Article

The Impact on Karst Aquifer Regimes Induced by a Surface Reservoir in Karst through Multiparametric Analyses (Reservoir Bileća—Herzegovina)

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Abstract: The results of long-term groundwater monitoring in the Bileća reservoir adjacent (eastern Herzegovina, Bosnia and Herzegovina) indicate that there is a good hydraulic connection between the reservoir and the karst aquifer located in the right bank of the reservoir. In remote parts of the right-bank karst aquifer, due to complex lithostratigraphic characteristics and a tectonic structure, the influence of the reservoir is very variable and has been insufficiently studied up until now. This paper presents the analysis and synthesis of new, relevant hydrogeological data, as a basis for the creation of a 3D spatial model, i.e., the analysis of the karst system's behaviour, both under regular and artificial hydrological conditions of surface reservoir construction and its continuous use (filling and emptying). The interactive connection of the model and complex surface and groundwater time series monitoring data of this system is presented through the analysis of its hydrodynamic characteristics, which completes the spatial model of the karst regime caused by low and high groundwater levels and low and high reservoir water levels. The integration of all the data into one model and further multiparametric analyses revealed the different types of hydrodynamic conditions prevailing in the karst aquifer with regard to the influence of the high or low waters of the reservoir.

Keywords: karst; groundwater; reservoir; multiparametric analyses; monitoring

1. Introduction

Karst areas are of great importance for the world's population, keeping in mind that they cover 15.2% of the Earth's ice-free land and that about 678 million people (or 9.2% of the world's population) use karst groundwater for drinking [1–3]. Although these facts indicate the very great importance of karst terrains, the monitoring of karst groundwater regimes is generally not at a satisfactory level, especially in the Balkans [4,5]. Areas with an uneven rainfall regime, especially those built from karst rocks, represented a real challenge for local populations to survive throughout history, but also for engineers to regulate the water regimes of these areas. Therefore, the construction of dams and reservoirs, which would retain and enable the usage of water throughout the year, represents a very complex engineering undertaking that has enabled the development of the population [4,6]. Water loss through the sides of the reservoir or under the body of the dam is often possible in karst terrains, although complex and expensive research (for the purpose of building dams and reservoirs) has been carried out for several years. Therefore, the results of this research for the purpose of the sustainable use of the water potential within karst terrains, and the purpose of projects and their sustainable use, could come into question. These problems precisely underscore the need for the constant monitoring of karst aquifers under the functioning conditions of the reservoir and preventive responses to possible

water loss occurrences [4]. The leakage of the dam is directly conditioned by the local geological and hydrogeological characteristics, and it is therefore necessary to carry out very detailed geological and hydrogeological research during the design and construction of each hydrotechnical facility of this type [4].

The paper presents research related to the definition of possible water losses from the right side of the Bileća reservoir, that is, the hydrodynamic characteristics of the influence of surface waters on the karst aquifer formation along the right bank of the reservoir. In general, the entire concept of the Trebišnjica Hydrosystem assumes that the impermeability of the right side of the Bileća reservoir is high, and therefore the sustainability of this system would be consistent, as well as the sustainability of the abundant use of karst groundwater. It was necessary to confirm the positive role of the dolomite anticline as a regional hydrogeological barrier, and to determine its role in the maintaining a high water capacity level of the right bank of the Bileća reservoir. Although the positive function of the Lastva dolomite anticline was confirmed during a long period of research and exploitation of the Bileća reservoir, the discharge of the Mlinica Spring formed in the karst and other similar karst springs on the right bank was hypsometrically lower. The Gorica reservoir was never investigated in detail. In particular, neither was the possibility that these springs represented drainage zones for water leaking from the Bileća reservoir, as well as collapse zones at the Orah location (the right side of the reservoir area), and their connection or disconnection through the karst underground [4,7,8]. The assumptions made with regard to the water capacity and functioning of the karst aquifer of the right bank of the Bileća reservoir are shown through the results of the observation of the comparative functioning of the karst aquifer, i.e., the groundwater level fluctuation and the reservoir (water level) itself. Observations of the groundwater level oscillations indicate that there is a good hydraulic connection between the Bileća reservoir and parts of the karst aquifer on the right bank and yet, in remote parts of the karst aquifer on the right bank (piezometers B-2, B-3, M-2, M-3, and B-4), the impact of the accumulation is quite variable, due to complex lithostratigraphic features and a tectonic structure. The hydrogeological characteristics of the functioning of this part of the aquifer have not yet been clearly defined. Based on earlier data, when the reservoir levels are lower than 360 m above sea level (a.s.l.), the restoration of the GWL to its natural state also occurs in that part of the aquifer.

During the phases of the design, research, and construction of the Bileća dam and reservoir, but also after the hydrosystem was put into operation, some standard and specific research methods were applied, and some of them are given in this paper. For example, speleological investigations were applied for the purpose of defining the place of potential water leakage and the interconnection of the water levels in the reservoir and the karst groundwaters in the wider vicinity of the dam. On the other hand, in the long history of research of this area, the application of exploratory drilling, dye-tracing tests, and thermometric, isotopic, and hydrological studies has taken place in order to form a regional hydrogeological conceptual model, define the directions of the groundwater circulation, and determine the stability of the dam, especially considering the aspect of water leakage through the dam body. All the results of this research were focused on deciding on remedial measures [4].

2. Materials and Methods

General Characteristics of the Researched Area

The study area is located in eastern Herzegovina in the heart of the Dinaric Karst (Figure 1). The Dinaric Mountain chain (karst system) extends in a northwest–southeast direction, starting in SE Slovenia, extending through Croatia, Bosnia and Herzegovina, Montenegro, Serbia, and towards the end in North Macedonia and the Albanian Alps [9]. The Dinaric system is built mainly of carbonates in the form of limestone and dolomite of the Mesozoic Age. The average thickness of this carbonate can be from 350 to 400 m, and it can extend to over 1000 m [9,10]. The thick sedimentation of the carbonate rocks was exposed to the influence of surface waters at the end of Lower Mesozoic and after that,

during the Paleogene, there were two phases of intense tectonic activity that caused the uplift, folding, and breaking of the carbonate systems and flysch formations [11]. Due to the different degrees of carbonate dissolution, the amount of atmospheric water, and other factors, the modern Dinaric system can be divided into three tectonic subsystems [11–13]:

- Outer Dinarides (or the Adriatic zone);
- Central Dinarides (or the High Karst Zone); and
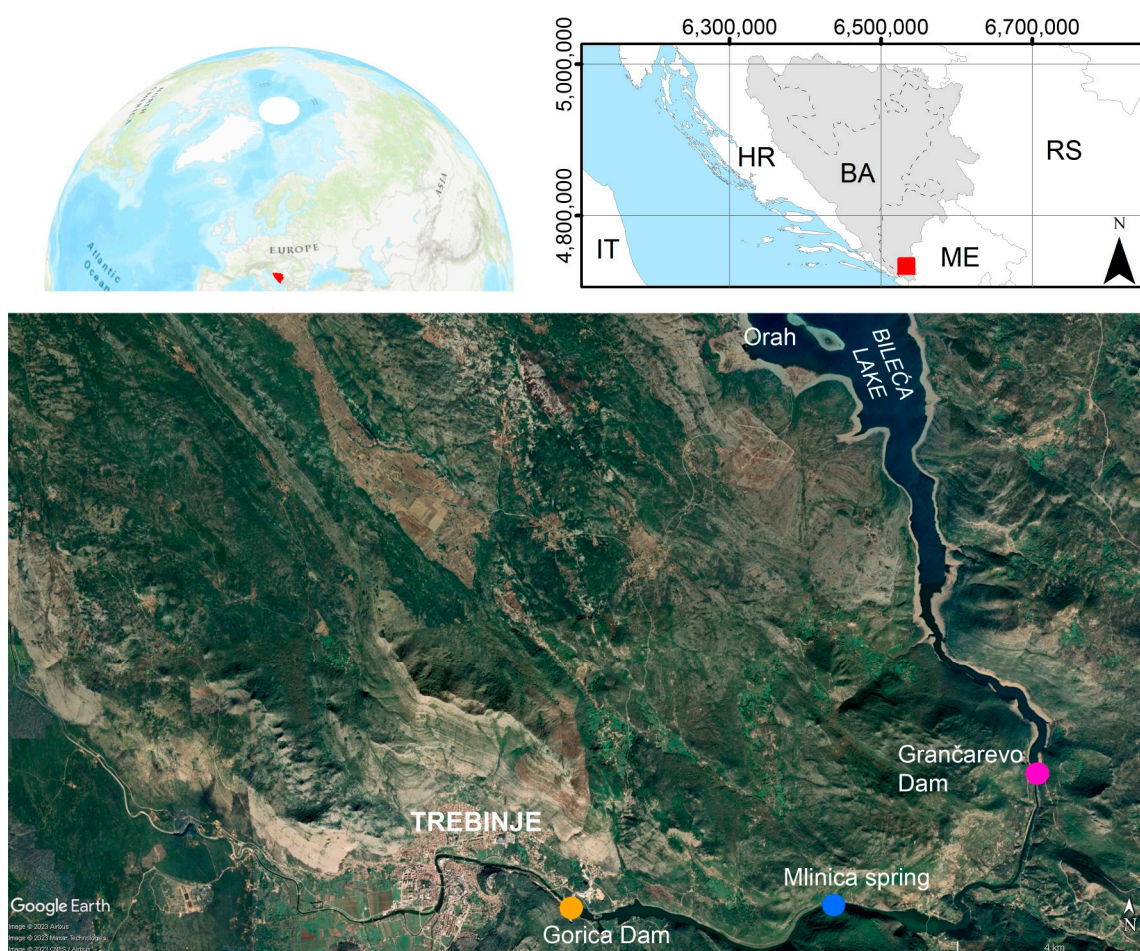- Inner Dinarides (zone of isolation and fluviokarst).

Figure 1. General setting of the area. Legend: IT—Italy, HR—Croatia, BA—Bosnia and Herzegovina, ME—Montenegro, RS—Serbia.

The Dinaric Karst is rich in groundwater and represents the region with the highest water balance in Europe [9]. However, considering the different climatic characteristics of certain parts of the Dinaric Karst and its unequal karstification degree, there is also an uneven distribution of karst groundwater [14].

A micro-location of the study area belongs to the Central Dinarides (High Karst Zone) of the Dinaric Karst and covers the area between the Bileća reservoir, built by the Grančarevo dam, and the Gorica reservoir, built by the Gorica dam. The Bileća reservoir, which is the subject of this paper, has a total length of 18 km and a total volume of 1.277 billion m^3.

The geology of the Bileća reservoir adjacent consists of Upper Triassic dolomites and limestones, Jurassic dolomites, and Upper Cretaceous limestones and dolomites. Such geological settings are the main reason why the risk of water losses is excluded on the left side of the dam, unlike the right side, which is located between the two mentioned reservoirs and lower erosion bases (Popovo polje and the Adriatic Sea) [4,15].

The source zone of the Trebišnjica River, which consists of large karst springs, Dejan's Cave and the Nikšićka vrela spring, as well as the Čepelica spring, is submerged by the reservoir. When the water reservoir is full, the springs of the Trebišnjica River are submerged with a column of water of 75 m. The reservoir also submerges the "Oko" cave, 5 km downstream from the spring zone of the Trebišnjica River, several pits, and a couple of smaller karst springs [16]. As already mentioned, the water-holding capacity of the "Bileća" reservoir is based on the hydrogeological role of the Lastva anticline, that is, on the watertightness of the core of this anticline, which is made up of Upper Triassic dolomites.

The researched terrain with the subject of the right bank of the Bileća reservoir represents the area between Orah village and Mlinica Spring (Figure 1). The research area also includes the following villages: Orah, Skrobotno, Mosko, Poljice, Dubočani, Gornje Vrbno, Budoši, Donje Vrbno, Gornje Grančarevo, Donje Grančarevo, Necvijeće, and Jasen.

In order to define the hydrogeological and hydrodynamic characteristics of the study area, all research methods were applied through several stages. The most interesting zone stretches from the Orah area to the Mlinica spring (Figure 1), so an investigation of the hypothetical connection between the sinkhole collapse zones in the Orah area with the karst springs in the lower zone of the Gorica dam was required in order to define the hydrogeological and hydrodynamic functions of the right bank of the Bileća reservoir [4]. Thus, all the methods were carried out in three zones: (1) the Orah collapse zone; (2) the area between the Orah zona and Mlinica karst spring; and (3) all the karst springs at a lower hypsometric level (Figure 2).

The approach to the problem solving took place following detailed and complex terrain analysis, such as:

- a thorough geodetic survey of the study area and detailed (hydro)geological field reconnaissance;
- extensive morphometric, speleological, and cave diving investigations in the whole study area;
- groundwater monitoring in the drainage zones (Mlinica spring), which was carried out on a daily basis during the research period, i.e., one hydrological year. The monitoring was carried out using a current meter (5 times per year for Q estimation) and a gaging station placed in the very zone of highlighting (for water level measurements).
- groundwater monitoring on piezometers, which was carried out on a 12 h basis on the selected piezometers;
- videoendoscopic logging of all the piezometers in the reservoir zone on the right bank and of all the piezometers in the very adjacent of the Gorica reservoir as the lowest hypsometric point of the investigated area;
- water sampling from the piezometers and springs for providing isotopic analyses;
- dye trace tests performed by the application of Na-fluorescein for a groundwater direction analysis within the selected piezometers and karst collapses in the Orah zone.

In order to create a reliable 3D hydrogeological model (Figure 3), all the hydrogeological data were collected and stored in a unique database. These data were obtained directly from the field survey and the groundwater monitoring network, consisting of 13 piezometers, 25 boreholes, 12 speleological sites, 3 karst springs, and 14 collapses.

During the field survey and hydrogeological mapping, several speleological objects were discovered and explored, and speleological explorations of the Mlinica Spring were carried out, which provided insight into the structure and potential location of karst conduits in the study area.

Isotopes are used in hydrogeology based on their content in surface and groundwater, as well as in the total environment. This type of research method is ideal for karst terrains, since different types of isotopes (stable and radioactive) can be used to obtain different data on the functioning of karst aquifers [17].

In the Orah–Mlinica area, water sampling was carried out to determine the content of stable and radioactive isotopes (oxygen ^{18}O and deuterium ^{2}H, and T + ^{3}He) in the September 2016–April 2017 period. Samples were taken from the reservoir itself and at Mlinica Spring, as well as at two piezometers, B-3 and V-2, in order to determine the connection between the surface and groundwater, i.e., the connection of the water from the reservoir with the Mlinica Spring (or groundwater in piezometers). A total of 16 samples were collected in order to define the content of stable isotopes, ^{18}O and ^{2}H. For the purpose of creating a Local Isotopic Meteoric Line, precipitation was sampled monthly when precipitation was present. Given that the research period was a period with very little rainfall, a total of 6 samples were taken, namely two samples in November, two in February, and two precipitation samples in March.
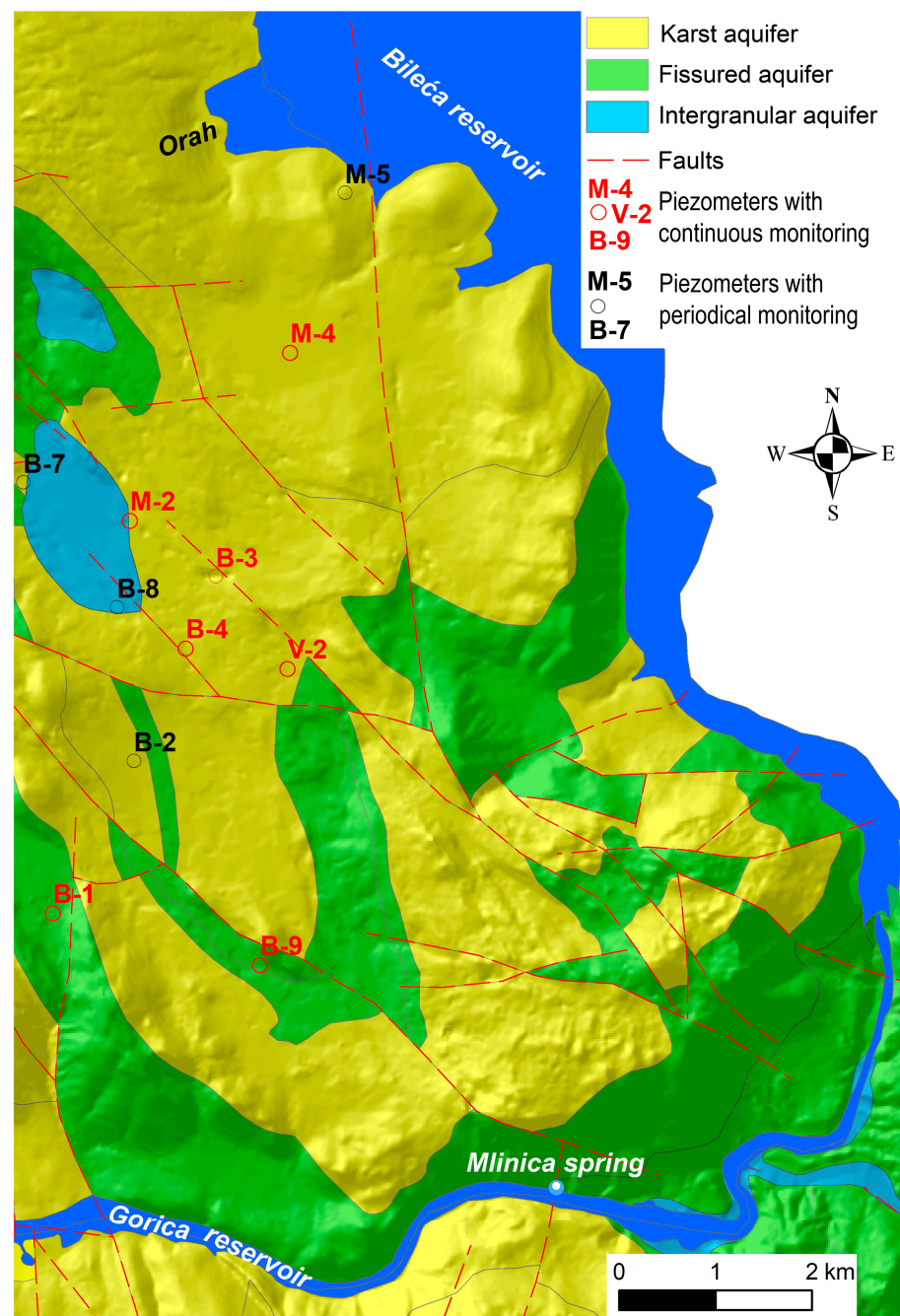

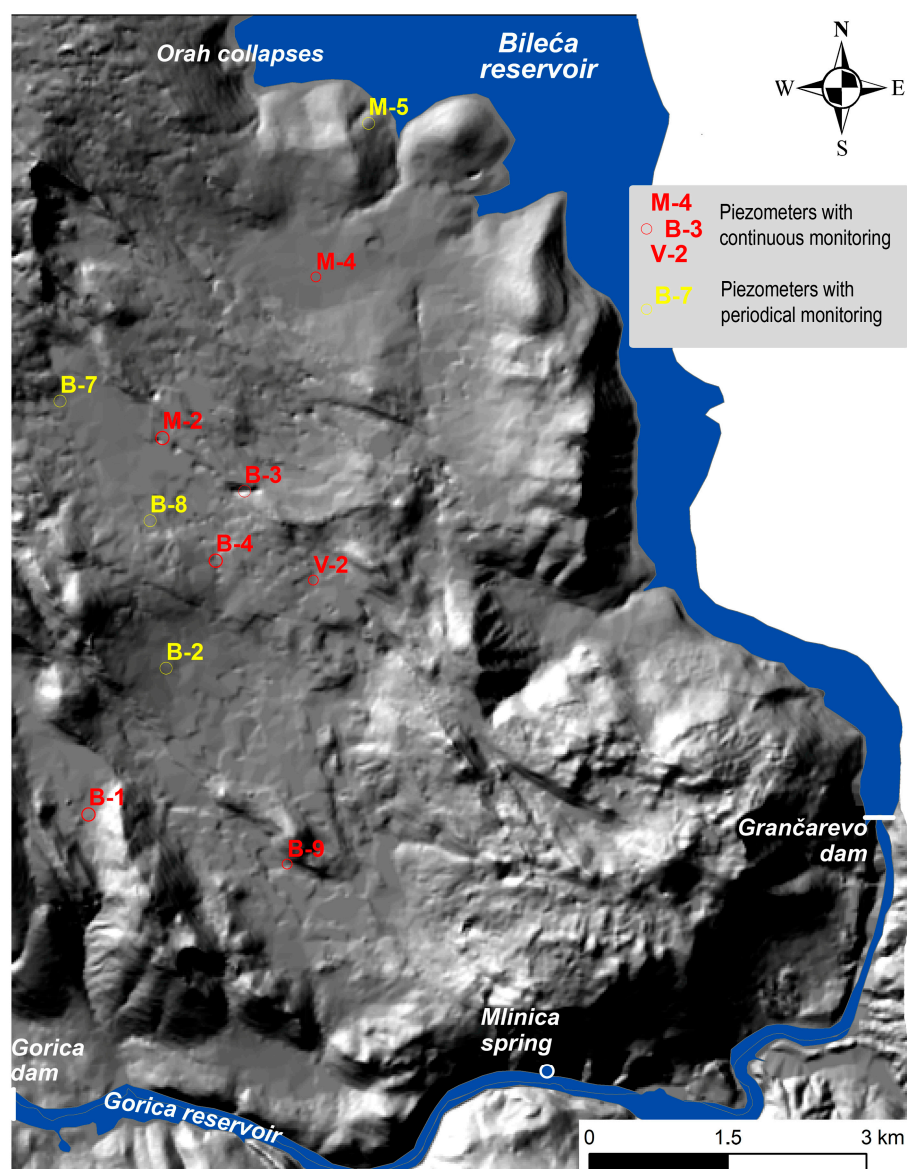**Figure 2.** Hydrogeology map of the wider study area.

Figure 3. 3D model of the area with locations of important objects.

The groundwater age in karst terrain can be determined by measuring the concentration of tritium isotopes remaining in the sample, the concentration of ^{3}He accumulated in the sample, and knowing the half-life of tritium (12.3 years) [18]. The equipment for the isotopic analysis included one-litre glass bottles, which were used for the ^{3}H sampling, while copper sampling tubes [19] were used for the noble gas content of the water.

The tritium content and noble gas contents were determined with a VG5400 noble gas mass spectrometer [4,20–22], while the stable isotopes ^{18}O and ^{2}H contents were determined with a DeltaPLUS XP isotope ratio mass spectrometer [4,23].

The tracer test in the researched area was carried out by injecting/pouring a fluorescent dye tracer (Na-fluorescein) during two campaigns:

- In the well B-3 (30 March 2017) and
- In 8 collapses in the Orah zone (20 April 2017).

The tracer test was carried out on piezometer B-3 on 30 March 2017. The dye tracer was poured into piezometer B-3. Although the yield from the most important observation point, the Mlinica Spring, at the time that the tracer test was conducted was about 35 L/s from a distance of approximately 7 km, according to the formula of Martel [24,25], only 0.5 kg

of Na-fluorescein would be enough to perform the experiment. As recession conditions prevailed at the time of the tracer test, and since the test was to be performed on the piezometer without any clear knowledge of the existence of a stronger groundwater flow, it was decided to perform the experiment with 4 kg of Na-fluorescein.

After the pouring of the dye tracer, about 600 L of water was injected into the piezometer via a previously installed hose system. Monitoring of the appearance of the tracer was performed at all the sites of its potential reappearance: piezometers B-4, B-9, M-2, V-2, and V-1, as well as Mlinica Spring. All the samples from the piezometers and Mlinica Spring were analysed at a laboratory with a fluorometer Turner Designe UV-10.

3. Results

The Orah collapse zone stands out as a potential location of water leakage from the reservoir, based on the total of 12 registered collapses in the area, which belong to the right side of the Bileća reservoir [4] (Figure 4).
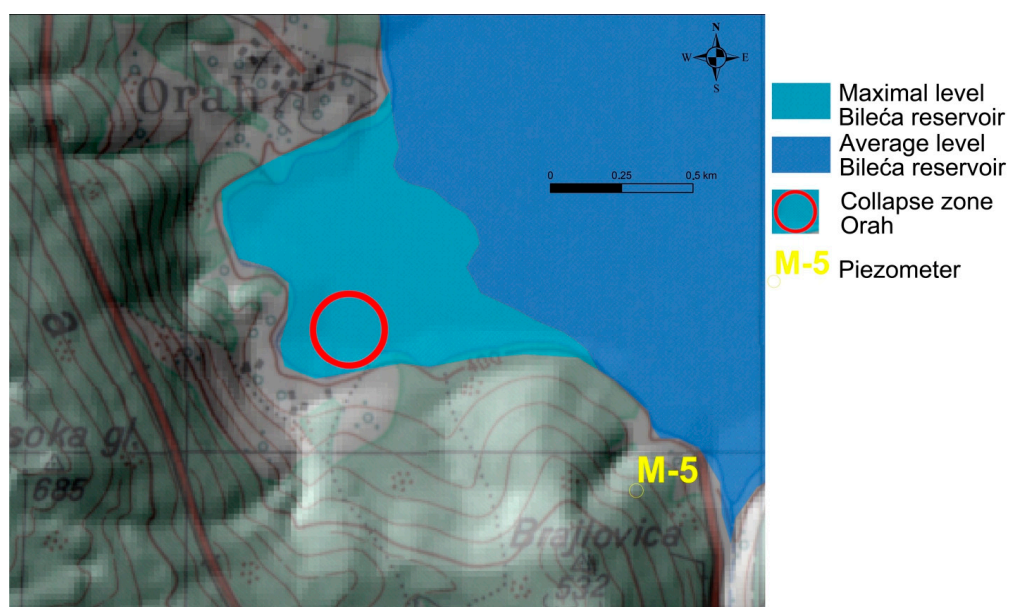

Figure 4. The Orah collapse zone (right bank of Bileća reservoir).

In the second zone, between Orah and the Mlinica Spring, the hydrogeological characteristics analysis was based on the data collected on the groundwater level oscillation from six selected piezometers (Figures 2 and 3), as well as the water levels in the Bileća reservoir and the data on Mlinica Spring.

The discharge zone of Mlinica Spring is presented in the highest drainage zone by a horizontal cave with a length of 200 m, which continues further through a lake and a siphon channel. Based on its hydrogeological characteristics, Mlinica Spring is considered to be one of the main drainage zones on the right side of the Bileća reservoir, as well as all the other springs at a lower hypsometric level, which fully corresponds to the precipitation and groundwater oscillations of this karst aquifer.

All the data collected from the piezometers on the right bank of the Bileća reservoir were analysed through the karst aquifer functioning model during periods of high and low water (Figure 5). Detailed monitoring, along with other hydrogeological research, also included observations of the groundwater fluctuation in the karst aquifer, as well as the water level oscillations in the reservoir, for the period from November 2016 to June 2017. To compare the karst aquifer behaviour in relation to recharge, precipitation (rainfall) data collected from a rain gauge station at the Grančarevo dam were also used. The groundwater level (GWL) monitoring data, rainfall data, water level data in the Bileća reservoir, and

Mlinica Spring discharge data are shown in Figure 6, where their mutual correlation can also be observed.

From the presented charts, it can clearly be observed that, apart from the GWL in piezometer B-3 and piezometer B-9, the GWL in all the other piezometers had a significant connection with rainfall, as well as influencing fluctuations in the reservoir water levels and Mlinica Spring discharges. The increase in the GWL in the piezometers fully corresponded to the increase in the Mlinica Spring discharge rates, so that these changes occurred practically with no delay. In addition, as expected, the water level in the Bileća reservoir oscillated in exactly the same way as the GWL in the karst aquifer in the hinterland.
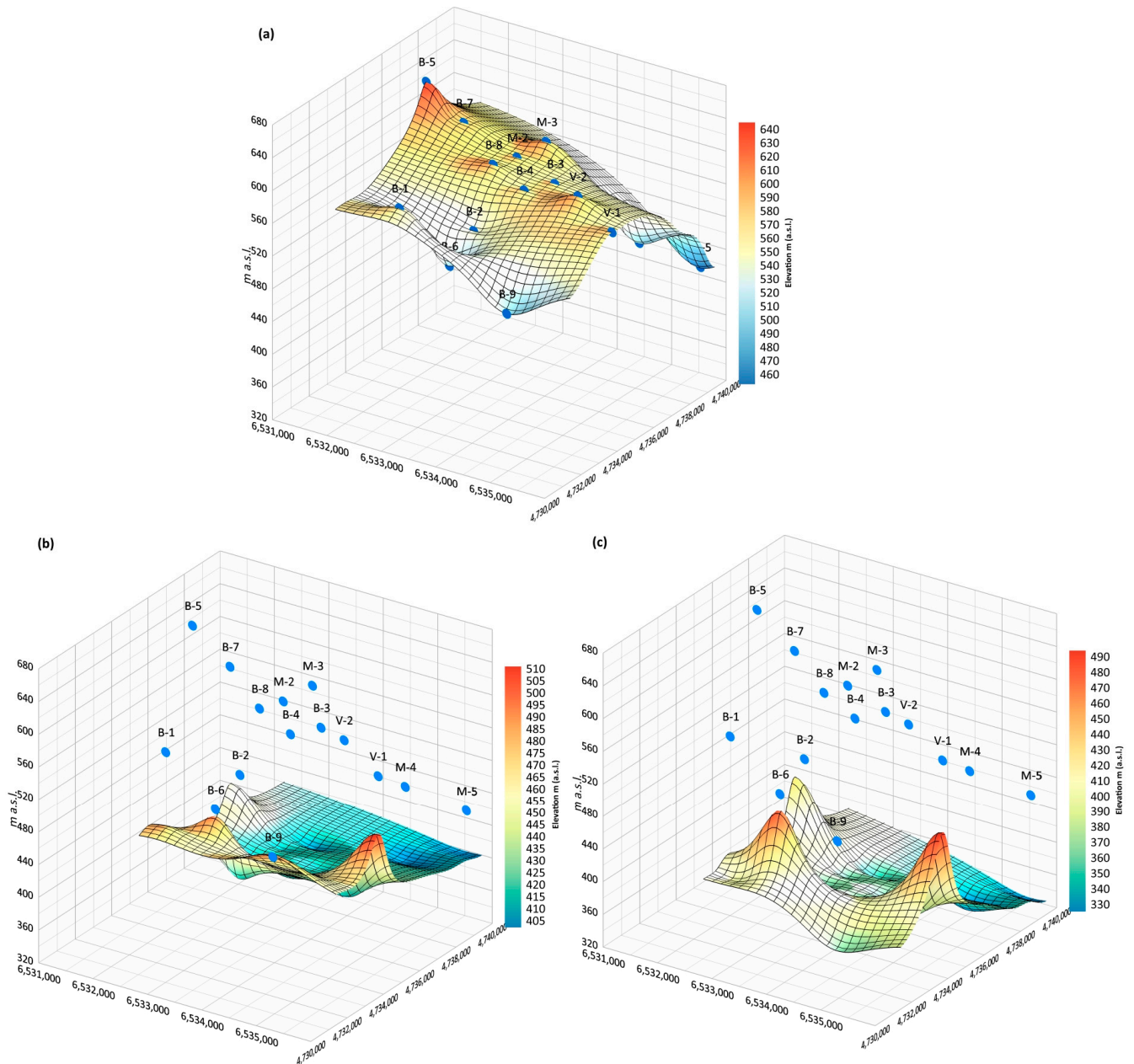

Figure 5. 3D model of the terrain based on piezometers position (**a**), maximal GWL (**b**) and minimal GWL (**c**) that is noted in piezometers.
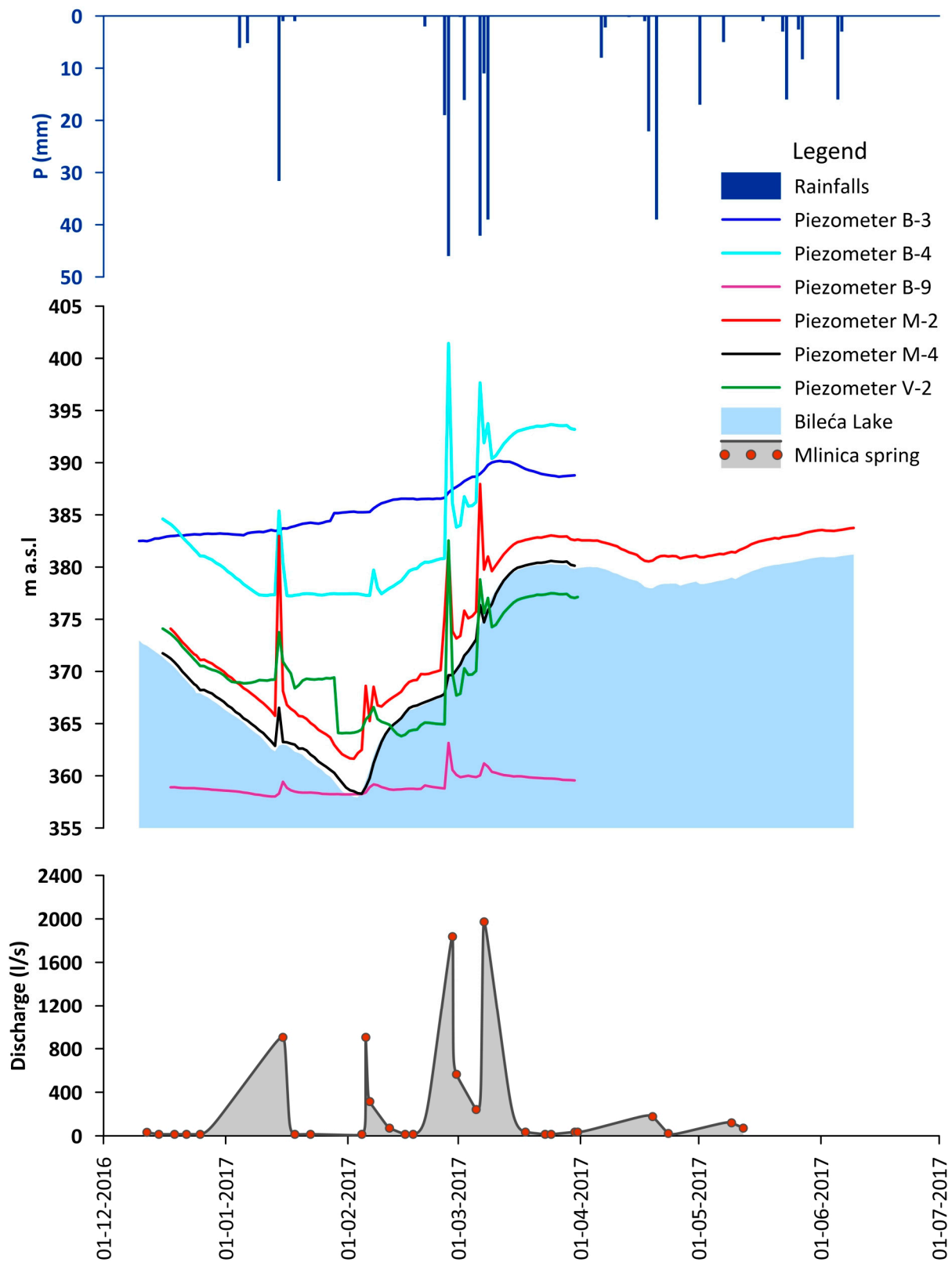
Figure 6. Rainfall, GWL in piezometers, Bileća reservoir water level, and Mlinica Spring discharge data.

The GWL in piezometer M-4 fully corresponded to the fluctuations of the Bileća reservoir water levels, but did not show reaction in terms of increased precipitation; on the other hand, the GWL in piezometer M-2 also correlated with the reservoir water levels,

which increased almost instantly following a precipitation event. Afterwards, the GWL dropped to "normal levels" that corresponded to the water levels in the reservoir. Like M-2, the GWL in piezometer V-2 had a good connection with the water level in the Bileća reservoir until a precipitation event occurred, after which, there was some discrepancy between the GWL and reservoir water level, which gradually decreased over time.

If the GWL in piezometers B-4, M-2, and V-2 is taken into consideration and compared with precipitation events, it can be observed that two precipitation events (4–6 January 2017 and 20 February 2017), which were noted at the Grančarevo dam measuring station, were not followed by a GWL increase in these piezometers. On the other hand, there was one significant GWL increase (3–9 February 2017) that was not, on first observation, a consequence of precipitation. These events imply that the data from the measuring station did not reflect the real-time conditions of the whole research area all of the time. Thus, it must be concluded that, in all three stated periods of time, precipitation existed, only it did not have the same effect on the groundwater levels in the whole area between Orah and Mlinica Spring.

The very high positive correlation between the GWL in the piezometers and the Mlinica spring discharge (Figure 5) clearly indicates that the spring zone and its catchment had a perfect connection with the karst aquifer of the right side of the dam. In order to support the aforementioned facts, tracer tests were conducted. These tests confirmed the strong connection between the water level in the Bileća reservoir and the GWL in the karst aquifer on the right side of the dam. Tracer tests were conducted to confirm the previously stated assumption that the groundwater circulation of the karst aquifer of the right bank of the Bileća reservoir has a strong connection with the water levels in the Bileća reservoir [4,25], as well as with the geological conditions of the whole terrain and the amounts and schedules (patterns) of precipitation.

The results of the tracer tests are given as follows. The tracer was detected at all the observation stations and Mlinica Spring (Figure 7). As can be seen, the first appearance of the tracer at all the piezometers was measured in the first sample, while the highest concentration was observed in piezometer B-4, which is "logical", since it is the closest to piezometer B-3 (Figure 7). The highest concentration during the monitoring was measured in piezometer V-1, in a sample that was taken on 10 April. The lowest tracer concentration was measured in piezometer B-9, which is the farthest from the injection point. Furthermore, the samples taken at Mlinica Spring showed that the tracer appeared in only one sample, 7 days following the dye tracer injection, in a concentration of 0.72×10^{-9} mg/L [4].
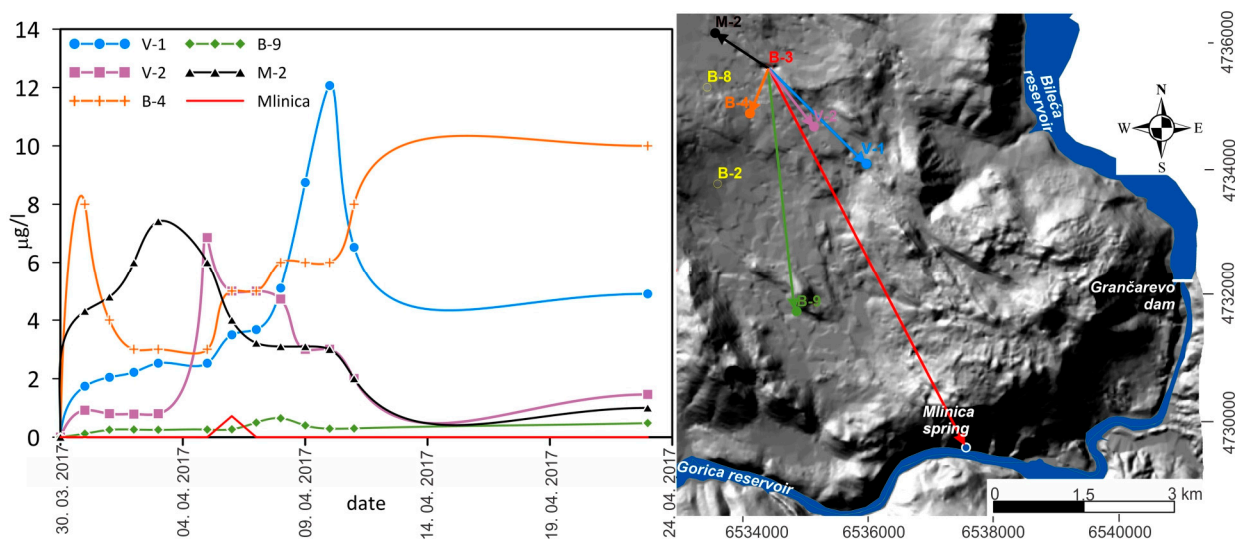

Figure 7. The results of the tracer tests in piezometer B-3.

The second campaign of the tracer test was carried out in the collapse zone (Table 1) at the Orah location on 20 April 2017. Originally, it was planned to carry out the experiment in a period of high water levels, i.e., when the accumulation level was above the Orah collapse zone, when it was considered that the best results would be achieved in terms of defining the sinking and circulation of the groundwater throughout this zone. Unfortunately, the second half of 2016, as well as the beginning of 2017, was "very dry", i.e., no significant rainfall occurred until April 2017, and the reservoir was not filled to the necessary elevation of 382 m a.s.l. (Figure 8). Thus, it was decided to perform the experiment with pouring water into the collapses after the dye tracer, similar to the test conducted within piezometer B-3. In each of the six smaller collapses, 0.8 kg of dye was dissolved in water and poured, and in the small collapse near the accumulation, 0.5 kg of dye was dissolved in water and poured, while 1.5 kg of paint was added to the largest collapse (Collapse K6). In total, 6.8 kg of Na-fluorescein was injected into 8 collapses (out of the 12 detected at the Orah location, Figure 8). The injection of the dye tracer, in quick succession, and the pouring of 18 m^3 of water per collapse (and 72 m^3 of water was poured into the largest collapse), was conducted for 4 h on the same day. The tracer tests showed the reappearance of the tracer in the Bileća reservoir only at several sites (Figure 9), and an absence of the tracers in the monitoring piezometres (M-5 and M-4). Therefore, based on these results, the hydraulic connection between the Orah collapse zone and the right bank of the Bileća reservoir cannot be proven under the minimal water period, when the tracer test was carried out [4]. According to the obtained results, it can be only proved that the groundwater with an injected dye tracer circulated through the karst channels towards the local erosion base, i.e., the old riverbed of the Trebišnjica river (Figure 10), and that it appeared in locations where there was a direct connection of the channel with the surface.

Table 1. Collapses at Orah zone.

Name	X	Y	Z	Length	Width	Depth
K1	6,534,512	4,740,434	381	1	1	0.5
K2	6,534,549	4,740,412	381	0.8	0.8	0.5
K3	6,534,569	4,740,419	381	9	9	4
K4	6,534,562	4,740,403	381	5	4	2.5
K5	6,534,560	4,740,377	381	7	6	3
K6	6,534,545	4,740,396	381	16	17	8
K7	6,534,531	4,740,391	381	7	6	3.5
K8	6,534,525	4,740,380	381	1	1	0.5
K9	6,534,526	4,740,315	381	6	4	3
K10	6,534,523	4,740,391	381	3	3	0.5
K11	6,534,522	4,740,395	381	0.3	0.3	0.5
K12	6,534,532	4,740,384	381	1.5	1.5	1.3

All the results clearly point out the reorientation of the groundwater circulation in different hydrological conditions within the karst aquifer of the right side of the dam. Furthermore, these results lead to the conclusion that the water leaked from the reservoir, first recharged the karst aquifer, and then went to Mlinica Spring, which is very suspicious [4] (Figure 11).
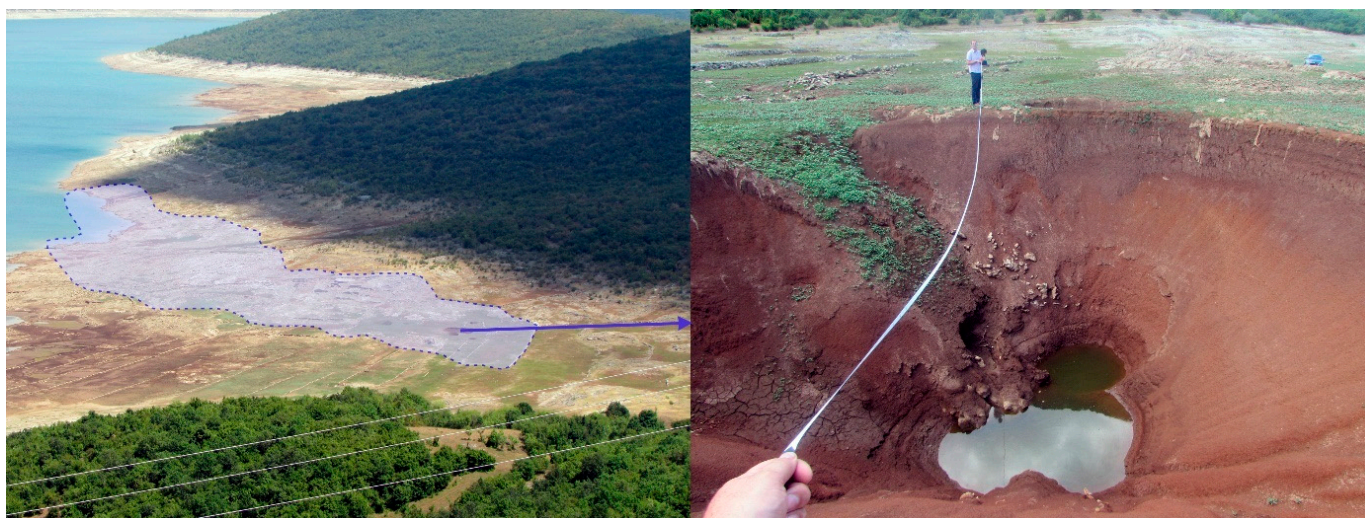
Figure 8. Orah zone collapses (**left**) and the greatest collapse—K6 (**right**).
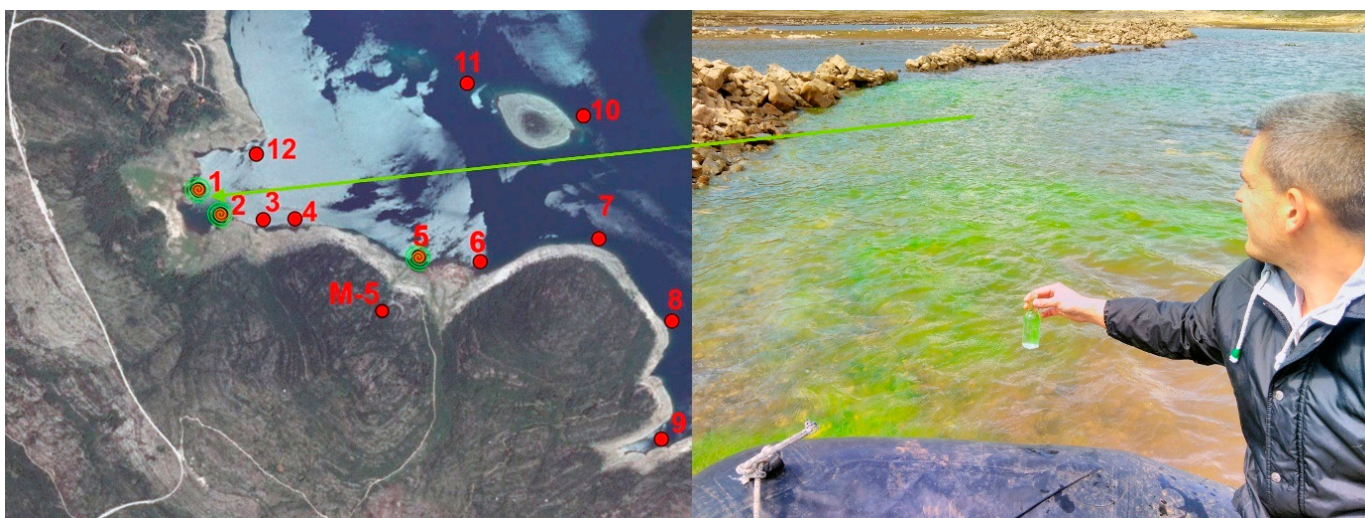

Figure 9. Locations of the sampling of water in the reservoir and appearance of the tracer, after dye tracer injection in the Orah collapse zone. Sampling locations (1–12) and piezometer M-5.

The discharge from Mlinica Spring during the monitoring period ranged from a few cubic meters to 5 L/s, which was recorded on 18 July 2015, while it dries up during very long dry seasons. As already mentioned, Mlinica Spring emerges from a cave that is located about 15 m above the maximum water level in the Gorica reservoir. A horizontal cave exists in the highest drainage zone, where a length of 60 m was examined during the preliminary reconnaissance. Detailed research was conducted and further channels were explored by speleo diving up to the siphon lake. In total, 90 m of new karst channels were recorded. Even though the cave is located well above the probable primary zone of discharge, during the dry period, a smaller, active flow was registered within it, as well as larger cave lakes further into the system.
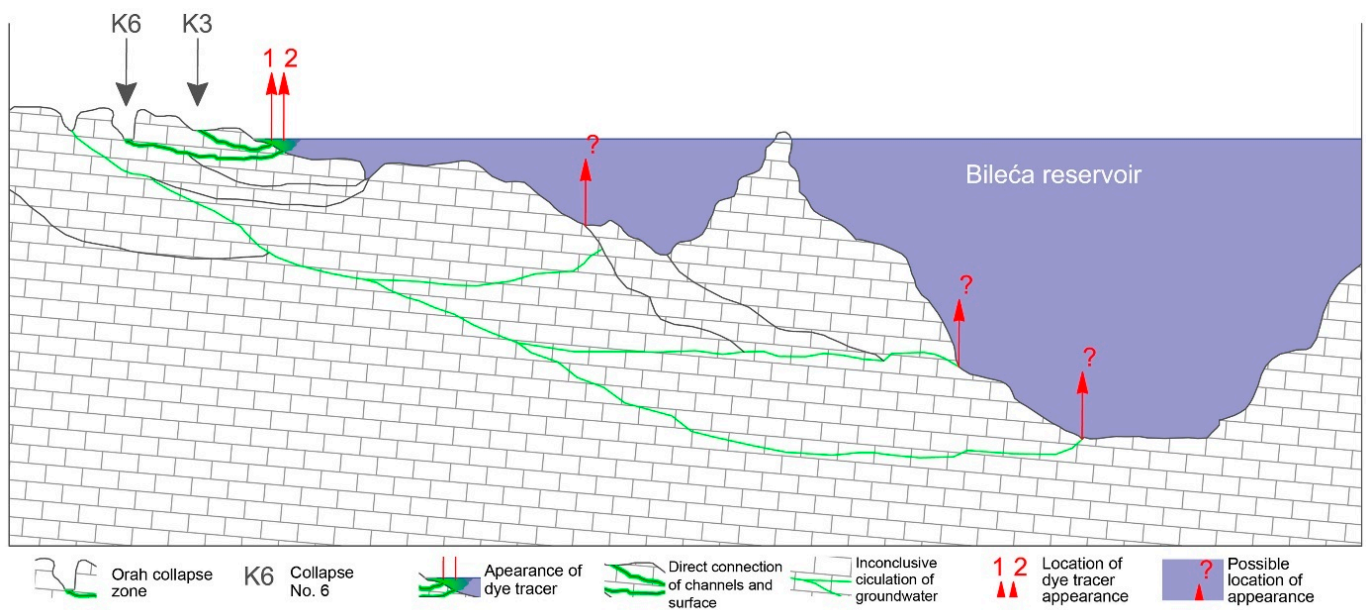
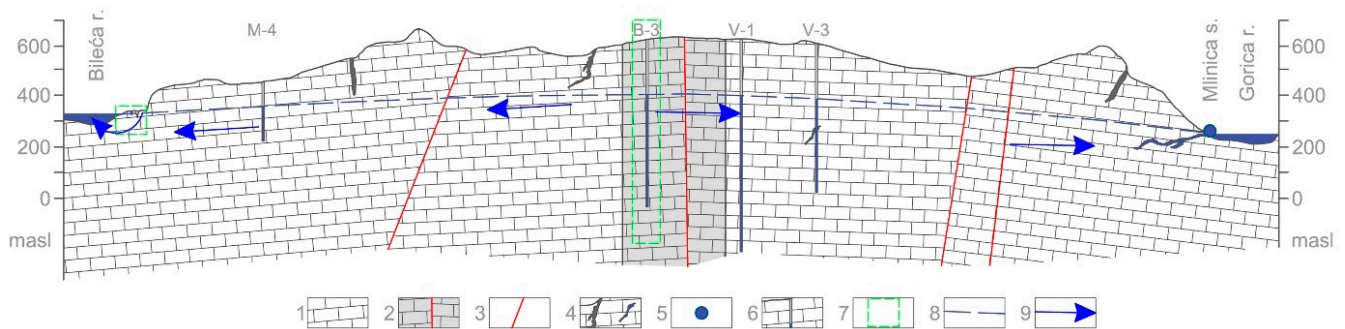**Figure 10.** The results of the tracer in the Orah collapse zone.

Figure 11. Hydrogeological watershed of the right bank of the Bileća reservoir: 1—limestones, 2—hydrogeological watershed, 3—fault, 4—cavern: dry and submerged, 5—Mlinica spring, 6—piezometer, 7—location of dye tracer injection, 8—GWL, and 9—groundwater direction.

According to the stable isotopes, oxygen ^{18}O and deuterium ^{2}H, it can be concluded that there is a strong relationship (Figure 12) between precipitation and the groundwater discharging from Mlinica Spring (in both measured cycles), as well as a strong relationship with the groundwater from piezometers B-3 and V-2, given that the measured values from these locations are plotted very close to, or almost on, the LML. The reservoir waters do not fit directly on this line, which is a consequence of pronounced primary fractionation, i.e., strong evaporation from the surface of the lake, where, due to the weaker connection of the lighter isotopes, they are primarily fractionated, leaving a heavier isotopic composition of oxygen and hydrogen in the lake. Strong winds, which are very pronounced in this zone during autumn and winter, also help the separation and fractionation of the lighter isotopes of oxygen and hydrogen from the surface of the lake.
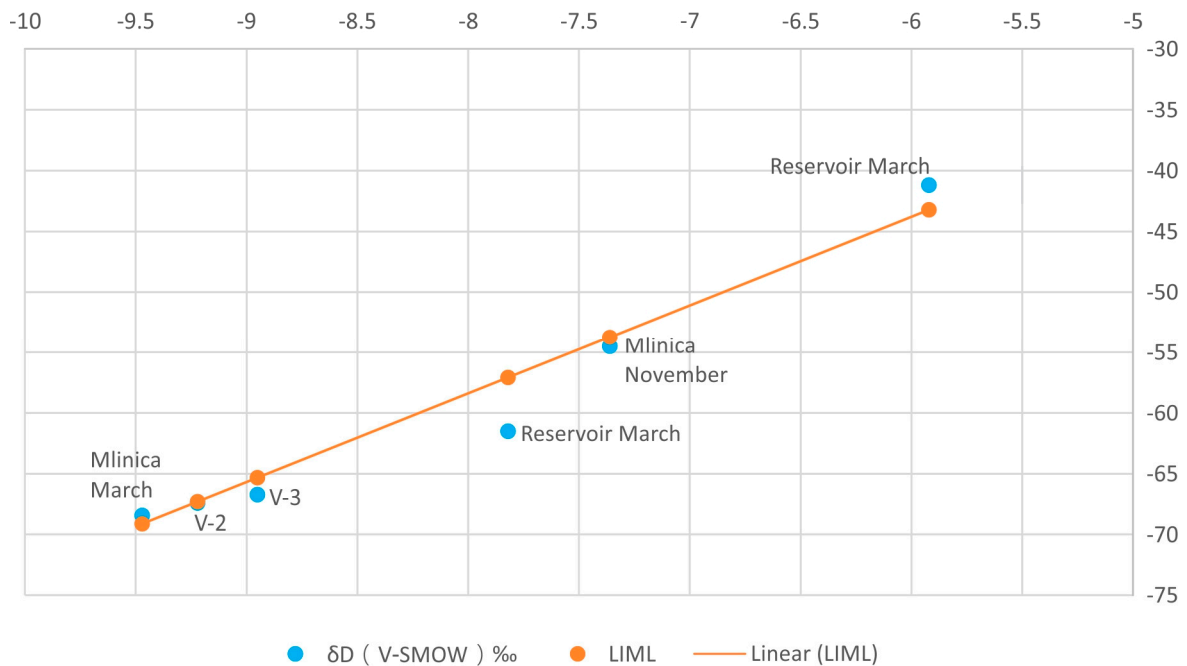
Figure 12. Ratio of surface and groundwater with the local isotope meteoric line (LIML).

A rough conclusion can be drawn that the groundwater from Mlinica Spring is not directly related to the waters from the reservoir, as well as that this groundwater (Mlinica and piezometers B-3 and V-2) is strongly related to precipitation, which speaks of a diffuse recharge of the karst aquifer and rapid underground circulation. In order to confirm these claims, it is necessary to sample water from the reservoir at different depths, as opposed to only sampling the surface layer that is exposed to fractionation.

The isotopic analyses of T + ^{3}He (0.187 TJ in average) of the groundwater from Mlinica Spring showed that karst groundwater in the right bank of the Bileća reservoir was very young, and that these waters are constantly connected with rainfalls. The age of the groundwater, in all the samples taken, ranged from a few days to a few months. The highest value of tritium was observed in the reservoir, which reflects the content of the isotope in the precipitation on the territory of Europe. When tritium enters groundwater, its decomposition begins, resulting in slightly lower observed values in groundwater than those observed in surface waters, which range from 5.7–7.8 TJ, indicating young water up to five years old.

All the applied methods, their results, and the daily groundwater monitoring data of the piezometers and Mlinica Spring discharge supported the fact that there is no significant water leakage from the Bileća reservoir in regular hydrological conditions. On the other hand, the correlation between the GWL data from the piezometers and Mlinica Spring discharge points out that the zone between the Orah collapse area and Mlinica karst spring discharges on the Mlinica Spring and other small springs along the right bank of the Bileća and Gorica Reservoirs, as well as directly into the Bileća (Gorica) reservoir [4].

4. Conclusions and Discussion

Based on all the collected and analysed data and the design of 2D and 3D spatial models, as well as the previously processed hydrodynamics of the karst aquifer, a complete spatial model of the karst system behaviour, in conditions defined by low and high levels of groundwater and low and high levels of the reservoir lake, was produced. The assessment and integration of all the data into one model gave results according to different types of combined conditions that prevail in the karst aquifer, and in relation to the influence of high or low waters of the reservoir lake. For such a model formation, a model of real conditions defined during the research period from November 2016 to June 2017, called

(Combined model 1), was used as a reference model. This, and other combined models of karst aquifer functioning dependant on the water levels in the reservoir and GWL, are given through four models:

- Combined model 1—low reservoir water levels and low GWL (benchmark model—defined during research);
- Combined model 2—low and medium reservoir water levels during floods, i.e., high GWLs;
- Combined model 3—high GWL and maximum reservoir water levels;
- Combined model 4—high reservoir water levels during the recession period, low GWL possible only in the conditions of the fully operative Upper Horizons (artificial conditions).

The first combined model (1) refers to the conditions of low reservoir water levels and low GWLs in the karst outcrop. These conditions prevailed throughout the entire research period. As can be seen from the obtained data, the connection with the karst aquifer is fully reflected by the data obtained from piezometer M-4 (the observed piezometer closest to the reservoir), while the data from piezometers B-4 and M-2 also followed the behaviour of the reservoir, but with considerably higher GWLs than the reservoir water levels.

On the other hand, the data of piezometer B-3, with the highest groundwater levels, indicated that a hydrogeological watershed may exist in that zone (Figures 4 and 7). Piezometer B-3 is located on the route of a large fault, which extends in a SE–NW direction. In addition, piezometer B-9, which has the lowest groundwater levels, did not correspond to the water level in the reservoir, which indicates that its hydrogeological activity is related to dolomite and dolomitic limestone. Piezometer V-2 also indicated a zone of possible water redistribution, that is, it did not reflect the state of the reservoir water level.

The data obtained from the investigative works at the Orah collapse area did not indicate the possibility for water loss from the reservoir under such hydrogeological conditions. The conclusion is that, under these hydrological and hydrogeological conditions, the aquifer discharges at Mlinica Spring and therefore, it can also be concluded that the groundwater discharge at Mlinica Spring has nothing to do with the surface water from the reservoir, but rather the groundwater from a large karst aquifer that covers about 80 km^2.

Combined models 2 and 3 are certainly not problematic and cannot affect the water loss from the reservoir, since these are about a high karst GWL on the right bank of the Bileća reservoir.

Unlike the models shown above, only the combined model 4 for the conditions of high water levels in the reservoir and a low GWL in the karst aquifer can cause leakage from the reservoir to the karst aquifer and further towards Mlinica Spring. Certainly, achieving this state during natural conditions and conditions of the normal functioning of the hydroelectric power plant "Grančarevo" is almost impossible (full reservoir at the end of the dry recession period). In such a case, the water level of the reservoir would be around 400 m a.s.l, while the groundwater levels in the piezometers would be 385 m a.s.l., i.e., significantly lower. Such levels would create conditions for water from the reservoir to infiltrate into the flanks of the reservoir, i.e., into the karst aquifer and circulate in the named zone towards Mlinica Spring. This condition is generally possible only in the working conditions of the Upper Horizons (artificial conditions). That is, when the reservoir would be filled from the higher-elevation reservoirs of the Upper Horizons during the recession period.

The main conclusion, which must be confirmed by a longer series of measurements of the GWL in all the piezometers on a daily basis, including the Mlinica Spring discharge, is that, under regular hydrogeological conditions, there is no significant water leakage, while on the other hand, the karst aquifer of the right bank of the reservoir, from the Orah collapse zone to Mlinica, drains mostly through the Mlinica Spring, and a smaller part of groundwater discharges into the Bileća reservoir.

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