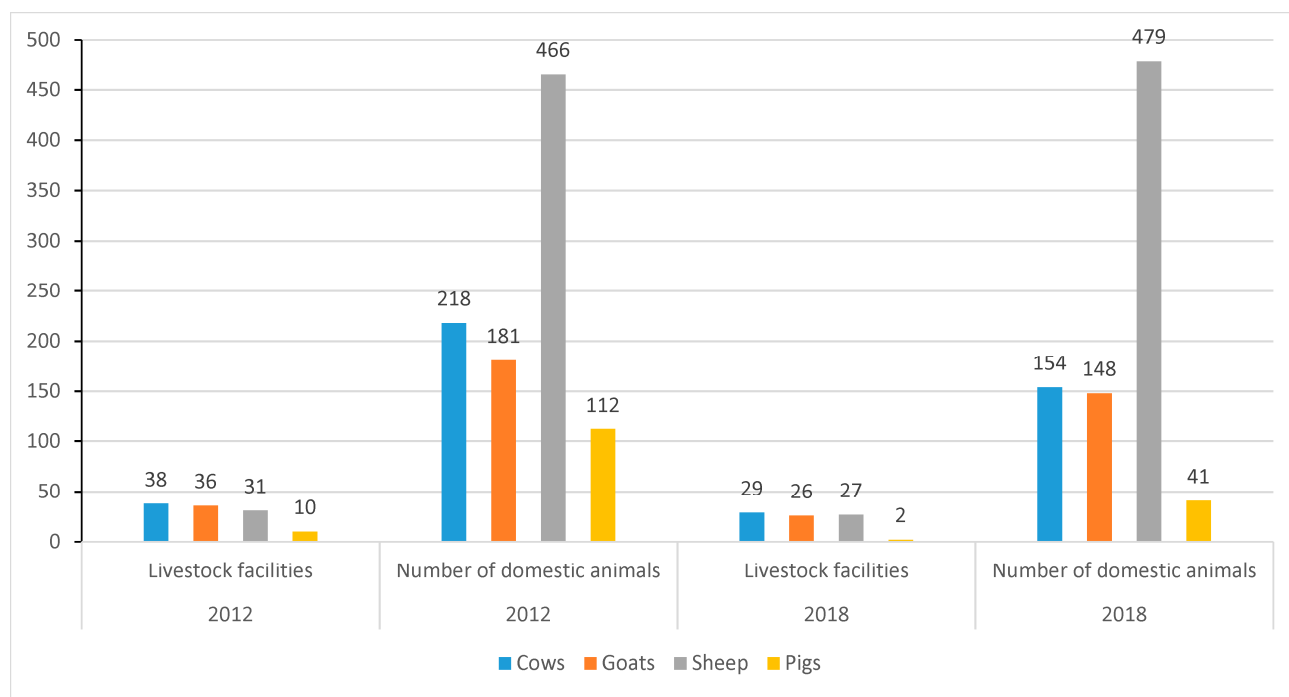


Figure 10. Number of livestock facilities and farmed animals in 2012 and 2018. Source: Bulgarian Food Safety Agency (BFSA).

Another important factor that affects the sustainable development of the BKG is the forestry activities that are carried out. Forests occupy 31.87% of the area, with the predominant ones being broad-leaved. They are located within the territorial limits of State Forestry-Teteven, but some of them are managed by the municipalities of Teteven and Yablanitsa, as well as by private owners. Anthropogenic pressure on forests is through logging (including illegal logging). Afforestation is kept to a minimum.

The BKG is also subject to industrial pressure (mining and processing industry). Active extraction of rock materials (limestone and marl) is carried out in the territory of the geosystem, which has a lasting effect on the karst relief and karstogenesis. The expansion of quarries has also caused the loss of a small area of deciduous forests. Several larger quarries, which were granted concession, operate within the boundaries of the geosystem. They have a total area of 1.46 km² (2018).

The mined rock material is used in cement production and construction. In the period from 2006–2012, there was an increase in the area of the quarries in the land of the village of Brestnitsa, which is in the Concession Area of the “Zlatna Panega Cement” JSC plant. Due to the increased road construction in the area (new sections of the “Hemus” highway), the quarries in the Nanovitsa quarter are also actively functioning. In 2019–2020, the new section of the “Hemus” highway was built through the karst geosystem. It is in the steep southern subsidence slope of the Brestnishki tectonic block and its construction was accompanied by many blasting activities. Large areas of the slope have been cut out and left as open rock “wounds”.

The largest object of the processing industry, which has a long-term influence on the BKG, is the “Zlatna Panega Cement” JSC plant. It is located in the northern periphery near the karst spring Glava Panega. Due to the favorable combination of a large water source (Glava Panega) and unlimited rock resources, the first cement plant was built as early as 1907 by an Italian company on the site of a small lime factory. In 1963, a new State Cement Plant, “Zlatna Panega”, was built with an annual capacity of 1,200,000 tons [44]. However, the production cycle turns out to be a very serious air polluter, especially in terms of dust. The pollution is especially high in summer, given the prevailing atmospheric circulation (Figure 6). After the political and socio-economic changes in Bulgaria in 1989, the plant was purchased by “Heidelberg Cement”, Germany (1997), and in 2003 by the Greek company “Titan”. Titan “Zlatna Panega Cement” JSC is a major producer of clinker and cement, which are sold in the Bulgarian and European markets. Thus, the company provides jobs for the local community.

In view of the ongoing socio-economic changes in Bulgaria over the last 30–35 years and their impact on land use in the BKG, an analysis of the spatial distribution and quantitative characteristics of the land cover and land use classes (LCLU) (Figure 11) was conducted using geographic information systems (GISs). The period studied is 1990–2018.

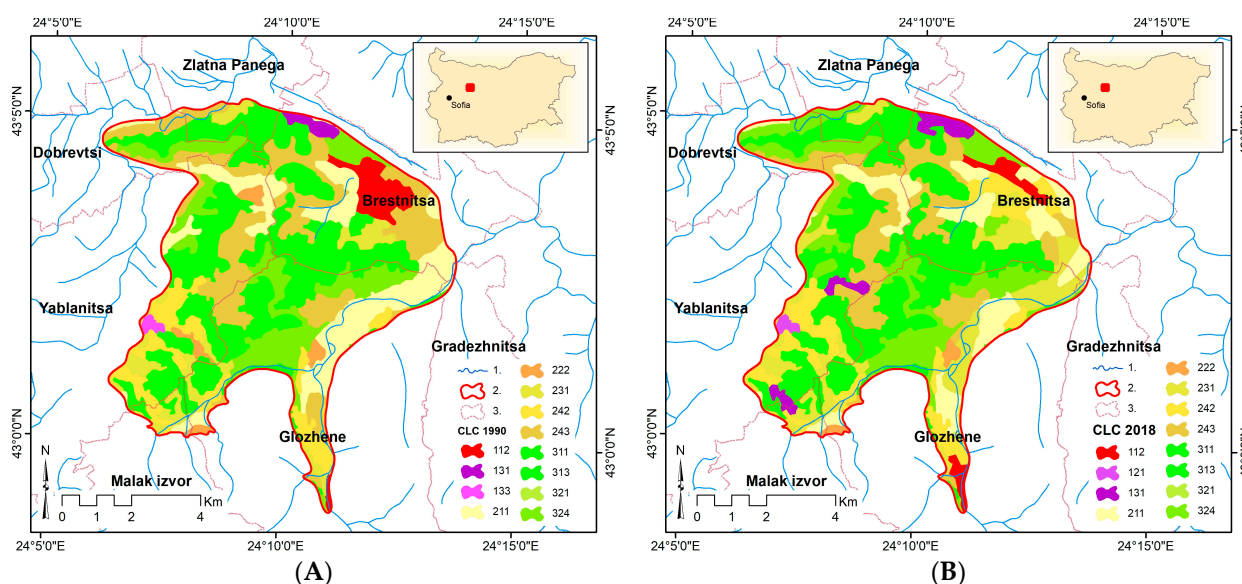


Figure 11. Territorial distribution of Corine, land cover (CLC) level 3 classes (Table 1) of BKG: (A). Year 1990; (B). Year 2018. [39]. 1. River 2. BKG border 3. SLUA border.

There are three classes of land cover and land use according to Corine, land cover level 1, within the boundaries of the geosystem: artificial surfaces (1), agricultural areas (2), and forest and semi-natural areas (3) (Table 1). The entire observed period is characterized with relatively close values of agricultural areas (2) and forest and semi-natural areas (3) (Table 3). There was no tendency in agricultural lands until 2006, when their relative share was close to 50% of the area of the geosystem, and there was a drop to 47.4% in the last two observed years. There is no change in forests in the first three observed years, when their share was just over 46%, and it increased by about 1% in the next two years. The analysis of level 1 of CORINE land cover shows that the areas of agricultural lands and forests are approximately equal, and they are mainly located in the SLUAs of the villages of Brestnitsa and Glozhene and the town of Yablanitsa. There are insignificant dynamics in the shares of the three identified classes in the geosystem.

Table 3. Share and dynamics of Corine, land cover level 1, on the territory of the BKG (%).

Year	1 Artificial Surfaces	2 Agricultural Areas	3 Forest and Semi-Natural Areas
1990	4.9	48.8	46.4
2000	4.9	48.5	46.7
2006	4.5	49.4	46.1
2012	4.7	47.4	47.8
2018	4.7	47.4	47.8

A total of 13 classes of Corine, land cover and land use level 3, were observed in the entire period (Table 4). In the five observed years, 311 broad-leaved forests had the largest share of over 30%, and the trend is a slight decrease of 1.49% at the end of the period compared to the beginning. What is significant is that four classes form about 3/4 of the land cover in the study area. These are 211 (non-irrigated arable land), 243 (land principally occupied by agriculture, with significant areas of natural vegetation), 311 (broad-leaved forest), and 324 (transitional woodland–shrub). In the last two years, the share of 231 (Pastures) overtook the share of 211 (non-irrigated arable land). There is also a permanent increasing tendency of the share of 324 (transitional woodland–shrub). Although only by slightly, there is a greater change in the share of class t2 agricultural areas.

Table 4. Share and dynamics of Corine, land cover level 3, on the territory of the BKG (%).

Year	Corine, Land Cover Level 3												
	112	121	131	133	211	222	231	242	243	311	313	321	324
1990	3.57	0.0	0.89	0.63	14.77	1.62	5.58	7.44	19.37	32.32	1.04	0.01	12.99
2000	3.57	0.0	0.89	0.63	14.77	1.62	5.58	7.44	19.05	32.10	1.04	0.01	13.53
2006	2.00	0.40	2.07	0	17.00	0.70	5.34	10.33	16.06	31.24	1.04	0.01	13.94
2012	2.00	0.40	2.33	0	8.21	0.70	15.14	9.61	13.74	30.98	1.04	0.01	15.95
2018	2.00	0.40	2.33	0	11.40	0.70	11.74	9.61	13.95	30.83	1.04	0.01	16.10

Source: [39] Corine, land cover level 3 nomenclature is listed in Table 1.

The analysis of Corine, land cover, and land use shows that in recent decades, there have been no significant changes in the land cover in the BKG. However, the more important ones are:

- conversion of deciduous forests into quarries (Figure 12). These changes are primarily related to the development of cement production. In recent years, there has already been a reversal process—reclamation of old quarries of the cement plant in the area of Glava Panega spring (planting of orchards). Another part of the old quarries is overgrown with shrub-tree vegetation and there is a process of restoring the soil layer.
- transformation of broad-leaved forests into transitional tree-shrub vegetation as a result of felling (Figure 12);
- transformation of pastures into arable lands (on the slopes of Brestnitsa karst polje and especially on the flood terraces of the river Vit) (Figure 12);
- no change of twice the smaller share of 21 (Arable land) compared to 24 (Heterogeneous agricultural areas) on the background of a drop in their absolute values for all observed years (Tables 1 and 4).

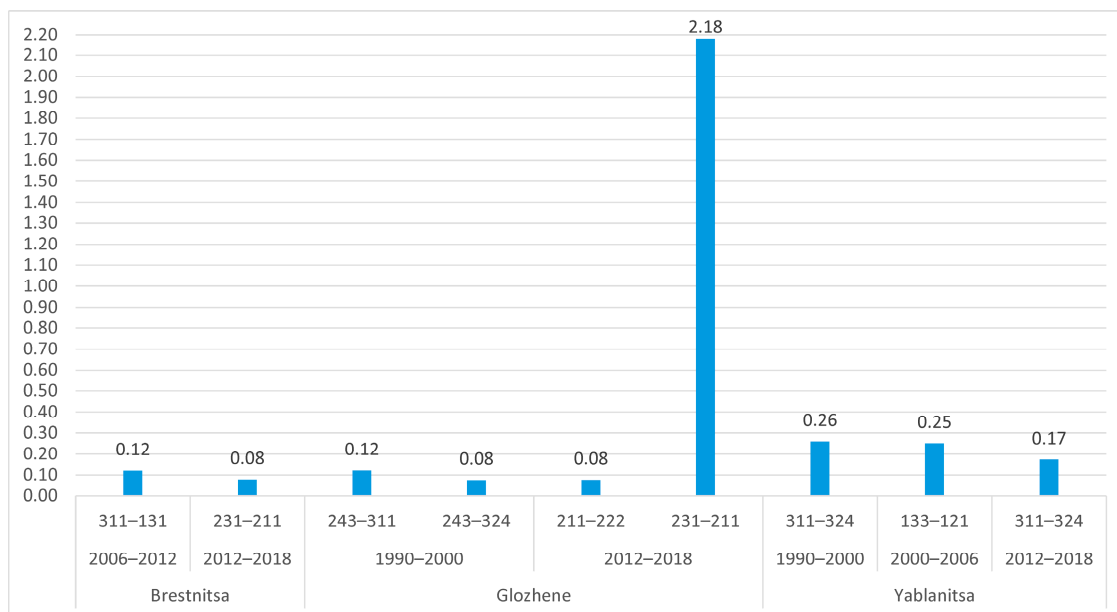


Figure 12. Change in land cover for the studied subperiods by SLUA in the BKG (in km²) [39].

Due to the attractiveness and accessibility of the karst forms, the BKG is an object of various forms of tourism—cave, extreme, bicycle tourism, and ecotourism. They are a potential source of economic benefits for the local community as well. The most significant tourist site is Saeva Dupka show cave (Figure 3). According to Bulgarian legislation, it is state property [15], and in 1962, it was declared a protected area (Natural Landmark with an adjacent area of 20 ha). After improvements and electrification, on 4 June 1967, the cave was opened for tourist visits [34]. Due to the accessibility and rich decoration of speleothems, Saeva Dupka cave quickly gained popularity and became one of the most visited tourist caves in Bulgaria (91,020 visitors in 1981). Saeva Dupka cave welcomes tourists all year round, without a day off. The cave continues to be one of the most popular and visited in Bulgaria—50,500 visitors in 2019 [15]. Due to the COVID-19 pandemic, the number of visitors in 2020 was only 34,823; however, in the following years, it gradually increased, and in 2023, it was 44,258.

In the immediate vicinity of Saeva Dupka cave is the karst abyss Ledenishka jama (Figure 2), which is adapted for extreme experiences through the constructed Via Ferrata. An object of increased tourist interest is the karst spring Glava Panega, declared in 1966 as a Natural Landmark with an area of 1.5 ha. In the recent past, Lower lake was also very popular and visited, where there was a restaurant and boat trips were offered. Another interesting object for tourism is Nanovo swamp (water area of about 20 decares, Figure 2), which is also a fishing site (pike, carp, and tench).

The continuing tourist pressure in Saeva Dupka cave already has lasting negative consequences for both the cave and the geosystem [8,15]. Some of them are dangerous for visitors and staff.

- Outdated and depreciated tourist infrastructure in the cave;
- Widespread “lamp flora”—green “islands” of parasitic vegetation (lichens, mosses, and ferns) developing on the calcite forms, which are illuminated for a long time with “warm” spotlights;
- Cases of vandalism in the cave—scratched and broken calcite forms;
- Periodic pollution of the cave and the adjacent territory with waste thrown by tourists;
- The visitor regime, which is not regulated according to the risks both for the vulnerable cave environment and for the health of the visitors, and especially of the cave tour guides [15,42];

- Non-compliant with the karst specifics and outdated sanitary and hygienic facilities in the cave area: a fountain next to the office (fed by a cistern) without sewerage for wastewater and outdoor toilets with uninsulated septic tanks;
- Auxiliary infrastructure inconsistent with the spatial location of the cave—the parking lot for Saeva Dupka cave and the external toilet serving it are located above the Cosmos hall of the cave.

These serious risks for the cave environment in Saeva Dupka require measures to be taken in order to eliminate them. The cave is a Natural Landmark, but there is no management plan. Caves in Bulgaria are state property, but they are managed by NGOs (in the case of Saeva Dupka) and municipal and park administrations, the controlling function of the relevant state institutions being reduced to a minimum. The results of the long-term research and monitoring in Saeva Dupka are a serious basis for solving these problems. Conservation of the cave environment of tourist caves and minimizing the anthropogenic impacts there is a worldwide problem [45–49].

Anthropogenic pressure on karst territories also has a particularly strong impact on the quality of groundwater. Considering that karst waters provide up to 20–25% of humanity's drinking water [2], this is already a global problem for the sustainable development of karst territories. It also exists in the BKG, where groundwater is highly vulnerable to contamination (chemical, biological, and mechanical). It is directly or indirectly related to the economic activities carried out in its territory. Another cause is the lack of sewers and treatment plants in the settlements (mostly in the village of Brestnitsa) and in livestock farms within the territory of the geosystem, as well as the unregulated disposal of animal feces on the karst's terrain. Yet another cause is unregulated landfills in some of the karst forms—dolines and sinkholes. The water flowing from the newly built section of the “Hemus” highway through the karst geosystem is not purified. Transport traffic is high and makes this road section risky for the geosystem. The problem with the toilets of the Saeva Dupka show cave, which were proven by hydrochemical monitoring to pollute the cave waters [15], has not been resolved either.

Given the allogenic type of karst in the BKG, the sinking waters of the Vit river have a large share in the pollution of its groundwater. The river basin before the sinkholes is very large and includes the lands of various settlements, e.g., the city of Teteven. Unfortunately, these settlements do not have wastewater treatment plants that meet modern requirements, and this makes them potential polluters of the waters of the Vit river. An additional source of pollution are the unregulated dumps on the flood terraces of the river. In the immediate vicinity of the river sinkholes near Glozhene, there was also a municipal landfill for solid household waste (the technical reclamation of the landfill was completed at the end of 2020) [8,15]. Muddying of the Vit river during heavy rainfall (there are a number of cases of flooding in the valley) or intense snowmelt is a source of clay and organic sediments, which enter the underground hydrographic network of the geosystem through sinkholes. It has already been noted that it is very large and complex. To a certain extent, this leads to self-purification of the sinking waters (deposition of clay sediments and pollutants in the high floors of the underground cavities and channels). However, when there are new waves of high water, these sediments are a potential additional source of pollution of the Glava Panega karst spring. Its muddying is typical during heavy rainfall, which is evidenced by the thick clay sediments (silt) at the bottom of Higher and Lower lakes.

Contamination was found in the drip water in Saeva Dupka cave [15]. The results of the hydrochemical analyses in Stack hall prove that during the entire monitoring period, the total mineralization of the drip water was 2–2.5 times higher, and the content of nitrates, sodium, and chlorides was several times higher compared to the infiltration waters in the inner speleoclimatic zone. The source of the pollution was located as the toilet built west of the cave entrance. It is apparently not within the reach of the cave, but dirty liquids seep through the tectonic cracks of the fault zone along which the cave system is developed. In the case of intensive infiltration, the pollution also affects the drip water in Collapse hall.

The karst spring Glava Panega is the most important water source in the entire surrounding region. Water extraction is carried out from the artificially created Lower lake. In terms of chemical composition, the waters are fresh hydrocarbonate-calcium with a total mineralization of 0.25 to 0.56 g/l and meet the Bulgarian standards for drinking and domestic water supply. The permitted water intake is approx. 8.5% of the exploitation resources of the spring [30]. Its waters are used for:

- drinking and domestic water supply (14 settlements from three municipalities, Yablanitsa, Lukovit, and Cherven Bryag, with a total population of over 34,000 people), carried out by Lovech Waterworks. The suction of the pumping station is discharged directly into the griffins between the Higher and Lower lakes. The water pipeline was built in 1984–1996. The authorized water use is 13,810 m³/d;
- industrial water supply—“Zlatna Panega Cement” JSC (allowed water use is 11,233 m³/d);
- water use for hygienic needs—laundry at the exit of Lower lake (allowed water use is 113.26 m³/d).

Due to the socio-economic importance of the spring, a project for Sanitary Protection Zones (SPZs) has been prepared, which is tailored to the karst specifics of the hydrogeological basin [30]. It largely coincides with the boundaries of the BKG.

Despite the fact that the two lakes of the spring are in the first zone of the SPZ (prohibited access), Glava Panega is a popular and massively visited tourist site, and the security regime is not adhered to. Tourist visits are also a source of waste pollution. Another problem related to the implementation of the SPZ is the new section of the “Hemus” highway, which passes through the SPZ. The stipulated measures to prevent the discharge of water from the highway into the SPZ have not been met.

4.4. Expected Effects of the Revealed Trends in Global Changes on the Development of the Geosystem and Guidelines for Its Sustainable Development

The main factors for karstogenesis in the BKG are endo- and exogenous processes. The exogenous processes are mainly controlled by climate and climate changes, and the endogenous ones by the geological structure and tectonic activity.

Because of climate changes, the climate in the BKG region has shifted from temperate continental [50] to transitional between temperate and subtropical (Mediterranean) [41]. The expected result of the revealed trends in climate is the activation of karstogenesis due to the extension of the vegetation period and increased production of soil CO₂. This leads to a higher aggressiveness, especially of soil waters, which are the main factor for karstogenesis in the epigenetic and vadose zones. The regime and intensity of precipitation are also of significant importance. Heavy rainfall, although episodic, causes the deposition of clay sediments in the underground system of the BKG, as well as accelerated soil erosion in the karst territory. In winter, there is a permanent trend of shortening of the period with snow cover. Climate extremes are more typical for the current climate. It has already been mentioned what the short-term impact on the ventilation regime of Saeva Dupka is, which is manifested only during the cold half of the year.

The MIKS in Saeva Dupka cave highlights other impacts of global climate change. The permanent trend of increasing air temperature is particularly clear. In Saeva Dupka cave, when comparing the monitoring data for the period 2010–2023 with the data from speleoclimatic measurements in 1968 [34], it was established that in the entrance and transitional speleoclimatic zones, there is a trend of increasing air temperature by 0.6 to 0.8 °C in the summer–autumn period after 2016 [15]. In the internal speleoclimatic zone, no changes have been detected, but the trend of increasing external air temperatures is reflected in an increase in CO₂ and radon concentrations in the cave [15,42].

Table 5 shows the relationships of some elements of the climate with CO₂ concentration in Saeva Dupka cave (Concert hall) for the period June 2011–December 2022. The approach for the warm subperiod (accumulation) was to consider only the carbon dioxide accumulated in the cave air during the specific month. For this purpose, the values for each

month were calculated as the difference between the value for that particular month and the value for the previous month. For the cold subperiod, due to the constant ventilation in the cave, the CO₂ concentration values measured in the corresponding month are used. During the warm subperiod, evaporation and specific humidity have a statistically significant relationship with carbon dioxide in the cave. Both correlation coefficients show a directly proportional dependence, bearing in mind that evaporation is given in negative values, i.e., larger negative values mean more evaporation, and vice versa. It should be pointed out that both climatic elements (evaporation and specific humidity) are complex temperature and humidity characteristics of the climate in the geosystem. They depend equally on air temperature and moisture content. Air temperature and precipitation individually do not show a statistically significant relationship with CO₂ content in Saeva Dupka cave. The main conclusion is that during the period of accumulation of gases in the cave, the elements of the climate, which represent the complex thermal and humidity characteristics of the atmosphere in the geosystem, are of primary importance. During the cold subperiod, evaporation and specific humidity are again in a statistically significant direct relationship with the concentration of CO₂ in the cave. This means that their influence is significant throughout the entire year. During the cold subperiod, the temperature of the air outside the cave is of leading importance for the carbon dioxide content in Saeva Dupka cave because it controls the ventilation regime. Higher temperatures reduce or stop ventilation in the cave and this leads to an increase in the concentration of CO₂, and vice versa, a decrease in the external temperature causes colder air to enter the cave, ventilating it and causing a drop in the concentration of CO₂.

Table 5. Spearman rank-order correlation coefficients between CO₂ concentration in Concert hall (Saeva Dupka cave) and different climate elements in the warm (V–VIII) and cold (XII–III) subperiods of the year for the period June 2011–December 2022. Statistically significant coefficients are shown in bold font.

Parameters	Concert Hall—CO ₂	
	Warm (V–VIII)	Cold (XII–III)
Air temperature outside (°C)	−0.10	0.49
Precipitation (mm)	−0.04	0.05
Evaporation (mm)	−0.48	−0.39
Specific humidity (kg*kg ^{−1})	0.44	0.51

The statistically significant positive trends in air temperature in February (Table 2), which are a result of changes in atmospheric circulation, also affect the ventilation regime in Saeva Dupka cave. The month of February belongs to the cold part of the year (Figure 5), but the increase in the temperature of outside air leads to an increase in CO₂ content in the cave. However, these periods are short and insignificant, since the cave is still in a ventilation regime during the cold (night) part of the day.

The increasing values of CO₂ and Radon-222 concentrations in Saeva Dupka show cave, especially during the active tourist season (Figure 8), create health risks for visitors in the cave, especially for young children and people with chronic respiratory and cardiac impairments. Tourists stay in the cave for between 30 and 40 min, but the cave guides have a very long daily and annual stay and the risks for them are the highest. A CO₂ concentration of 5000 ppm (0.5%) is considered the maximum permissible for a workplace, and concentrations above 1% can cause headaches and discomfort and endanger human health and life. Particularly dangerous are high concentrations of radon, which cause radiation exposure. The values established during the monitoring in Saeva Dupka cave (average annual concentration 1300–2000 Bq.m^{−3} [15,42]), are many times higher than the reference level of 300 Bq.m^{−3} for workplaces in closed rooms. Given the short stay of tourists, these concentrations do not endanger their health. However, a serious risk

exists for tour guides, and this is proven by the calculated individual effective doses of radiation exposure, which are at the limit of the reference value of 6 mSv. Therefore, the expected increase in concentrations of CO₂ and radon in Saeva Dupka cave (Figure 8) as a result of climate change also increases the health risks and requires corresponding changes in the visitor regime and the working hours of the tour guides. It should be taken into account that visitors are also one of the main sources of CO₂ in Saeva Dupka cave, especially during the tourist period when there is no ventilation in the cave. The limitation of health risks in Saeva Dupka is related to the solution of a very serious problem—the workplace “tourist cave” and the profession “tour guide in a tourist cave” are not included in Bulgarian legislation [15,51]. It is also extremely important to organize and maintain continuous instrumental speleomonitoring in tourist caves (Saeva Dupka being a good example).

The 15-year monitoring of karst waters in the BKG has revealed other important relationships between global changes and karstogenesis. During this period, the share of the sinking waters of the Vit river in the feeding of Glava Panega spring is on average 53% (from 36 to 50% in cases of heavy rainfall and intense snowmelt), and from 59 to 76% in cases of prolonged drought and in cases of the Vit river drying out. River waters have very low mineralization (conductivity on average 212, varying between 152 and 289 µS/cm) and are not aggressive (they do not dissolve limestone). However, the hydrochemical experiments that were conducted with river water in Saeva Dupka cave have shown that, falling into the underground cavities, it is enriched with CO₂ and becomes aggressive [15]. There is a similar effect in the condensed water in the cave [52–54]. It is formed during the warm period of the year (May–June to September–October) on the cave walls and ceiling. Although it is only between 0.034 and 0.203 l/m², the high concentration of CO₂ in the cave during this season makes it very aggressive and proves the important role of condensation in speleogenesis and the volume growth of caves—a scientific aspect that is still poorly developed. Expected trends in climate are likely to extend the period of condensation in the cave. The drip water in Saeva Dupka cave is not aggressive throughout the year. During the warm period without ventilation, it is highly mineralized (electrical conductivity between 600 and 850 µS/cm), and during the ventilation period, due to degassing and the deposition of calcite, its mineralization drops sharply (electrical conductivity between 200 and 250 µS/cm). The CO₂ released through degassing is the third source of this gas in Saeva Dupka cave, but due to ventilation, its concentration in the cave air remains low. The expected shortening of the ventilation period in the cave due to climate change will reduce the duration of calcite deposition. The large volume of calcite forms in Saeva Dupka cave (Figure 3) raises another question—under what climatic conditions were they formed? There is no doubt that a warmer and wetter climate activates karst processes and increases the mineralization of drip waters in the epikarst. However, in the case of Saeva Dupka cave, there is another factor—the ventilation regime—which has changed sharply after the cave’s chimneys (open sinkholes on the surface) were filled with clay sediments, which also formed the cave sediment cones. This has resulted in limiting the intensity of calcite deposition. This tendency will deepen with current climate changes, which shorten the ventilation period in the cave. The model of these expected changes should also be based on the upcoming paleogeographical reconstructions using the speleothems in the cave, which have a very long period of formation.

The mixing of river and underground karst waters is the cause for the relatively low mineralization of Glava Panega karst spring—electrical conductivity averages 395 µS/cm, varying between 300 and 518 µS/cm during the year. Through the “in situ” hydrochemical monitoring of the spring water, it was established that it is aggressive all year round (contains free CO₂), which is not typical for karst springs in Bulgaria. This is probably related to hydrogeological features in the locality of the spring. Aggressive spring waters in Higher lake have carved out two underwater griffins through which they flow, starting the Panega river.

The great economic importance and long-term practical exploitation of the water resources of the BKG raise serious questions about their protection and efficient use. A very important problem is their protection from pollution, especially given the allogeneic karst type of the geosystem. The risks of contamination and the detected violations are mentioned in Section 4.3. It is necessary to specify the SPZs according to the structure of the BKG. Strict control by the relevant authorities for the application of SPZ norms is also needed.

Given the active tectonic regime of the region recorded in the geological history of the BKG, the question of the role of neotectonics in modern karstogenesis is important. At this stage, it was found that the region's predominant vertical uplift had subsided, but there are short-term pulses of seismotectonic activity, especially at fault zones in the geosystem. The proof is the results of the monitoring with a TM-71 dilatometer in Saeva Dupka cave, which was formed in the most active fault zone in the BKG (Garvanishki fault). This is evidenced by old seismogenic and gravitogenic deformations, which are found in cave stalactons and stalagmites [15]. For the period of monitoring with the TM-71 (2012–2023), two stages of tectonic movements are clearly distinguishable: active, with a very clear pulse of tectonic pressure, which ended in 2015 [55], and passive, of relative tectonic calm, which continues until now. Data recorded by the extensometer show that during the first period, the southern block of the Concert hall fault sank by about 0.075 mm, while at the same time, it slipped horizontally to the east by about 0.05 mm. A general trend of fault opening by about 0.05 mm is also observed [55].

Active human activities are superimposed on the endo- and exogenous processes in the karstogenesis. Extensometric monitoring with the TM-71 in Saeva Dupka cave did not register movements due to the blasting works in the quarries of the “Zlatna Panega” JSC cement plant and during the construction of the new section of the “Hemus” highway.

The established land cover changes in the BKG in Section 4.3 lead to structural and functional impacts on the karst geosystem [11,12] and cause transformation of karst types [43], e.g., green karst into naked karst and subsoil karren into karrenfelds (due to intensive erosion of arable humus-carbonate soils or deforestation/felling).

Agriculture and forestry in the BKG are developed on specific azonal karst soils, mainly Rendzic (humus-carbonate). They are shallow and highly susceptible to erosion. The intense and long-lasting erosion causes the formation of bare karst with karst poljes. Therefore, the preservation of Rendzic is particularly important, especially since it is also arable land. In addition to gentle plowing of arable land and taking into account the slope of the slope, the protection of Rendzic also requires regulation and control of the grazing of farm animals. Another serious factor that affects karst soils is forestry activities, especially logging. Clear-cutting should be avoided in karst terrains. In the BKG and especially on the slopes of Brestnitsa karst polje, illegal logging (firewood) is taking place. The construction of forest roads and the removal of timber have an additional degrading effect on soils, especially on steep slopes. In recent decades, artificial afforestation of bare areas has hardly been practiced on the territory of the geosystem, and there is a tendency for natural expansion of areas with shrub vegetation. It also covers abandoned arable lands. Another problem with arable land is soil pollution through fertilization and industrial and construction waste. Given the specifics of the karst territory, control over the use of agricultural land and forests should be a priority for municipal governments [8].

The largest industrial source of impact on the BKG is the cement plant near its northern periphery. The long-term industrial pollution of atmospheric air has the most serious consequences. Given the atmospheric circulation, it is potentially the most dangerous for the territory of the BKG in summer (Figure 6). Due to the serious environmental problems related to cement production, the management of “Zlatna Panega Cement” JSC is already introducing new technologies and strictly adheres to environmental norms, which is why industrial air pollution is minimized (Figure 7). In the period from 2005–2019, there was a permanent decrease in emissions of nitrogen and sulfur oxides in the air, which are the cause of increased acidity of precipitation. The drop in dust emissions is particularly

noticeable. In 2018, three monitoring wells were built in the quarries of the plant to monitor the quality of underground water. Wastewater from the plant is treated through a three-stage treatment installation. All control measurements show that the plant and its quarries are not a source of pollution in Glava Panega spring [56]. The company maintains its own nursery with forest species characteristic of the area, which are used for reclamation of old quarries. There is a biodiversity management plan for the large quarry on the border of the geosystem being developed by the plant. “Zlatna Panega Cement” JSC is a good example of how industrial anthropogenic pressure in karst territory can be reduced according to the requirements for sustainable development.

5. Conclusions

The features of karst geosystems described in the introduction section explain why they are so sensitive and vulnerable to both natural and anthropogenic impacts. However, every system has the potential to adapt to external changes and pressures. If there are episodes of very strong pressure, its individual elements and subsystems undergo structural or functional changes. The latter option can exhaust the potential of the system to adapt and can cause its disintegration. The results of long-term interdisciplinary research in the BKG, which is a classic model natural system, prove that, despite its strong vulnerability, it still has normal development and successfully adapts both to climate change and to anthropogenic pressure. Historically, during its long existence, the geosystem has been subject to much stronger changes in the natural environment (e.g., paleoclimatic), but it has successfully adapted to them. Anthropogenically induced changes in recent decades have had an impact not so much on the functioning of the geosystem but on the quality of its resources used by man. A telling example is the chronic geosystem pollution of underground karst waters, which are the main water source for a very large region. The application of the scientific methodological platform ProKARSTerra (Figure 4) in the BKG proves that it successfully and effectively helps to solve these problems because it combines three areas important for sustainable development: scientific research (1), management of karst territories and business with karst resources (2), and training and education about and through the karst (3):

1. Karst areas worldwide are recognized as critical areas, but the fact that they comprise different karst geosystems is ignored. This requires the study and assessment of risks in the karst territories to be carried out on the basis of determination of the boundaries and structure of the geosystems, in which appropriate integrated monitoring is organized. MIKS, developed for the ProKARSTerra platform, is such a model. It is a base for original studies on the impact of global changes on karst and the role of karst in global changes [12,15]. Therefore, MIKS has a leading role in the assessment of the impacts on karst geosystems with a view to their sustainable development and the choice of effective management decisions.

The geosystem approach should be leading in the first international standard for karst, “Specification of monitoring technology for karst critical zones (KCZs)”. This was developed by the International Organization for Standardization (ISO), and for this purpose in 2018, the Karst Technical Committee (TC 319 KARST) was established, which now comprises 30 countries. At the proposal of ELK, in 2019, the Bulgarian Institute for Standardization (BIS) became a member of ISO/Technical Committee 319. The accumulated Bulgarian experience with MIKS should contribute to the development of this standard.

The practical importance of karst territories and the growing volume of interdisciplinary research, as well as the complexity of this research given its specificity (surface and underground), make scientific integration increasingly imperative. It is also necessary due to the worldwide occurrence of karst and its unique diversity. It creates a wide palette of consequences due to global changes. Thus, the elaboration of effective models for sustainable development requires the creation of an integrated international monitoring network in selected model karst geosystems, representative of the different climatic and natural zones of the planet [3,4,57]. For this purpose, the ELK team has prepared

a conceptual project, “ProKARSTerra-NET: Scientific-practical Network for sustainable development of karst territories in the context of global changes (on the example of model karst geosystems)”.

2. The deepening problems of the sustainable development of karst territories and, at the same time, the poor knowledge of the specifics of karst by the various institutions that manage them, as well as by the business circles that exploit karst resources, require the adoption of adequate measures for the sustainable development of these specific territories. Given that they, and the geosystems that they consist of, are within the boundaries of different territorial administrative units, management and management policies must be integrated at different levels—between municipalities, between economic sectors, and between municipal administrations and the administrations of protected territories. An additional complicating factor is the regulatory deficit regarding karst territories and objects, regardless of the fact that they cover $\frac{1}{4}$ of the area of Bulgaria. This necessitates the preparation, discussion, and adoption of changes in the Bulgarian legislation to guarantee the norms, regulations, control, and protection of the karst territories and geosystems. Achieving this goal requires the interest, activity, and initiative of the communities that inhabit them and exploit their resources, as well as coordination with the karst researchers. A good example in the BKG is the successful cooperation of ELK with the company “Zlatna Panega Cement” JSC and with municipal administrations in the cities of Yablanitsa and Teteven. Various ELK initiatives were carried out together.

3. It is becoming increasingly clear that success in the sustainable development of karst territories cannot be achieved without the necessary knowledge about the nature of karst. In order to reach balanced natural use, development and management of the karst territories together with specialized educational and training programs must be implemented. This is especially imperative given the low knowledge of the specifics of karst by Bulgarian society. Increasing knowledge about karst will have a positive impact both on regional socio-economic policies for the efficient use of karst resources and the development of strategies for sustainable development of karst territories, as well as on the quality of life and economic prosperity of local communities. It is especially important to attract the interest of young people, who are potential users and researchers of the karst territories. The attractiveness of karst and karst formations fuels this interest. For this purpose, ELK has developed a specialized educational strategy, ProKARSTerra-Edu [21]. With the support of UNESCO, three international initiatives of the strategy have already been successfully implemented: the International competition “Karst under protection—gift for the future generation”—with five editions (2005, 2012, 2015, 2019, and 2022), a Traveling Summer School for karst in Bulgaria (2015 and 2023), and The First International Competition for students “Karst—the last “white spot” on the planet Earth” (2019). More than 1000 participants from 26 countries took part in them. The main base for implementation of the strategy is the BKG, which is a unique natural laboratory for innovative training and education about and through the karst with an emphasis on its sustainable development.

Implementation of ProKARSTerra-Edu in educational systems will be an important step towards a change in the previous conceptual model—from traditionally taught narrow scientific disciplines through Earth Sciences to Earth Systems Science. The need for this change at all educational levels is becoming more pressing considering the global changes and the resulting sustainable development problems. For this purpose, karst geosystems, with their clearly expressed systematicity, turn out to be one of the “most visible” and most promising.

In conclusion, it should be emphasized that the application of the developed scientific methodological platform ProKARSTerra helps the implementation of UN goals for sustainable development for the period 2016–2030. Of its 17 goals, nine (№. 3, 4, 6, 12, 13, 14, 15, and 17) directly concern karst territories. Due to the specificity of karst, these goals are more difficult to fulfill in karst territories, especially because of the deepening global changes. Experience stemming from the application of the ProKARSTerra platform would help in solving this problem.

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