

IMPACTS OF CONTEMPORARY GLOBAL CHANGES ON THE WATER
CYCLE OF THE BRESTNITSA KARST GEOSYSTEM IN NORTHERN
BULGARIA

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Brestnitsa Karst Geosystem (BKG) was formed in the Pre-Balkans in Northern Bulgaria. It is developed in Mesozoic organogenic limestones with a very high carbonate content. A complete karst morphological complex has been formed in the relief of the geosystem, which is the result of the combination of autogenous and allogenic types of karst. The BKG region is located in the transitional area between the subtropical and temperate climate. The karst aquifer is recharged by infiltration through the aeration zone of precipitation, irrigation and waste household and fecal waters from livestock farms and inflow of river waters and periodic surface runoff of precipitation waters into sinkholes. The specific structure of the karst geosystem is the reason why its water cycle is very sensitive to global changes of both natural and anthropogenic types and is highly vulnerable to pollution (mechanical, chemical, bacteriological). This is a serious problem, because the geosystem drains into the karst spring Glava Panega, which is the highest flow concentrated spring in Bulgaria. Its waters are used for industrial and drinking-domestic water supply. The aim of this study is to track and analyze the consequences of global changes on the water cycle through application of a geosystem approach and the original model for integrated monitoring of karst geosystems (MIKS). Special attention is paid to the sources of anthropogenic pressure influenced by socio-economic changes in regional, national and global aspects and their impact on the pollution of karst waters.

Keywords: Karst, Brestnitsa karst geosystem, Water and Carbon cycle, Geosystems approach, Integrated monitoring of karst systems (MIKS), Global changes, Anthropogenic pressure

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ВЪЗДЕЙСТВИЯ НА СЪВРЕМЕННИТЕ ГЛОБАЛНИ ПРОМЕНИ ВЪРХУ ВОДНИЯ ЦИКЪЛ НА БРЕСТНИШКАТА КАРСТОВА ГЕОСИСТЕМА В СЕВЕРНА БЪЛГАРИЯ

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Резюме: Брестнишката карстова геосистема (БКГ) е формирана в Предбалкана в Северна България. Тя е развита в мезозойски органогенни варовици с много високо карбонатно съдържание. В релефа на геосистемата е формиран пълен карстов морфоложки комплекс, който е резултат от комбинацията на автогенен и алогенен тип карст. Подхранването на карстовия водоносен хоризонт на БКГ се осъществява чрез:

- Инфилтрация през зоната на аерация на валежни и почвени води и на поливни води по цялата разкрита площ на варовиците;

- Инфлуация в понори на речни, повърхностни отточни и отпадъчни води. Най-голям е дялът на инфлуация на води от р. Вит в участъка между речните проломи при с. Гложене и в местността Боаза;

- Кондензация на водни пари в зоната на аерация.

БКГ се отводнява в карстовия извор Глава Панега – най-високодебитният (ср. 3764 l/s) концентриран извор в България. До 8,5 % от неговите води се използват за промишлено и питейно-битово водоснабдяване. Специфичната структура на карстовата геосистема е причина водният цикъл в нея да е много чувствителен на глобалните промени както от природен, така и от антропогенен тип и да е силно уязвим на замърсяване (механично, химично, бактериологично).

Цел на представеното в тази публикация изследване е чрез приложението на геосистемен подход и оригинален модел за интегриран мониторинг на карстови геосистеми (МИКС) да се проследят и анализират последиците от глобалните промени върху водния цикъл. Мониторингът се провежда от 2010 г. в 3 форми: експедиционен, стационарен (в пещерната система Съева дупка и в нейната прилежаща територия) и дистанционен (с налични данни от измервания със спътници в орбита около Земята). За идентифицирането на въздействията от човешката дейност върху карстовата геосистема и нейния воден цикъл е приложен специално разработен модел за социално-икономически мониторинг.

Резултатите от провежданите изследвания са обобщени в 2 аспекта:

1. Роля на водния цикъл в карстогенезиса. Хидрохимичните анализи доказаха, че в карстогенезиса най-активни са валежните и почвените води (със съдържание на агресивен CO_2 съответно 3,6 mg/dm³ и 8,6-9,2 mg/dm³). В разширяването на подземните карстови кухни участие имат и кондензните води – в пещерата Съева дупка те съдържат средно 3,3 mg/dm³ агресивен CO_2 . Капковите води в пещерата се отличават с най-висока минерализация – специфична електропроводимост средно 678 $\mu\text{S}/\text{cm}$ с вариации от 327 $\mu\text{S}/\text{cm}$ (през зимата) до 819 $\mu\text{S}/\text{cm}$ (през лятото и началото на есента). Тези големи сезонни вариации се дължат на режима на въглеродния цикъл в пещерата, който се управлява от естествената пещерна вентилация. Тя е причина калцитни пещерни форми да се образуват само през студеното полугодие, когато капковите води се дегазират вследствие ниските концентрации на CO_2 в пещерния въздух. Интересен и

нетипичен за карстовите извори е Глава Панега, който целогодишно съдържа агресивен CO_2 (от 0,7 до 28,6 mg/dm³). Причината е, че изворът, който дренира водите от БКГ е в разломна зона.

3. Въздействия на глобалните промени (климатични промени и антропогенен натиск) върху водния цикъл. Анализирани са климатичните тенденции в района на БКГ за периода 1950–2026 г. и са изчислени средномесечните и средногодишните трендове в различни климатични елементи. Предвид водещата роля на валежите във водния цикъл на БКГ са показани и вариациите на броя дни без валеж и на броя дни с валеж над 20 mm по години.

Антропогенните въздействия върху БКГ в исторически план са обобщени в 4 периода. Последиците от антропогенния натиск върху водния цикъл на геосистемата са разгледани в 3 аспекта:

1. Стопанско използване на водите (промишлено и битово водоснабдяване, водопой на животни и поливно земеделие).

2. Промени в земеползването, които рефлектират върху количеството и качеството на инфилтрационните води в геосистемата.

3. Замърсяване на инфлуационните и инфилтрационните води – много сериозен проблем в БКГ, който е представен с конкретни примери.

Заключението от направените изследвания е, че БКГ въпреки голямата си уязвимост все още има нормално развитие и успешно се адаптира както спрямо климатичните промени, така и спрямо антропогенния натиск. Антропогенно предизвикваните през последните десетилетия промени имат влияние не толкова върху функционирането на БКГ, колкото върху качеството на използваните от човека нейни ресурси, от които най-важни са водните. Показателен пример е хроничното за геосистемата замърсяване на подземните карстови води, които са основен водоизточник за много голям регион. На този фон са обобщени проблемите и отговорностите за опазването на карстовите води в БКГ. Проведеното изследване и резултатите от него потвърждават и ефективността на разработения и приложен геосистемен подход.

Ключови думи: карст, Брестнишка карстова геосистема, воден и въглероден цикъл, геосистемен подход, интегриран мониторинг на карстова геосистема (МИКС), глобални промени, антропогенен натиск

INTRODUCTION

In territories built of carbonate rocks, some of the most typical geosystems are formed - karst. Their genesis is closely related to the joint course of two cycles - water and carbon - as a result of which the waters are saturated with carbonic acid and, by dissolving the carbonate rocks, they form the karst forms and the structure of the karst geosystems. They are complexly structured and material-energy interactions take place between their parts at great depth (Andreychouk and Stefanov 2021; Stefanov et al. 2025). Thus, karst geosystems have a well-defined vertical structure

with two subsystems - surface (karst relief) and underground (karst cavities and channels). There is high structural permeability between them, which is the reason for the high vulnerability of karst geosystems. Another their characteristic is the frequent discrepancy of the boundaries between the surface and underground subsystems. The structure of karst geosystems and the active and complex water cycle make them important natural reservoirs of groundwater. Therefore, they store one of the most important and increasingly relevant global resources - water. About 10% of the world's population consumes drinking water from karst aquifers (Stevanovic 2017, 2019). A comprehensive review of publications with a focus on water resource management in the context of climate change was made by Ciampittiello et al. (2024). Some of the publications also focus on the water cycle in karst, e.g., Liu et al. (2020), as well as on the protection of karst waters (Gutiérrez et al. 2014). This problem is becoming increasingly relevant because karst geosystems, due to their high vulnerability, are exposed to increased impacts, especially against the background of increasing global changes – natural and anthropogenic (Vörösmarty et al. 2000; Nojarov et al. 2024; Stefanov et al. 2025). This requires a good knowledge of the specifics of karst geosystems, which is a prerequisite for the effective use of their water resources.

Karst is widespread in Bulgaria (Popov 2002) and various karst geosystems have been formed. A typical example is the Brestnitsa Karst Geosystem (BKG) in Northern Bulgaria (Stefanov 2020; Stefanova and Stefanov 2021; Stefanov et al. 2023, 2025; Nojarov et al. 2024), which is the subject of this study. It aims, based on the geosystem approach and the conducted integrated monitoring, to clarify the impacts and consequences of global changes on the water cycle in the geosystem, as well as their effect on modern karstogenesis and on the economic use of karst water resources. This is especially important considering that karst waters in BKG are vulnerable (naturally unprotected) to surface pollution and belong to the type of highly vulnerable waters (Antonov and Danchev 1980).

CASE STUDY AREA

BKG has an area of 62.57 km² and was formed in the Pre-Balkan block step in Northern Bulgaria (Alexiev 2002). Karstogenesis occurs in micrograined organogenic (reef) limestones (J3-K1bs) with a thickness between 200 and 450 m (Tsankov et al. 1991; Cheshitev et al. 1994), which have a very high carbonate content – 95-99% (Kovachev 1959; Popov 1979). The region of the geosystem is located in the transitional zone between the subtropical and temperate climates (Nojarov 2017). The average annual temperature for the period 1996-2025 is 11.1°C. The monthly minimum in temperature is in January, and the maximum is in July and August

(Nojarov et al. 2024). The prevailing winds are southwest, and the frequency of northerly winds increases in summer.

The geosystem is representative of classical karst and a complete karst morphological complex of the nested type is formed in its relief (Fig. 1). Complex connections are established between precipitation, surface flow and groundwater within the boundaries of the BKG and hydrogeological zones classic for karst are formed (Kovachev 1959; Galabov et al. 2000; Penchev and Velichkov 2012; Nojarov et al. 2024). It is characteristic of the geosystem that it is formed as a combination of allogenic and autogenic types of karst (Jakucs 1979). The karst aquifer of the BKG is recharged in three ways:

- Infiltration through the aeration zone of rainwater and irrigation water over the entire exposed area of the limestones. A vast undrained basin (36.544 km²) has been formed within BKG, which covers 58.41% of the geosystem's area (Nojarov et al. 2024) (Fig. 1).

- Condensation of water vapor in the aeration zone.

- Inflow into sinkholes of river, runoff and wastewater. The largest share of inflow of water from the Vit river (directly through river sinkholes and through the alluvial terrace) is in the section between the river gorges near the village of Glozhene and in the Boaza locality. Three sinkhole areas are localized in the riverbed (Fig. 1). In summer and autumn, when the river flow is below 1 m³/s, after the sinkholes near the quarter Asen (locality Yamite), the river dries up.

The underground karst waters of BKG are drained into the Glava Panega spring, which is also the outlet of the geosystem. It is pressurized and flows into a natural lake (Upper Lake, Siniloto), which flows underground into the artificially created Dolno Ezero, from which the Panega River starts (also known as Zlatna Panega - from the old name Altan Panega). A hypothesis about a connection between the sinking waters of the Vit river and Glava Panega spring was made as early as 1887 (Shkorpil 1900). On December 10, 1937, an experiment was conducted with the coloring of the river waters, but it ended without results (Panchev 1938). In 1947 and 1955, indicator experiments with table salt conducted by hydrogeologists proved that the sinking river waters at Glozhene and at quarter Asen flow into the karst spring Glava Panega (Kovachev 1959). The complex and very large volume of the BKG structure as an underground water reservoir was revealed by the described case of temporary drying of the Glava Panega spring in 1867 for 8 hours (Shkorpil, H. & K., 1900).

BKG is a typical example of underground piracy of waters from the Vit river into the Iskar river through its tributary, the Zlatna Panega river. However, this piracy through the karst is inherited, because in the geological past, before the formation of the Boaza Gorge, the Vit river flowed into the Iskar river (Nojarov et al. 2024).

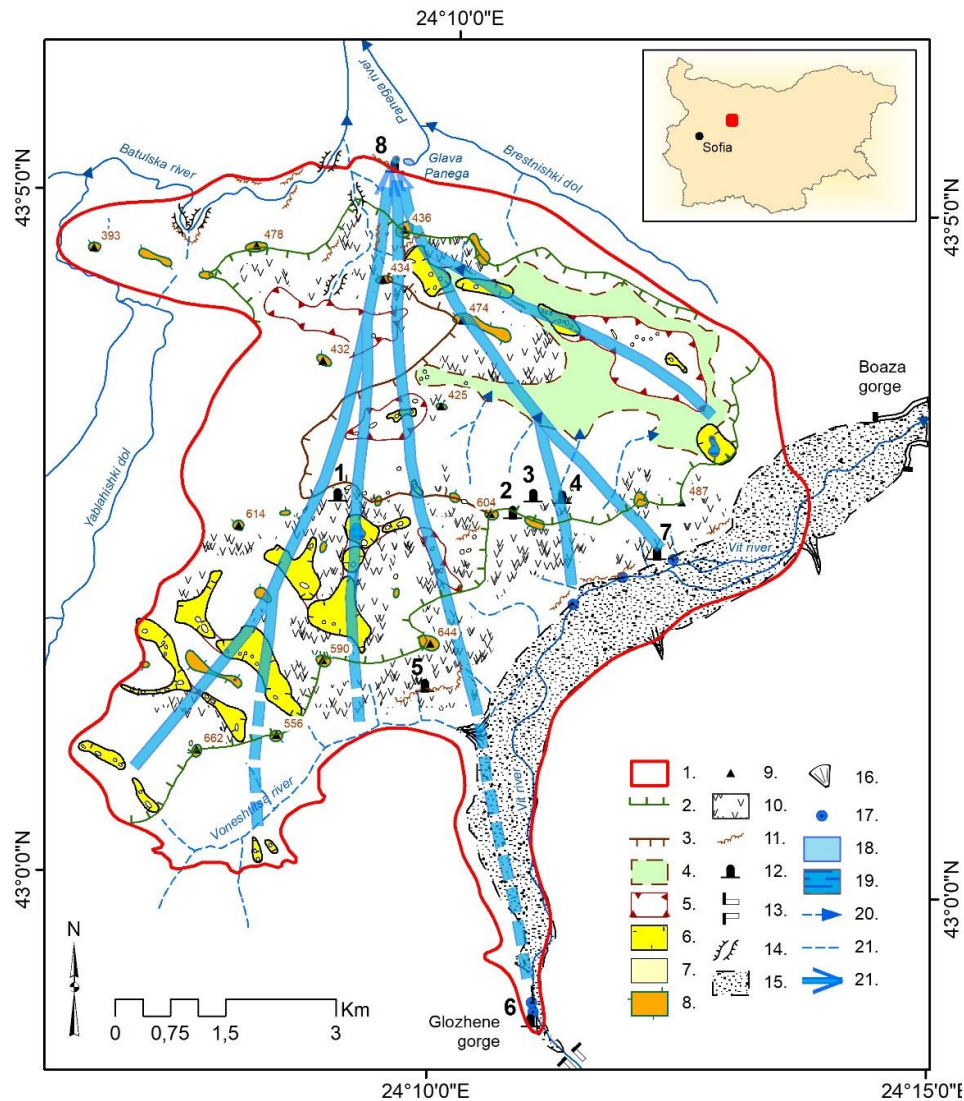


Fig. 1. Structure of Brestnitsa karst geosystem (after Nojarov et al. 2024): 1. Geosystem boundary; 2. Boundary of the non-drainage area; 3. Boundary of karst polje; 4. Bottom of karst polje; 5. Border of uvala; 6. Valog; 7. Doline; 8. Hum; 9. Peak with elevation; 10. Karrenfeld; 11. Rock wreath; 12. Cave (numbers indicate the entrances to: 1. Bezdanniyat pchelin; 2. Golyamata Ledenitsa; 3. Ledenishka yama; 4. Saeva Dupka cave; 5. Draganchovitza; 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

According to the data from drilling studies (Kovachev 1959), the groundwater level in the Brestnitsa polje is 40 m below its surface, but through exploratory drilling, karstification of the limestones was established more than 150 m below this level. This “drowned” karst is the result of the tectonic subsidence of about 150-200 m of the northern Brestnitsa block of the Garvanitsa fault (Kovachev 1959; Popov

1979; Nojarov et al. 2024; Stefanov et al. 2025). Brestnitsa karst polje was formed in the already formed Eopleistocene graben. In 1893, after intense rainfall, the groundwater level in the polje rose sharply and caused flooding. Fountains began to gush from the sinkholes. A temporary lake measuring 1000/500 m was formed, which drained over 12 days (Shkorpil, H. & K., 1900). In the high part of BKG, south of the fault, karst processes occur at a depth of over 250 m. It is assumed that the underground flow of karst waters in the geosystem has a common level (Kovachev 1959).

METHODOLOGY OF THE STUDY

The complex structure of BKG and its highly vulnerable water cycle require interdisciplinary research within the framework of a geosystems approach. For this purpose, the original scientific and methodological platform ProKARSTerra was used, which was developed by the Experimental Laboratory of Karstology (ELK) at the National Institute of Geophysics, Geodesy and Geography-BAS based on many years of research experience (<http://www.prokarstterra.bas.bg/lab/methodology.html>). ProKARSTerra is consistent with the systemic nature of karst and global changes, and it is successfully implemented in a scientific network of model karst geosystems of ELK, representative of the different types of karst in Bulgaria. One of them is BKG.

ProKARSTerra also includes an original model for Integrated Monitoring of Karst Systems (MIKS). It is a process of continuous or periodic observations and registrations of the parameters determining the state of the geosystem (Stefanov et al. 2025). MIKS has been conducted at BKG since 2010 and provides objective information on the reactions to impacts - both anthropogenic and various extreme natural phenomena and changes of a global nature. Due to the specificity of the underground part of karst geosystems, Speleo-MIKS has also been developed within MIKS - integrated monitoring of the cave karst system of the Saeva Dupka cave (Stefanov 2020; Nojarov et al. 2024; Stefanov et al. 2025). MIKS at BKG is focused on 2 main areas: carbon cycle monitoring (CO₂ concentration, ppm) and water cycle monitoring (hydrometric and hydrochemical), which is the object of the present study. It is carried out in 3 ways (Stefanov et al. 2025):

1. Periodic field trips using portable instruments to measure at fixed points, selected according to the structure of the BKG;
2. Stationary with instrumental equipment for continuous measurements in the Saeva Dupka cave system and its adjacent territory;
3. Remote - uses the available results of measurements in the BKG region, including instruments mounted on satellites in orbit around the Earth.

The monitoring conducted in BKG covers both the factors and dynamics of the water cycle, as well as the anthropogenic pressure on the water cycle.

Monitoring the water cycle

The field trip version of the monitoring in BKG is carried out with a frequency of 1-1.5 months. The objects are the surface waters in the recharge zone (precipitation, soil, river, marsh) and the underground karst waters (cave and spring in the discharge zone) within the boundaries of the geosystem. Hydrochemical analyses of the waters are carried out “in situ” with a field laboratory of the MP type (Markowicz and Pulina 1979), also equipped with multifunctional portable hydrochemical equipment (Stefanov et al. 2025). In case of suspicion of contamination, water samples are taken and analyzed in certified laboratories. Sampling and analyses of the Glava Panega spring are carried out at the Upper Lake.

Precipitation water (rain and snow) is subject to periodic (seasonal) sampling in the area of Saeva Dupka cave. It is collected in the open air and under the shrub-tree vegetation. Original lysimeters (Stefanov 2020; Stefanov et al. 2025) were constructed to collect soil water, and they are installed in the soil horizons 10 and 50 cm above the Concert Hall of the Saeva Dupka cave. Lysimetric monitoring provides original information about the time of penetration of precipitation water into the cave and about its aggressiveness due to the absorbed CO₂ from the soil. Karst groundwater in the transit zone (infiltration/drip, condensation, cave ice, cave lakes) is measured and sampled at representative points along the profile of Saeva Dupka cave. The sampling of drip water is carried out at 7 points and in two ways – for the period of time between two consecutive field trip measurements, or for a fixed time within one visit (if the intensity of the drip allows the collection of a sufficient quantity of water sample). Sampling is also used to determine the intensity of drip. Condensed cave water is collected in the Stack and Collapse halls of the Saeva Dupka cave, and original condensate meters have been installed for this purpose (Stefanov 2020).

Precipitation is also subject to stationary monitoring, and for this purpose 2 stations have been equipped: in the village of Brestnitsa with a standard rain gauge (since 2010), and at the entrance to the Saeva Dupka cave with a VAISALA WTW520 automatic meteorological station (since 2018). It is part of the established network for continuous instrumental monitoring (Speleo-MIKS Saeva Dupka) of the elements of the cave environment, including cave gases (Stefanov, 2020; Stefanov et al., 2025).

This study also used available published data from stationary hydrometric measurements of the waters of the karst spring Glava Panega (Damyanova 2024). The NIMH's "Zlatna Panega" hydrometric station, installed in 1959, is at the outlet of the artificially created Lower Lake of the spring Glava Panega, from which water withdrawals for drinking and industrial needs constitute up to 8.5% of the average annual water quantity of the spring. The measurements conducted at the hydrometric

station do not take into account these water withdrawals and the data from the hydrometric station are correct only for the Panega River. However, they are indicative of the trends in the flow regime of the spring.

There are no weather stations of the National Institute of Meteorology and Hydrology (NIMH) network within the boundaries of the geosystem. Therefore, when clarifying the impact of climate change on the water cycle, remote sensing data from the ERA5-Land reanalysis (Sabater 2019) of the European Center for Medium-Range Weather Forecasts (ECMWF) were also used. The period from 1950 to 2025 was analyzed in line with the available data. The resolution of this reanalysis is $0.1 \times 0.1^\circ$. Thus, the BKG area is covered by four grid cells with coordinates of their center as follows: 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 are averages of the values of the four grid cells. The study uses monthly average data for air temperature, precipitation, and evaporation. Daily data for precipitation amounts were also used in order to identify days without precipitation or days with intense precipitation (in which the amount exceeds 20 mm). The main methods applied for data processing are statistical (Wilks 2006). The level of statistical significance at which the null hypothesis is rejected is $p \leq 0.05$. Linear regression was used to calculate trends, in which the independent variable is time, and the dependent variables are air temperature, precipitation, evaporation, and the precipitation-evaporation difference. The frequency of a certain phenomenon is calculated by counting the number of days in a year. A second-degree polynomial equation (quadratic equation) was used in order to better represent the time course of some studied climate elements.

Monitoring of anthropogenic pressure on the water cycle

To identify the potential negative impacts of human activity on the karst geosystem and its water cycle, a specially developed socio-economic monitoring model has been applied (Stefanova et al. 2020; Stefanova and Stefanov 2021; Stefanova 2022). It is in three directions with a corresponding methodology: 1. Identification of types of land use and economic activity and inventory of socio-economic infrastructure; 2. Monitoring of: visitors in the karst tourist sites; sites and facilities of socio-economic infrastructure and related activities; activities that directly use natural resources of the karst geosystem; changes in land use/land cover; 3. Surveys of the knowledge, practices and attitudes of the local community, local business, and local, regional and state authorities for the creation and implementation of regulations in land use and management in karst territories. Results from the remote monitoring of the land surface of the Copernicus program (CORINE Land Cover (CLC)) were also used. Thus, vector layers with land cover types (Land Cover - CLC sites) are periodically updated (Jeleu et al. 2021).

RESULTS AND DISCUSSION

Structure of the water cycle in BKG

The water cycle begins with **precipitation**. It consists of rain during the warm part of the year and snow during the cold part, as well as mixed precipitation of rain and snow in the period November-March. The annual precipitation amount is about 825 mm. There are two maxima in the intra-annual course of precipitation, the primary one is in May and the secondary one is in December. The primary minimum is in November and the secondary one is in January. During the monitoring period in the BKG region, the average monthly precipitation is 61.2 mm, varying from 1.1 to 270 mm. Given the predominant shrub-tree vegetation in the geosystem, part of the precipitation remains in the canopy layer of the trees and shrubs and in the leaf cover below them, from where it evaporates. There is also active evaporation of precipitation that has penetrated the soil cover, including through evapotranspiration. On average, about 700 mm evaporates from the territory of the geosystem annually. The maximum in evaporation is in June and the minimum is in January. The difference in precipitation-evaporation has positive values in the period from October to May. Accordingly, negative values cover the period from June to September. On average, the BKG region has a water surplus of about 125 mm. Hydrochemical analyses have proven that the precipitation water has very low mineralization (the specific electrical conductivity is 15 $\mu\text{S}/\text{cm}$) and low hardness (0.1 $^{\circ}\text{dH}$) (Table 1).

Precipitation that has penetrated the soil forms *soil water*, some of which penetrates through the rock cracks into the karst cavities. In the area of the Saeva Dupka cave, in conditions of tree-shrub vegetation and Rendzic Leptosols with dense leaf cover, about 20.2% of the average annual water quantity penetrates through the 15 cm soil horizon, and an average of 10.7% through the 30 cm soil horizon. Therefore, the penetration of precipitation water through the soil cover to the rock massif depends on both the soil structure and thickness, and on soil moisture. The latter depends on the amount, intensity, and duration of precipitation and its temporal distribution, as well as on the thickness of the snow cover and the intensity of its melting. Another factor for soil moisture is the temperature, which regulates the processes of evaporation and vegetation, on which evapotranspiration depends. Therefore, there is a complex combination of many factors that influence the formation and composition of soil water. It has low mineralization (the specific electrical conductivity is between 168-216 $\mu\text{S}/\text{cm}$, and its hardness is between 62.5 and 90.6 mg/l (3.5 - 5.1 $^{\circ}\text{dH}$) (Table 1).

Infiltrating into the rock massif, soil waters form *drip waters* in karst cavities. A typical example is the Saeva Dupka cave, developed in the epikarst of the BKG. The drip waters, which are an object of monitoring in the cave, have a very high average mineralization – the specific electrical conductivity is 600-700 $\mu\text{S}/\text{cm}$, but

during the year it varies from 327 (in winter) to 819 $\mu\text{S}/\text{cm}$ (in summer and early autumn). This is due to the carbon cycle regime in the cave, which is governed by natural cave ventilation (Stefanov 2020; Nojarov et al. 2024; Stefanov et al. 2024, 2025). These waters also have the highest measured hardness in the water cycle of the geosystem – 316 mg/l (17.7°dH) (Table 1). The intensity of drip waters is variable throughout the year and depends on the regime and intensity of precipitation and soil moisture. The most active infiltration during the monitoring period in the Saeva Dupka cave was recorded in spring (up to 325.8 ml/h in the Concert Hall on April 29, 2025). In autumn and winter, it decreases to 2-10 ml/h (1.12 ml/h on December 22, 2019).

Speleo-MIKS in Saeva Dupka also recorded active condensation processes that occur only during the warm period (from April-May to October-November), when warmer and more humid atmospheric air penetrates the cave (Stefanov 2020). Then, between 0.1–0.2 l/m² of *condensation water* is formed (average 0.12 l/m²), which condensation water has very low mineralization and hardness (Table 1).

Precipitation water that has penetrated through the epikarst and vadose zone, transformed into soil and infiltration drip water, in the underground subsystem of BKG forms a complex phreatic hydrogeological zone saturated with underground karst waters (Kovachev 1959; Galabov et al. 2000; Stefanov et al. 2023; Nojarov et al. 2024). It drains into the karst spring Glava Panega, the outlet of the geosystem.

However, as already noted, inflow surface waters also play an active role in the water cycle of BKG. Their main source is the Vit river. Its average annual runoff at the “entrance” of the geosystem (the sinkholes between the village Glozhene and quarter Asen) is 8.43 m³/s. (Penchev, Velichkov 2012). Hydrometric measurements conducted over the years have revealed that the sinking river waters in the sinkholes between the village of Glozhene and Kamenna Mogila are between 600 and 900 l/s at a flow rate of the Vit river of 4500 and 3300 l/s, respectively (October 1955, Kovachev 1959) and between 1282 and 2605 l/s at a flow rate of the Vit river of 1500 and 8200 l/s, respectively (summer-autumn period of 1999, Galabov et al. 2000). The river waters are weakly mineralized (specific electrical conductivity is about 200 $\mu\text{S}/\text{cm}$) and have a hardness of 107 mg/l (6°dH) (Table 1).

After the area with the sinkholes, the Vit River very often dries up. During the period of monitoring conducted by the authors, the longest dry spell was observed from the end of July 2012 to mid-January 2013 (6 months). In 2016, the dry spell lasted 3 months (from mid-September to mid-December). Since 2017, the dry spell of the Vit river has been of very short duration, and in 2022, the river did not dry up at all. However, in September 2025, the river dried up at the mouth of the Voneshtitsa River. During intense rainfall or snowmelt, floods and spills of river water occur on the floodplain river terrace (e.g., October 2025 and March and May 2026).

Surface water inflow into BKG also occurs through sinkholes in the Voneshtitsa River valley (Nojarov et al. 2024). Their share in the groundwater of the geosystem and, accordingly, in the Glava Panega spring is too small considering the catchment area of the river valley (Fig. 1).

Periodic inflow of surface water into karst valleys and sinkholes of the karst relief of the geosystem is observed after intense rainfall and snowmelt. The sediments in these waters can clog some of the sinkholes, resulting in the formation of karst swamps. The object of monitoring in this study is the waters of several karst swamps in BKG, among which the largest are: the Swamp near the Varpey quarter and the Big Swamp near the village of Brestnitsa. Hydrochemical analyses showed that they are low-mineralized (specific electrical conductivity from 84 to 257 $\mu\text{S}/\text{cm}$) and have low hardness (1.7 to 6.6 $^{\circ}\text{dH}$) (Table 1).

The water cycle in BKG ends at its outlet – the Glava Panega spring. It is the highest-flow (avg. 3764 l/sec) concentrated spring in Bulgaria (Penchev and Velichkov 2012). For the period 1959-2011, the measured maximum flow rate was 35,700 l/sec (January 1971), and the minimum was 580 l/sec (December 1970). The spring is of the vacluse type and its location is predetermined by the Brestnitsa fault in the contact zone of limestones with marls ($K_1^{\text{bs-b}}$). A natural lake (Upper Lake, Siniloto) with a depth of 5 to 11.5 m is formed around the spring, in which scuba diving speleological explorations have revealed an underwater cave. In 1992, a depth of -52 m was reached (Zhalov 1999). The cave is an entrance to the complex phreatic zone of the geosystem.

The spring waters have a relatively low mineralization for this type of water (specific electrical conductivity is about 400 $\mu\text{S}/\text{cm}$) and hardness (average 200 mg/l or 11.2 $^{\circ}\text{dH}$) (Table 1). The indicator experiment conducted in October 1955 has proved that the sinking river waters at quarter Asen appear in Glava Panega karst spring after 12 days (Kovachev 1959). The straight-line distance between the sinks and the spring is 6.5 km, and the calculated speed of the salted water is 572 m per day. This speed is typical for the autumn low water. During heavy rainfall, the maximum flow rate of the spring is delayed by 8-10 hours.

Due to the active participation of sinking waters of the Vit river, the question arises of what their share is in the spring waters of Glava Panega. Solving this question is complicated due to the lack of parallel stationary hydrometric measurements of the Vit river before the sinkholes and of the Glava Panega spring. That is why we used our results from field trip monitoring of the specific electrical conductivity of these waters, conducted in the period 2009-2026 (Fig. 2). They showed that the average recharge of the spring with river waters for this period is 53.4% (from 36.1% during heavy rainfall to 76.2% during drought). This explains the low mineralization of the spring waters. The maximum share of river recharge is from September to December (dry karst terrain and weak infiltration of precipitation

water), and the minimum is from February to June (heavy precipitation and snowmelt, over-moistened soil and active infiltration of precipitation water). Despite these main regularities, the complex combination of factors that influence the flow rate of Glava Panega also causes several variations between the precipitation regime and the flow rate of the spring (Fig. 2). They also form the basis for the analysis of the impacts of global changes (see section 5).

Table 1.

Composition and properties of the water cycle in the Brestnitsa karst geosystem (for the monitoring period 2010-2026)

Elements of the water cycle	Water Quantity	Water Temperature	Specific Electrical conductivity	Water Hardness (Ca ²⁺ +Mg ²⁺)		Aggressive CO ₂	Chloride s
		°C	μS/cm	mg/l	°dH	mg/l	mg/l
Precipitation (average monthly), v. Brestnitsa	61.2 mm (1.1 - 270)	10.5 (-0.5 – 18.8)	15 (6.5 – 30)	- (1.5 – 2)	0.1	3.6 (2.2 – 4.4)	- (0.8 – 7.2)
Inflow waters:							
Swamps:							
1.1. The swamp, quarter Varpey	-	- (2 – 25.5)	- (84 – 110)	30	1.7	-	7.31
1.2. The Great Swamp, v. Brestnitsa	-	7.5	257	118	6,6	- (0 – 3.3)	-
1.3. The Swamp, v. Brestnitsa	-	9.5	228	106	5,9	0	-
Vit river, quarter Asen	8.430 m³/s*	12.7 (-0.3 – 30)	212 (152 – 289)	107	6 (4.3 – 9.2)	- (0 – 3.3)	6.7 (4.5 – 10.2)
Infiltration waters:							
Soil water:							
1.1. Soil horizon 15 cm	24.1 l/m² (0.3 – 57.3)	13.6 (5.8 – 22.3)	216 (105 - 376)	90.6 (38 – 152)	5.1 (2.1 – 8.5)	9.2 (4.4 – 17.6)	13 (6 – 18.2)
1.2. Soil horizon 30 cm	12.2 l/m² (1.2 – 39)	13.2 (7.2 – 17.8)	168 (76 – 380)	62,5 (30 – 148)	3.5 (1.7 – 8.3)	8.6 (3.3 – 13.2)	18.9 (11.2 – 28.8)
1. Cave waters (Saeva Dupka):							
1.1. Drip water (Concert hall)	95.7 ml/h (0.6 – 385.7)	10 (8.4 – 11.3)	678 (327 – 819)	316 (118 – 630)	17.7 (6.6 – 29.7)	0	8.1 (6.6 – 13.8)
1.2. Condensation water	0.120 l/m²		2.3 (1.5 – 2.8)	2	0.11	1.6 (0.9 – 3.3)	0
Spring waters:							
1. Karst spring Glava Panega	3.764 m³/s (0.58–35.7)*	12.8 (8.6–15.8)	397 (300 – 518)	199 (144 – 269)	11.2 (8.1 – 15.1)	5.5 (1.1 – 17.6)	12.2 (5.9 – 18.7)

* After Penchev and Velikov (2012)

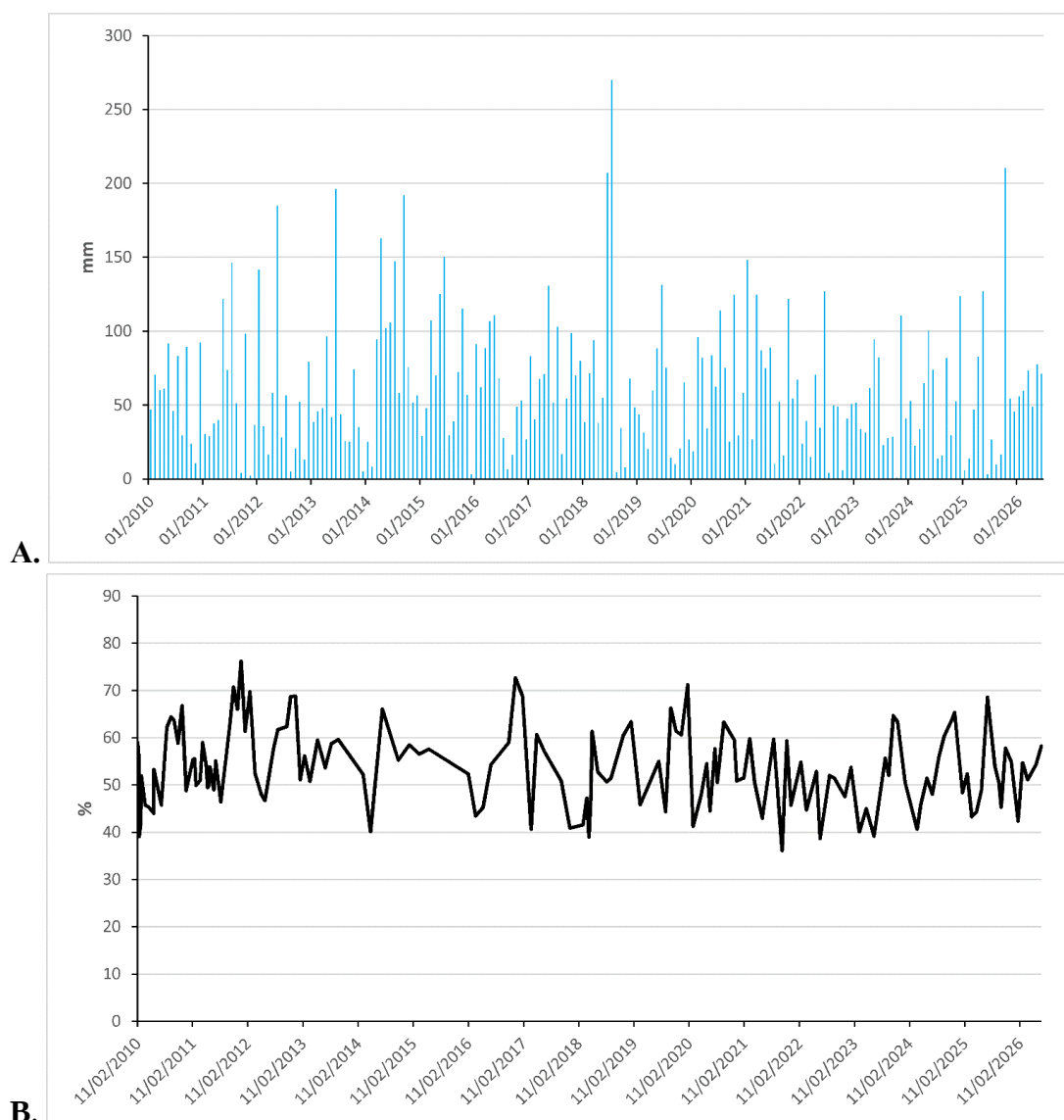


Fig. 2. Dependence between precipitation and the relative share of the Vit river's sinking waters in the flow of the Glava Panega karst spring (for the monitoring period 2010-2026):
A. Average monthly precipitation (mm), recorded by the rain gauge in the village of Brestnitsa; **B.** Share (%) of the Vit river's sinking waters in the waters of the Glava Panega spring (according to the measured specific electrical conductivity of the waters)

The role of the water cycle in karstogenesis

It is determined by the aggressiveness of the waters, i.e., by their ability to dissolve carbonate rocks, which is due to the carbonic acid formed during the dissolution of CO_2 . The conditions for this are different in different parts of the BKG, and therefore the waters participating in its water cycle contain different amounts of aggressive CO_2 . This affects the activity of karst processes, which is why, when

conducting MIKS, the aggressive CO₂ in the waters of the water cycle is experimentally determined with marble powder (according to Heyer) (Table 1).

The most aggressive is precipitation water (average of 3.6 mg/dm³ of aggressive CO₂) and soil waters (average of 8.6-9.2 mg/dm³). In the soil, chemical-biological processes are the cause for a very high content of CO₂ in the soil gas: on average about 4000-5000 ppm for the monitoring period 2016-2026, 1100 to 3500 ppm in winter, and 15,000 ppm in summer. These high concentrations are the reason why soil waters are saturated with carbonic acid all year round and are very aggressive, which is confirmed by the results of the hydrochemical monitoring of lysimeter soil waters (Table 1). Therefore, these waters are the most aggressive in the water cycle (average content of aggressive CO₂ between 8.6 and 9.2 mg/dm³) and are the main source of active karst processes in the geosystem. By infiltrating into the rock massif, soil waters actively dissolve limestone and become saturated with dissolved carbonates. Thus, they increase their mineralization but lose their aggressiveness. An example of this is the cave drip waters in Saeva Dupka. As mentioned in the previous section, they have the highest mineralization in the water cycle, but it varies throughout the year due to the ventilation regime of the cave and seasonal differences in CO₂ concentrations in the cave air (from 420 to 19,120 ppm). During the period of active ventilation in Saeva Dupka and low CO₂ concentrations in the cave air (November-March), the waters that have infiltrated the cave are degassed and actively deposit calcite, due to which their specific electrical conductivity decreases to an average of 350-400 µS/cm (Stefanov et al. 2025). However, they remain non-aggressive (do not contain aggressive CO₂). This cyclicity in the mineralization of drip waters also affects the growth regime of speleothems in the cave – it has already been established that it currently manifests itself only during the cold half of the year, with active cave ventilation and low values of concentration of CO₂ in the cave air (Stefanov 2020; Stefanov et al. 2025).

Formation of condensation water in Saeva Dupka coincides with the period of the highest concentration of CO₂ in the cave air, due to which the condensation water is saturated with carbonic acid (content of aggressive CO₂ up to 3.3 mg/dm³). According to the experiments conducted by the authors, 1 liter of condensation water is able to dissolve approx. 100 mg of limestone. This is indisputable evidence of the important role of condensation in the genesis and “volumetric” growth of caves – a scientific aspect that is still poorly developed (De Freitas and Schmokal 2003; Dreybrodt et al. 2005; Dublyansky and Dublyansky 2000; Stefanov 2020; Stefanov et al. 2025).

Despite the low mineralization, the river waters of the Vit river do not contain aggressive CO₂. During the entire monitoring period, there were only a few cases when aggressive CO₂ was detected in high, mostly winter and spring river waters (from 0.4 to 3.3 mg/dm³). However, the experiments we have conducted with river

waters brought into the Saeva Dupka cave proved that when entering the underground channels at the river sinkholes and in the karst cavities, they change their temperature and become saturated with CO₂, which makes them aggressive (Stefanov 2020).

An interesting and atypical example for karst springs is Glava Panega, which contains aggressive CO₂ all year round (from 1.1 to 17.6 mg/dm³, the average value being about 5.5 mg/dm³) (Table 1). The cause is that the spring that drains the waters of BKG is in a fault zone. In addition, it has been proven that groundwater in the geosystem reaches a greater depth than that of the spring (Kovachev 1959). The latest geophysical studies (Stefanov and Radulov 2020) also suggest hydrothermal activity in the fault zone, which is also confirmed by the hot springs in the Lower Lake area (Penev 1930; Azmanov 1940; Kovachev 1959). As a result of the aggressiveness of the spring waters, there are griffins (natural underground tunnels) through which water from the Upper Lake drains into the Lower Lake.

Impacts of global changes on the water cycle in BKG

Global changes include both paleogeographical and climatic, political and socio-economic changes on a regional, national and global scale and the associated anthropogenic pressure in karst areas.

Paleogeographic stages of the water cycle's formation

The Early Pliocene (approx. 3 million years ago) – when a denudation surface formed over the limestones – is considered the initial stage of karstification in the BKG (Popov, 1962). An erosion-corrosion network developed, directed toward the forming valley of the Voneshitsa river. During the Quaternary, the region was affected by differentiated cyclic tectonic movements, also marked by a series of river terraces along the slopes of the Vit and Panega rivers. At the beginning of the Quaternary, the already karstified northern tectonic block (the Brestnitsa block) subsided along the Garvanitsa fault, causing its system of underground karst cavities and channels to drop below the base level of erosion (submerged karst). This explains why boreholes from hydrogeological studies in the karst polje reveal limestone karstification at depths far below the groundwater level (Kovachev, 1959). Ongoing karst processes gradually transformed the Brestnitsa block, and by the mid-Quaternary, it had become a closed karst polje. This is evidenced by early Quaternary terraces along its eastern rim, situated 32–35 m above the polje floor, which drains into the Glava Panega karst spring. The gradual formation of the antecedent gorge of the Vit river also began during the Quaternary in the locality of Boaza, which caused the Vit river to shift its course from being a tributary of the Iskar river to a tributary of the Danube river. The complete sequence of fluvial terraces preserved along the left valley slope of the Vit river (Popov, 1962) marks the key stages of karst evolution

in the BKG during the Quaternary (the last 2.588 million years). The Meso-Pleistocene terraces (the fourth at 35–45 m and the third at 25–30 m), featuring paleosinkholes, indicate that the sinking of the Vit river began no later than the Meso-Pleistocene; the oldest paleosinkholes are located near quarter Kamenna Mogila, while the youngest are near the village of Glozhene (Nojarov et al., 2024).

Impacts of climate change

Climate change primarily affects the regime and quantity of the water cycle (Gutiérrez et al., 2014; Liu et al., 2020; Vörösmarty et al., 2000). Given the long-term development of BKG, before analyzing the expected effect of current climate change, a brief review is also necessary in historical context. Karstogenesis in the geosystem occurred under numerous cyclical variations of climate, typical of the Pliocene and Quaternary (Nikolov 2011; Nojarov et al. 2024). During the Pliocene, conditions with higher-than-current temperatures and precipitation prevailed, and accordingly there were more active corrosion processes in limestones, as evidenced by weathering materials in karst forms - red clays ("terra rossa"). Over 80 glacial episodes have been established during the last 2.5 million years (Quaternary), during which air temperatures were 5-7°C lower than current ones. During interglacial episodes, the trend is the opposite - higher temperatures than current ones. This climatically determined cyclicity in the development of karst is evident in the rich palette of speleothems in the caves of the geosystem. Unfortunately, they have not yet been an object of dating for the purposes of paleogeographic reconstructions.

The available meteorological data and the 15-year integrated monitoring of karstogenesis in BKG make it possible to track and assess the impact of current climate change. The climate in the BKG region has changed from temperate continental (Velev 2002) to transitional between temperate and subtropical (Mediterranean) (Nojarov 2017). The established trends in climate change are expected to activate karstogenesis due to the extension of the growing season and increased production of soil CO₂. This leads to higher aggressiveness, especially of soil waters, which are a major factor for karstogenesis in the epikarst. The regime and intensity of precipitation are also of significant importance, but it is still difficult to establish what the trends of their change are.

The climate trends in the BKG region for the period 1950–2025 are shown in Table 2. The average annual air temperature is increasing statistically significantly. In all months of the year, the temperature trends are positive, and in half of them, they are also statistically significant. The months with a statistically significant increase are concentrated mainly in the summer and winter seasons. The average annual precipitation is decreasing, but insignificantly. The average annual evaporation values are increasing, but the trend is not statistically significant. It should be noted here that the evaporation values are negative, and only when there is condensation of water

vapor from the air do these values become positive. There are statistically significant negative trends in January, March and June, which means that evaporation is increasing.

The difference in precipitation-evaporation does not have statistically significant trend values, which is good with regard to the water reserves in the studied territory, which do not change during the studied period due to natural causes.

Given the leading role of precipitation in the water cycle of BKG, Figure 3 shows the variations in the number of days without precipitation and the number of days with precipitation over 20 mm by year for the period 1950-2025. The figure also shows the graph of the quadratic function of the two climatic elements. The number of days without precipitation has been decreasing until the end of the 1970s, after which an increase followed. In the last decade, the number of days without precipitation is already above the values at the beginning of the period. The value of the linear trend for the studied period is statistically significant, which means that despite the decrease in the 20th century, the tendency is towards an increase in the number of days without precipitation in BKG. On the other hand, the number of days with precipitation over 20 mm does not show any significant trend for the period 1950-2025. The quadratic function shows a slight increase in the middle of the studied period, which somewhat coincides with the decrease in days without precipitation.

Table 2.

Monthly and annual trends in various climatic elements during the period 1950-2025.

Statistically significant values are bolded

	Air temperature (°C)	Precipitation (mm)	Evaporation (mm)	Precipitation- evaporation (mm)
January	0.041	-0.001	-0.001	-0.003
February	0.038	-0.002	-0.002	-0.004
March	0.042	0.005	-0.005	0.000
April	0.014	-0.005	-0.003	-0.007
May	0.011	-0.004	-0.003	-0.007
June	0.021	-0.011	-0.004	-0.015
July	0.029	-0.007	0.000	-0.008
August	0.024	-0.004	0.001	-0.003
September	0.008	0.007	0.002	0.009
October	0.013	0.007	-0.001	0.006
November	0.017	-0.009	0.000	-0.009
December	0.020	0.001	-0.001	0.000
Annual	0.023	-0.002	-0.001	-0.003

In order to check whether there is any change in the amount of heavy precipitation in the study area, Figure 4 was compiled. It shows the specific amounts of each daily precipitation above 20 mm during the period 1950-2025. It can be seen that the largest daily precipitation in the BKG region is in the range of 60-70 mm. However, these events occurred both at the beginning of the period (1957) and at its end (2007, 2017). The linear regression does not show a significant trend for the study period. Thus, it can be concluded that there is no trend of increase or decrease in heavy precipitation in the area.

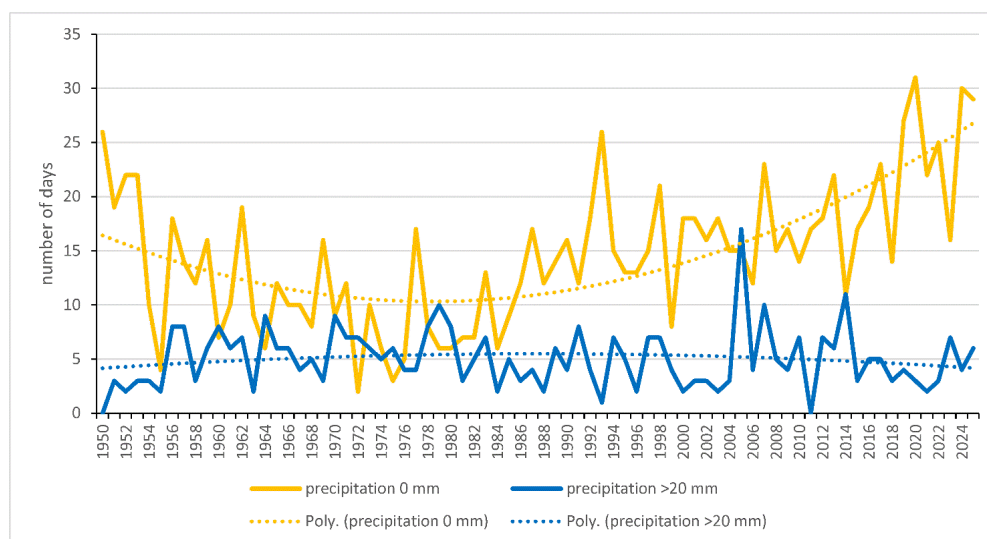


Fig. 3. Variations in the number of days without precipitation (0 mm) and the number of days with precipitation over 20 mm by year for the period 1950-2025 in the BKG region. The dotted lines show the graphs of the quadratic function of the two climatic elements

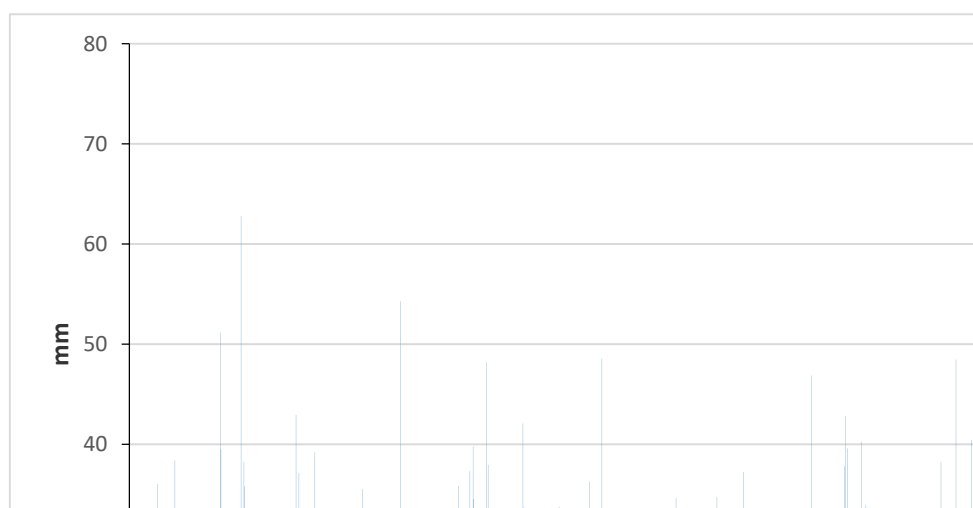


Fig. 4. Amounts (mm) of each daily precipitation above 20 mm during the period 1950-2025 in the BKG region. The dotted line shows the graph of the linear function

The study of the time series of precipitation during the period of complex monitoring in the BKG region (after 2010) has shown various anomalous periods. Heavy 24-hour precipitation occurred on 03.07.2017 (68.7 mm) and on 16.09.2014 (53.4 mm), as well as in the spring of 2026 (40.85 mm on March 28). On the other hand, during the periods 27.08-18.09.2019, 6-30.10.2019, and especially 4.10-7.11.2022 (35 days), there was no precipitation in the region. A similar situation was observed in 2025 – the periods from 7 to 26 June and from 2 to 26 September were without precipitation. In winter, a persistent trend of shortening of the period with snow cover is observed. A typical example is 2024, when after January 21 there was no more snowfall in the geosystem's area. The first snowfall after that was on November 22.

The impact of precipitation regime on the water cycle in BKG can be traced through the flow rate of the source of the Panega River (the outflow from the Lower Lake). Daily measurements conducted by NIMH show that during the period 1959-2011 the minimum was in January (avg. 2273 l/s, varying between 2273 and 2598 l/s from November to January), and the maximum was in May and June, 5158 and 5160 l/s, respectively (Penchev and Velichkov 2012). After 2013, there has been a persistent trend of a decrease in the average annual flow rate by approx. 1500 l/s for the period until 2023 (Fig. 5).

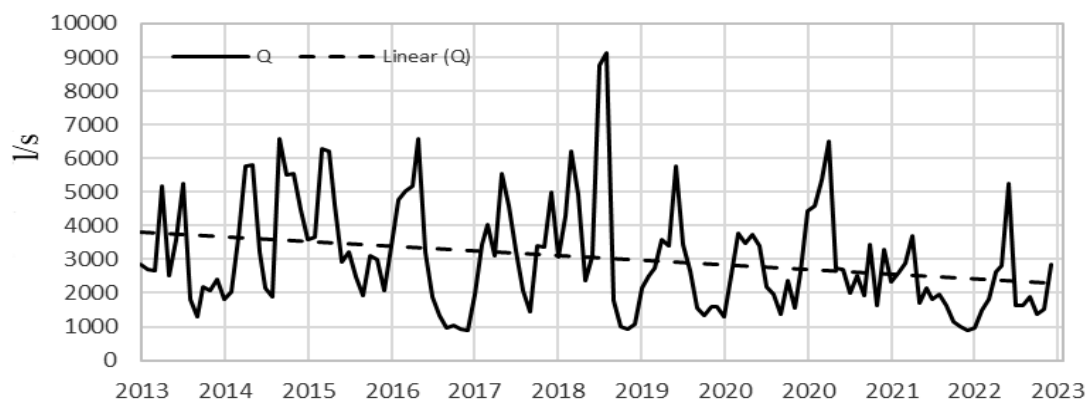


Fig. 5. Measured flow rate at hydrometric station No. 152J2 “Zlatna Panega river” of NIMH for the period 2013-2023 (after Damyanova 2024)

However, heavy precipitation still occurs. Although episodic, they cause accelerated soil erosion in the karst territory, especially after a long drought, and, as a consequence, the deposition of large amounts of clay deposits in the underground subsystem of BKG. In 2025, there were two such cases - in May (May 24-26, total precipitation of 94 mm) and in early October (from October 2 to 8, total precipitation of 175 mm), when the waters of the Vit river and Glava Panega had a very high flow

rate and high turbidity. Analyses of these waters showed that each liter of turbid river water contains 0.3 grams of insoluble (suspended) solids, and of spring water - 0.42 grams. This proves that a high quantity of sediment is transported during intense rainfall and is deposited both in the underground subsystem of BKG and in the lakes of the Glava Panega spring. A similar situation occurred in the spring of 2026 due to periods of intense snowmelt and heavy precipitation (65 mm from March 27 to 29).

Impacts of anthropogenic changes on the water cycle in the Brestnitsa karst geosystem

Based on the available information, historically, anthropogenic impacts on BKG can be summarized in 4 periods:

1. Until 1890: there were no villages on the territory of the geosystem, and it was used primarily for pastures, the animals' watering places being natural or artificially created by tamping down sinkholes in karst swamps.

2. After 1891: the population of the old village of Brestnitsa in Survanski (Brestnishki) dol has moved south into the karst polje and has founded the village of Malka Brestnitsa (Filkov 2001). The settlers continued to develop traditional agriculture and cattle breeding (cattle, sheep, goats) in the new karst terrain. Cattle breeders also settled at the foot of the karst polje and formed small quarters, which are part of the village of Malka Brestnitsa. The main problem for the population became the lack of drinking water, which is why fountains, water pipes, and wells were built. In the late 1930s was the beginning of the use of artificial fertilizers imported from Germany.

3. From 1949 to 1989: in the village of Malka Brestnitsa, the Labour Cooperative Agricultural Farm was founded (1949), which was equipped with a new material base, and it applied mechanized agricultural production (Filkov 2001). Pumping stations were built for irrigation of field and vegetable crops with karst waters. A water supply system was built for water supply of the village. In 1964-68, near the Lower Lake of the Glava Panega spring, the State Cement Plant "Zlatna Panega" was built, and the area transitioned from agricultural to industrial. In the northern periphery of the geosystem, in the area around the spring, new quarries are actively being developed. Cement production created another very serious problem - excessive dust in the air during the period 1968-79. It has led to a decrease in agricultural yields by 30-40%, as well as to a deteriorated quality of fodder, which affected livestock farming. This crisis was overcome in 1979, when a dust removal system of electrostatic filters was built at the plant.

4. After 1989: the significant political and socio-economic changes that occurred in Bulgaria have affected BKG. This was the period of intensification of global changes – both anthropogenic and natural.

The main sources of anthropogenic pressure on BKG are various economic activities: agriculture, livestock breeding, forestry, extraction of construction/aggregate materials (quarries for limestone and marl), industrial production (cement and clinker), construction of water supply and sewage systems and road infrastructure, formation of landfills (incl. illegal ones), tourism. The impacts of these activities on the water cycle of BKG are considered in three aspects:

1. Economic use of water (industrial and domestic water supply, animal watering and irrigated agriculture).
2. Changes in land use that impact the quantity and quality of infiltration waters in the geosystem;
3. Pollution of inflow and infiltration waters;

Economic use of waters in Brestnitsa karst geosystem

The karst relief and the waterlessness in the territory of the geosystem are the reason why the karst swamps are used for watering of farm animals (e.g. Golyamo blato, Zabcheto, Blatoto, Gyolovete in the land of the village of Brestnitsa, Blatoto near Varpey quarter, etc. Fig. 1). For this purpose, some of the sinkholes in the swamps have been artificially tamponed to collect and retain runoff precipitation. Several wells have also been built to collect precipitation. At Golyamo blato (area 5-6 decares and depth up to 3-4 m) in the southeastern part of the Brestnitsa karst polje, a pumping station was built in 1954, with which over 350 decares of agricultural crops were irrigated (Filkov 2001). At the beginning of the 19th century, the outflow from the swamp was artificially dammed to provide year-round watering for farm animals (Panchev 1938).

Water from the Vit river is also used for water supply, pumped before the karst sinkholes near the village of Glozhene. For this purpose, four pumping stations have been built: "Teteven - high zone", "Teteven", "Polaten" and "Vidrite". The water supply group "Glozhene" (flow rate 150 l/sec) comprises the pumping station "Vidrite", which is located 3 km south of the village of Glozhene. It includes two karst springs (Upper and Lower Vidra) on the right slope of the Vit river valley, south of the village of Glozhene, and the "Vidrite" drainage of the river. Beginning at the pumping station, a main water supply line (62 l/sec) was built in 1959 to the town of Lukovit, which also supplies water to the village of Brestnitsa. Water from the Vit river is used for irrigation of arable land on the river terraces southeast of the village of Brestnitsa (Vit field locality), the western part of which is within the boundaries of the geosystem (fig. 1).

From the point of view of the economic importance of the waters in BKG, the most important and long-standing karst spring is the Glava Panega. The water is drawn from the Lower Lake, which is up to 7 m deep. It was created at the beginning of the 18th century, and for this purpose, the water flowing through the two griffins

from the Upper Lake was blocked with a dam, 50 m long, 30 m wide and up to 6-7 m high (Penchev, 1938). This created conditions for the construction of mills - they operated all year round, because the spring did not dry up and the karst water did not freeze. Water from the lake began to be used for the production of hydraulic lime from local marls in the factory built in 1907 on the shore of the Lower Lake (Panchev 1938). Since 1923, only lime has been produced, and in 1947 cement production began. In 1968, the newly built State Cement Plant "Zlatna Panega" was opened. During the socialist period, water from the lake was pumped into an irrigation system built between 1959 and 1962 to irrigate more than 1,500 acres of arable land in the village of Brestnitsa (Filkov 2001).

The chemical composition of the spring waters of Glava Panega is fresh hydrocarbonate-calcium with a total mineralization of 0.25 to 0.56 g/l and meets the Bulgarian standards for drinking and domestic water supply (Penchev and Velichkov 2012). That is why a pumping station has been built at the Lower Lake for drinking and domestic water supply (Water Supply Group "Zlatna Panega") for 14 settlements from 3 municipalities: Yablanitsa, Lukovit, Cherven Bryag. It is carried out by the Lovech Water Supply and Sewerage Company through a water pipeline built in the period 1984-1996. The suction of the pumping station is placed directly into the griffin between the Upper and Lower Lakes. The permitted water use is 13810 m³/d. A second pumping station has also been built for industrial water supply to the cement plant "Zlatna Panega Cement" with a permitted water use of 11233 m³/d. Part of the spring waters are also used for hygienic needs (laundry facility at the outlet channel of the Lower Lake with permitted water use of 113.26 m³/d). The permitted total water withdrawal is approx. 8.5% of the exploitation resources of the spring. Due to the socio-economic importance of the spring and its high vulnerability to pollution, as already indicated, it is in the first belt of the SPZ (Penchev and Velichkov 2012). Glava Panega is also among the six Bulgarian springs proposed for inclusion in the Global List of the Most Important Springs from Karst Aquifers in the world (compiled under the international project MIKAS, Benderev 2022).

Glava Panega spring is an example of a positive effect of changes in water use, introduced by one of the largest and long-standing users of spring water – the Zlatna Panega Cement plant, acquired in 2003 by the Greek company Titan. The plant is a major producer of clinker and cement, which are sold on the Bulgarian and European markets. The plant's quarries, which are being developed actively, are at the northern periphery of the geosystem, with the concession being in proximity to the spring. However, the plant maintains a specialized monitoring program for the ecological state of the karst territories used (Shilegarska et al. 2020). For this purpose, in 2018, three monitoring wells were built in the quarries to monitor the quality of groundwater. Thanks to the modernization of the production cycle after 2008, the

plant sharply reduced its consumption of spring water (Fig. 6). For comparison, in 2007 it was 3,261,000 m³/y, and after 2011 it is below 300,000 m³/y. Regular monitoring of the discharged wastewater from the plant's production cycle is carried out. Its quality is guaranteed by a three-stage treatment plant for domestic wastewater, a flotation device for industrial cooling water, and a system of oil and mud collectors for water from the production site. A large part of the spring water used by the cement plant is also used to irrigate the plant's orchards, created during the reclamation of old quarries.

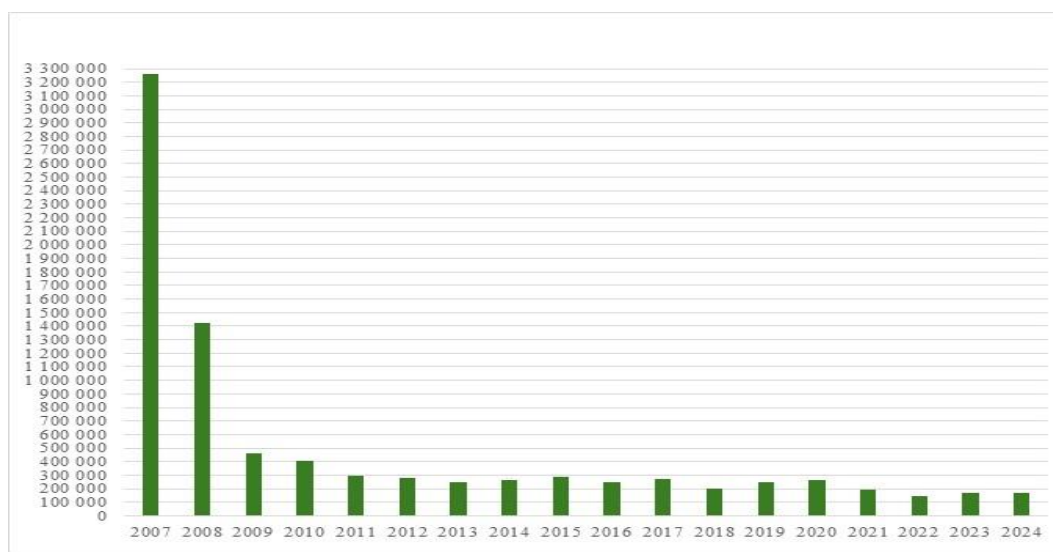


Fig. 6. Water consumption (m³/y) from the Glava Panega spring for the period 2007-2024 for the needs of “Titan – Zlatna Panega Cement”. Source: Integrated annual reports of Titan-Bulgaria.

Land use changes in Brestnitsa karst geosystem

They have been analyzed in previous publications by the authors. Changes in the spatial distribution and quantitative characteristics of land cover and land use classes (LCLU) have been studied for the period 1990-2018 (Stefanova et al. 2020; Stefanova 2022). The identified most important changes are:

- *conversion of deciduous forests into transitional tree-shrub vegetation due to logging.* Afforestation of the geosystem's territory is minimized.

- *conversion of pastures into arable land.* It was carried out on the slopes of the Brestnitsa karst polje and especially on the floodplain terraces of the Vit river in the land of the village of Glozhene (2.18 km² for the period 2012-2018), where agricultural crops are irrigated with river water. This is the area between the river's sinkholes.

The socio-economic changes in agriculture that have occurred over the past 30-35 years and the depopulation of small settlements (quarters) in BKG that began

in 1956 have caused most of the limited in area and difficult-to-maintain arable land to be abandoned and to overgrow with shrub-wood vegetation. This limits erosion processes and increases the carbon dioxide content in the soil - the processes of natural karstogenesis in the epikarst are restored. Modern agricultural production in the geosystem is concentrated mainly in the Brestnitsa karst polje, as well as on the river terraces of the Vit river. It is carried out both by local users of agricultural land and by external tenants. The crops grown are mainly cereals: wheat, corn, oats, barley, sunflower, etc. In recent years, sorghum has also begun to be planted. A problem for infiltration waters in cultivated areas is their chemical pollution from the actively used artificial fertilizers and plant protection products.

- *conversion of deciduous forests into quarries*. BKG is object to industrial pressure (mining and processing industry). Long-term active extraction of rock materials (limestones and marls) is carried out in the territory of the geosystem, which has a lasting effect on the karst relief and karstogenesis. The expansion of the quarries has also caused the loss of a small area of deciduous forests. Several larger quarries, granted concessions, operate within the boundaries of the geosystem (<https://www.me.government.bg/themes/koncesii-za-dobiv-735-1613.html>). They have a total area of 1.46 km² (2018). The extracted rock material is used in cement production and construction. In the period 2006–2012, an increase in the area of the quarries in the land of the village of Brestnitsa, which are in the concession area of the Zlatna Panega cement plant, was observed. In connection with the increased road construction in the area (new sections of the Hemus highway), the quarries near Nanovitsa quarter are also actively operating.

The construction of the new section of the Hemus highway in 2019-2020 had an impact on the water cycle in the geosystem. This section was laid in the steep southern faulted slope of Brestnitsa karst polje using many explosives. Large areas of the slope have been cut and remain as open rock “wounds”. Construction waste materials contaminated the Golyamo blato in the Brestnitsa polje. In addition, the construction of this section of the highway, as well as its ongoing construction in the Vit river valley, activated quarrying in the geosystem. Transportation of quarry material for the highway by heavy trucks has an additional negative effect. In the summer of 2025, the traffic from the quarries near quarter Nanovitsa was diverted through a ford on the Vit river, north of the village of Glozhene. This is in proximity to the river's sinkholes in the Yamite locality and causes periodic turbidity of the river water, also observed in the Glava Panega karst spring.

The active work in the quarries near quarter Nanovitsa, and especially the intensified blasting activities, are expected to have an impact on the underground karst geosystem, which is developed at great depth in this area (over 250 m, Kovachev 1959). Adjacent to the quarries is the Bezdanniat Pchelin cave – the deepest cave in the geosystem (Fig. 1), as well as the karst swamp Blatoto, which

dried up in the summer of 2025. There are two causes for this: the prolonged drought since 2023 and the active blasting operations in the neighboring quarry.

Pollution of inflow and infiltration waters in BKG

Water pollution, especially given the large role of inflow recharge, is the most significant impact of global changes on BKG. Given the allogenic type of karst, a large share of the pollution of its groundwater is due to the sinking waters of the Vit river. The river basin before the sinkholes is very large and includes the lands of various settlements, including the town of Teteven. Unfortunately, these settlements do not maintain functioning wastewater treatment plants that meet modern requirements, and this makes them potential pollutants of the waters of the Vit river. An additional source of pollution is unregulated landfills on the floodplain terraces of the river. The Teteven Municipal Council periodically organizes cleaning of landfills, but new ones are constantly emerging or old ones continue to be used. In the immediate vicinity of the river sinkholes near the village of Glozhene, a Municipal Landfill for Solid Municipal Waste was also operating (the technical reclamation of the landfill was completed at the end of 2020). However, since 2016, a Solid Municipal Waste Transfer Station has been put into operation in the village of Glozhene, built on the river terrace of Vit.

Given the karst territory, livestock farming is a significant local polluter of the waters in the geosystem, but the hygiene standards of livestock farms are not controlled. Unregulated dumping of animal feces in dolines of the karst relief is also practiced.

A consequence of both climatic and anthropogenic impacts is the periodic turbidity of the waters in the water cycle. Intense rainfall activates erosion processes and accumulation of sediments from surface runoff waters in the eddies, which can clog the sinkholes and cause the formation of temporary karst swamps. These runoff waters, and especially the river waters of Vit, which are turbid during heavy rainfall or intensive snowmelt, penetrate through the river ravines and sinkholes into the underground subsystem of the BKG. It has already been noted that it is very large and complexly structured. To a certain extent, this leads to self-purification of the sinking waters (deposition of clay deposits and pollutants in the underground cavities and channels). However, with new high waves of groundwater, the old clay deposits accumulated in the underground cavities and channels are washed away and further increase the turbidity of the spring waters of Glava Panega. This is evidenced by the thick clay deposits (silt) at the bottom of the Upper and Lower Lakes. These growing deposits are also a potential problem for water abstraction in the Lower Lake.

The comparison of the chloride content, which is representative of water pollution, shows that in the Glava Panega spring it ranges from 5.9 to 18.7 mg/dm³

(average 12.2 mg/dm^3), and in the Vit river waters it is from 4.5 to 10.2 mg/dm^3 (average 6.7 mg/dm^3). This proves serious pollution of the infiltration waters in the non-drainage basin of the geosystem. As already mentioned, arable land is a source of sediments in the sinkholes due to intensive soil erosion, which is especially active during heavy precipitation and snowmelt, as well as chemical pollutants from fertilizing and processing crops with various chemicals. Local pollutants are also livestock farms and settlements (quarters and especially the village of Brestnitsa), because they do not have sewers and treatment plants for domestic and wastewater. Other local pollutants are unregulated landfills in dolines and valogs. There is an old tradition in the land of the village of Brestnitsa - in the distant past, dead domestic animals were dumped in sinkholes and abyssal caves in the vicinity, e.g., in Popovata yama (Filkov 2021). The audit field surveys that were conducted in 2024-2026 revealed that most of the dolines in the village's land are used as landfills. They are very often hidden because the dolines are densely overgrown with trees, shrubs, and grass. There is also a landfill on the slope of Blatoto in the village of Brestnitsa, right next to the borehole, where the now non-functioning pumping station was built. A particularly large landfill has been formed in the valog with the sinkhole Zabcheto, southeast of the center of the village, which is also the lowest point (281 m above sea level) in the Brestnitsa karst polje (Fig. 7). In the village, Roma settlers also practice local arson of the dried grass vegetation in the areas between the houses.



Fig. 7. The unregulated landfill in the valog with Zabcheto sinkhole, village of Brestnitsa

In connection with the construction of the Hemus highway on the southern slope of the Golyamo blato above the sinkhole, there is a landfill in which a large amount of crushed stone is being deposited (fig. 8). It is a very serious pollutant of the waters of the swamp, which was established during hydrochemical analyses in the spring of 2026. The swamp water in the sinkhole under the landfill has a specific electrical conductivity of $1015 \text{ } \mu\text{S/cm}$, while the water in the northern part of the swamp has a specific electrical conductivity of $250 \text{ } \mu\text{S/cm}$, typical of the karst swamps in the Brestnitsa karst polje (Table 1). The newly constructed section of the

Hemus highway through BKG has heavy traffic, and this makes it a hazardous source of pollutants, especially considering that the water flowing away from the highway is not treated. A mud-oil separator (metal tank) has been installed under the highway at the bridge over the road to the Saeva Dupka cave, but it is not maintained at all.

The problem with the “Turkish” toilets of the Saeva Dupka cave has not been solved either, which were proven by hydrochemical speleomonitoring to pollute the cave’s drip water (Stefanov 2020; Stefanov et al. 2025). The toilets are apparently not within reach of the cave (fig. 9), but the dirty fluids from their uncleaned septic tanks seep through the tectonic cracks of the fault zone along which the cave system is developed. These are just a few examples that confirm that the Brestnitsa karst polje has dangerous uncontrolled pollutants in the infiltrating karst waters.

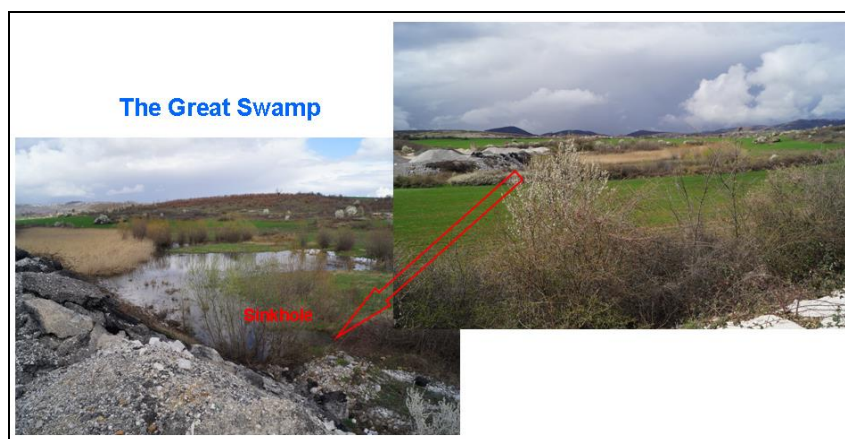


Fig. 8. The road construction materials depot on the slope of the Great Swamp (Golyamo blato), village of Brestnitsa

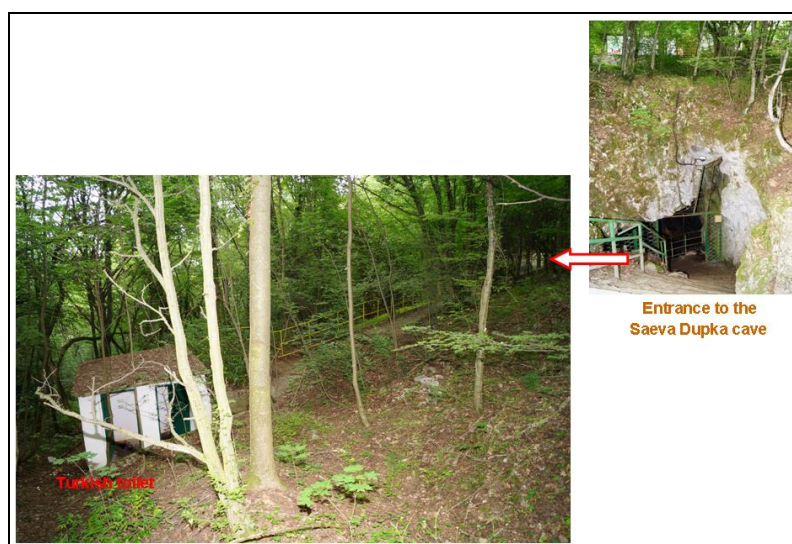


Fig. 9. The toilet of the Saeva Dupka cave

The great economic importance and the long-term practical exploitation of the water resources of BKG raise serious questions about their protection.

An attempt in this regard is the developed project for sanitary protection zones (SPZ) on the territory of the geosystem (Penchev and Velichkov 2012). However, their application and control are still ineffective. We will present a few examples. Despite the fact that both lakes of the Glava Panega spring are in the first belt of the SPZ (the direct protection zone - with prohibited access), the spring continues to be a popular and massively visited tourist site, which is why the protection regime is not respected. Tourist visits are also a source of pollution with household waste. In addition, on the western shore of the Lower Lake are the ruins of a large abandoned and dilapidated hotel. They, as well as newly formed landfills among the hotel ruins, are an additional serious source of pollution of the lake waters. Another problem related to the implementation of the SPZ is the new section of the Hemus highway. The measures envisaged in the construction project to prevent the discharge of water from the highway within the SPZ and to treat water in the mud-oil separator have not been met. Another example is the newly built Solid Municipal Waste Transfer Station near the village of Glozhene, which is in zone III of the SPZ and is located about 200 meters southwest of the border of zone II. A serious problem is the fact that according to the Conceptual Model of the Zlatna Panega Karst Basin, the SPZ sizing includes only the aquifer with infiltration recharge (Penchev and Velichkov 2012). Therefore, the quality of the river waters in the Vit river catchment basin before the river sinkholes is not controlled. However, these river waters form half of the flow of Glava Panega spring.

CONCLUSION

The results of the applied geosystem approach prove that BKG is very sensitive and vulnerable to both natural and anthropogenic impacts. If there are periods of very strong pressure, individual elements and subsystems undergo structural or functional changes. But every system has potential for adaptation to external changes and pressures. The long-term interdisciplinary research confirms that BKG, despite its great vulnerability, still has normal development and successfully adapts to both climate change and anthropogenic pressure (Nojarov et al. 2024). Historically, during its long existence, the geosystem has been subject to much greater changes in the natural environment, including paleoclimatic changes (Nikolov 2011), but it has also successfully adapted to them. Anthropogenically induced changes in recent decades have an impact not so much on the functioning of BKG as on the quality of its resources used by humans, of which water is the most important (Ciampittiello et al. 2024). A telling example is the chronic pollution of the

underground karst waters of the geosystem, which are the main water source for a very large region.

The conducted research also reveals a number of management problems. Against the background of the serious pollution of the waters of BKG and the karst spring Glava Panega, the legitimate question arises as to whether the work of the state and local institutions responsible for water resources and water supply from the karst spring is effective. And why, with such obvious pollutants in the karst territory of the geosystem, are no measures taken to limit and eliminate them? Responsibility is transferred institutionally or neglected, but the result is very worrying, especially for the users of the waters from the karst spring Glava Panega. Since this spring, representative of the karst in Bulgaria, has been proposed for inclusion in the Global List of the Most Important Springs from Karst Aquifers in the World (Benderov, 2022), the state institutions must implement the necessary measures for its protection.

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