DOI: https://doi.org/10.3986/ac.v54i2.14389

FACTORS INFLUENCING THE GROUNDWATER CIRCULATION IN MALI ME GROPA KARST MASSIF, CENTRAL ALBANIA

DEJAVNIKI, KI VPLIVAJO NA PODZEMNO VODO IN NJENO KROŽENJE V KRAŠKEM MASIVU MALI ME GROPA V OSREDNJI ALBANIJI

Romeo EFTIMI[1], Viacheslav ANDREYCHOUK[2], Peter MALÍK[3], Tatiana OREHOVA[4], Małgorzata NITA[5] & Perikli QIRIAZI[6]

Abstract UDC 551.44:556.33(496.5)

Romeo Eftimi, Viacheslav Andreychouk, Peter MalÍK, Tatiana Orehova, Małgorzata Nita & Perikli Qiriazi: Factors influencing the groundwater circulation in Mali me Gropa karst massif, Central Albania

There are 23 carbonate karst areas in Albania with a total area of 6440 km^2, or 24% of the country's territory. Karst aquifers are the richest in the country and about 80% of the water supply for the population living in cities is supplied by karst water. One of the most interesting karst massifs of Albania is called Mali me Gropa (MMG) with a total surface area of 157 km^2. It is the subject of this paper. Although this massif has attracted attention due to its exceptional development of surface karst landforms (karst pits, sinkholes, swallow holes) and its large and high-quality groundwater resources, it has not been the subject of comprehensive research. In this paper, for the first time, is a summary of the results of a combination of specialized studies, including geomorphological characterization, analysis of long-term groundwater regime observations in relationship with meteorological data, water balance studies applying the recently developed WaterbalANce software method, assessment of groundwater quality and its variability, determination of the groundwater flow velocity with an artificial tracer, and the use of hydrochemistry and runoff data to determine groundwater flow patterns and sensitivity of spring water to contamination. The results of the multi-method studies conducted on the MMG karst massif will inform future studies of the numerous

Izvleček UDK 551.44:556.33(496.5)

Romeo Eftimi, Viacheslav Andreychouk, Peter MalÍK, Tatiana Orehova, Małgorzata Nita & Perikli Qiriazi: Dejavniki, ki vplivajo na podzemno vodo in njeno kroženje v kraškem masivu Mali me Gropa v osrednji Albaniji

V Albaniji je 23 karbonatnih kraških območij s skupno površino 6.440 kilometrov^2 ali 24 % ozemlja države. Kraški vodonosniki so najbogatejši v državi, s kraško vodo pa se oskrbuje približno 80 % prebivalcev mest. Eden izmed najzanimivejših kraških masivov v Albaniji se imenuje Mali me Gropa s skupno površino 157 kilometrov^2. Ta je jedro tega članka. Čeprav je ta masiv z izjemnim razvojem površinskih kraških oblik (kraške jame, vrtače, požiralniki) ter z velikimi in visoko kakovostnimi viri podzemne vode pritegnil pozornost, še ni bil predmet celovite raziskave. V tem članku so prvič povzeti rezultati kombinacije specializiranih študij, kot so geomorfološka karakterizacija, analiza dolgoročnih opazovanj režima podzemne vode v povezavi z meteorološkimi podatki, študije vodnega ravnovesja z uporabo nedavno razvitega programa WaterbalANce, ocena kakovosti podzemne vode in njene spremenljivosti, določitev hitrosti toka podzemne vode s poskusom z umetnim sledilom ter uporaba hidrokemičnih podatkov in podatkov o iztoku podzemne vode, za določitev vzorcev toka podzemne vode in občutljivosti izvirske vode na onesnaženje. Rezultati raziskav, izvedenih z več metodami in na kraškem masivu Mali me Gropa bodo podlaga za prihodnje raziskave številnih karbonatnih kraških območij v Albaniji. Zadnji pomembni cilj tega članka

[1] Independent Researcher, Rr. Rreshit Çollaku, pll. 10/3/18, Tirana, Albania, e-mail: eftimiromeo@gmail.com
[2] Akademia Bialska im. Jana Pawła II, Sidorska 95/97, 21-500 Biała Podlaska, Poland, e-mail: czeslaw.andrjczuk@gmail.com
[3] Štátny geologický ústav Dionýza Štúra - Geological Survey of Slovak Republic, Mlynská dolina 1, 817 Bratislava 11, Slovakia, e-mail: peter.malik@geology.sk
[4] Climate, Atmosphere and Water Research Institute at Bulgarian Academy of Sciences, Sofia, Bulgaria, e-mail: tvorehova@gmail.com
[5] Faculty of Natural Sciences, Institute of Earth Sciences, University of Silesia in Katowice, Będzińska 60, 41-200 Sosnowiec, Poland, e-mail: malgorzata.nita@us.edu.pl
[6] Geographical Research Unit, Academy of Sciences of Albania, e-mail: perikli.qirjazi@gmail.com

Received/Prejeto: 15. 3. 2025

carbonate karst regions in Albania. A final important objective of this article is to raise public awareness about the vulnerability of karst waters and the need to protect the associated ecosystem, especially now that the MMG karst massif is in the spotlight for tourism development.
Keywords: MMG karst massif, spring's regime, effective precipitation, water resources, Albania.

je ozaveščanje javnosti o ranljivosti kraških voda in nujnosti zaščite povezanega ekosistema, zlasti zdaj, ko je kraški masiv Mali me Gropa v središču pozornosti zaradi razvoja turizma.
Ključne besede: kraški masiv Mali me Gropa, režim izvirske vode, efektivne padavine, vodni viri, Albanija.

1. INTRODUCTION

Karst aquifers provide drinking water to almost a quarter of the world population (Hartmann et al., 2014; Bakalowicz, 2005; Chen et al., 2017; Stevanović, 2015, 2019). They are used even more extensively in the Mediterranean area (Margat, 1998; Bakalowicz, 2015; Günay & Ekmekci, 2015; Stevanović, 2019; Liso & Parise, 2020). Southeastern Europe is one of the most water-rich regions of the world and some large cities like Rome, Vienna, Rijeka, Dubrovnik, Sarajevo, Skopje and Tirana are supplied with water from karst sources (Stevanović & Eftimi, 2010).

Albania is characterised by a wide presence of karst aquifers. The karst rocks in Albania cover about 6750 km^2, which is about a quarter of Albania's territory. They form 23 carbonate karst regions and two evaporitic regions (Eftimi, 2020). The estimated natural karst groundwater resources of Albania consist of 227 m^3/s, while the exploitable groundwater resources are about 90 m^3/s (Eftimi, 2010). The Mali me Gropa Mountain (in Albanian, "The Mountain with Holes"), further referred to as MMG, is of extraordinary practical and scientific importance. The practical importance of this massif is related to the large and very good quality of groundwater resources, which mostly discharge as large springs. The scientific value of the study of MMG massif is related to the exceptional karstification of this massif and the relation of this to the quantitative and qualitative characteristics of the groundwater.

Location of the springs in relation to tectonics and karst morphology, as well as the use of karst water quality and of the regional flow type and groundwater sensitivity to pollution of the karst massif, are particularly discussed in this paper.

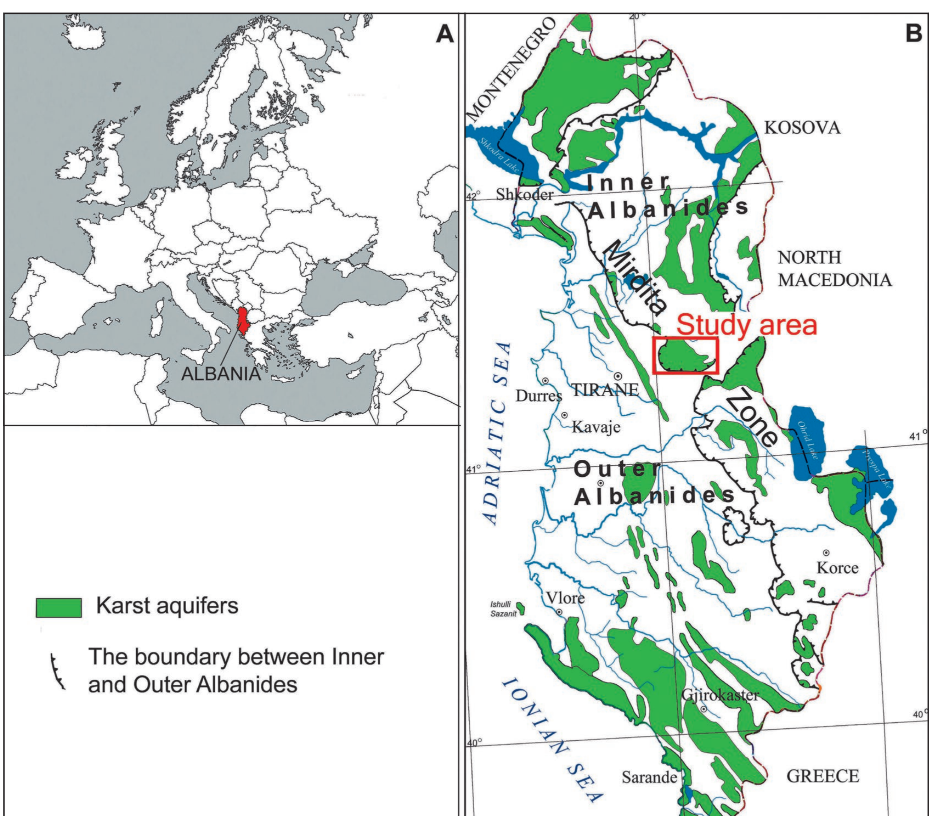

Figure 1: Location map. A Europe; B Karst aquifers of Albania (after Eftimi at al., 1985) and location of study area.

2. STUDY AREA

The karst massif of MMG is located in Central Albania, about 20 km north-east of Tirana (Figure 1). Against the backdrop of its surroundings, this massif creates quite a compact area in which the elevation varies about 1500-1800 m above sea level (a.s.l.) and dominates 400 to 1000 m a.s.l. above the surrounding valleys. It is built mostly of Mesozoic limestone overthrown on a Paleogene flysch formation. The massif extends for 15-18 km from west to east, and 5-11 km from south to north, while its area is ~157 km^2 large. Linos's valley, dipping gently from south to north, geographically separates the MMG into western and eastern blocks (Figure 2).

2.1 CLIMATE AND HYDROLOGY

According to the classification of the Institute of Hydrometeorology of Tirana (Jaho et al. 1975), the climate of the study area is mountainous Mediterranean. To characterize the precipitation and air temperature regime, data from the meteorological stations of Selita Malit (810 m a.s.l.) on the Western Plateau and Lena Martanesh (1000 m a.s.l.) on the periphery of the Eastern Plateaus were used (Figure 2). The average precipitation and air temperature values for the Western Karst Plateau are 2100 mm and 6.5° C, respectively, as interpolated from values measured at Selita meteorological station. For Lena station with consideration of its altitude the corresponding values are 1600 mm and 10 °C.

According to the data for the observation period 1961-1985, for the 6-month period (from October to March) in Selita station, the average amount of precipitation is 1470 mm, or 67% of the annual amount; and for the period April-September, it is 680 mm, or 33% of the annual amount. During a period of about 50-60 days per year, the air temperatures fall below zero and the plateaus are snow-covered. The maximal thickness of the snow cover is about 50-70 mm (Jaho et al., 1975).

As often in karst areas (Ford & Williams, 2007; Bakalowicz, 2005; Eftimi, 2010), the surface hydrographic network of the Mali me Gropa is not well developed and in contrary the subsurface hydrographic network is intensively developed. The only permanent river of the massif is the Mat River, which flows along a deep canyon in the eastern periphery of the MMG massif, in contact with the intrusive rocks (Figure 3). The karst groundwater of the entire eastern part of the massif consisting of the Central and Eastern Plateaus practically drains into the canyon (Figure 3). Based on runoff measurements at the beginning and end of the canyon consisting of carbonate rocks, it is estimated that a groundwater quantity of about 4.6 m^3/s drains into the canyon of the Mat River. Another permanent river, the Biza River, whose watershed is about 25 km^2, is located in the southernmost part of the Vali valley. After flowing only about 300 m in this valley, the river disappears into the Vali Cave (Figures 2 and 3). The discharge of the Biza River, before disappearing in the cave, varies from zero to about 5-6 m^3/s during very heavy rains, but the mean discharge is estimated at about 330 l/s (Figure 3).

2.2 GEOLOGICAL STRUCTURE

Albania is part of the Mediterranean Alpine Folded Belt and the Dinaric-Hellenic range (Aliaj 2012; Meco & Aliaj, 2000; Xhomo at al., 2002). The MMG massif belongs to the Mirdita Zone, which is known also as the zone of magmatic rocks (Figure 1) and is equivalent of the Serbian Zone in the Dinarides and the Subpelagonian Zone

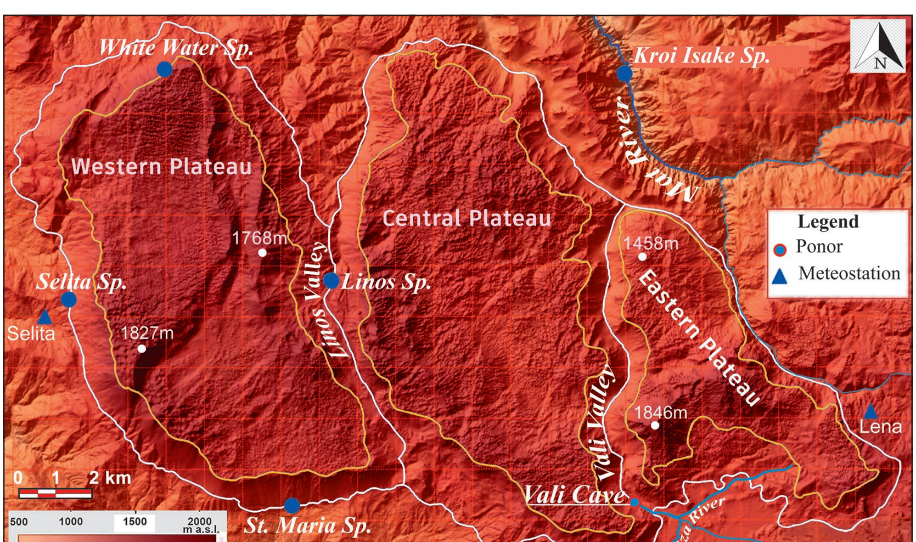

Figure 2: Relief shadow model of the MMG karst massif, karst plateaus and main karst springs, using shading and colour model as visualization tools to show the terrain relief. A thin yellow line inside each plateau marks the boundary between its levelled plateau-like part and its steep slopes (after Andreychouk et al., 2022).

in the Helenides. The magmatic rocks, mostly of Jurassic age and the Triassic-Jurassic volcano-sedimentary and the sedimentary formations are quite widespread. Among the sedimentary formations there are several large carbonate structures, the MMG being one of the largest.

This structure, which has an allochthonous character (Aliaj & Bushati, 2019; Gjata & Kodra, 1999) and consists of Mesozoic Triassic-Jurassic and Cretaceous (T_3-J_1 and J_3-Cr_1) carbonate formations overthrusted over younger Paleogene flysch formations (Pg_{1-2}) of the Krasta geological zone (Liko, 1962; Gjata & Kodra, 1999). The carbonate rocks consist of massive limestones of high chemical purity with a total thickness of 700 to 800 m, which lie on Lower Triassic radiolarites and Jurassic effusive sedimentary of the basement of the massif (Figure 3). The Linos valley, located in the central part of the MMG study area, is tectonically predisposed and consists of Upper Jurassic – Lower Cretaceous series of a mélange of effusive-sedimentary rocks. The higher susceptibility of these sediments to erosion compared to the Upper Triassic limestones was of significant importance in the formation of the described valley, which in tectonic and geological terms divides the MMG massif into two well defined separate massifs: the western massif (Western Plateau) and the eastern massif consisting of Central and Eastern Plateaus (Andreychouk et al., 2022; Figures 2 and 3).

The limestone rocks lay horizontally or sub-horizontally. A detailed cartography shows that the contact elevation between massive limestone and the basement rocks of the western platform (Figure 2) is an undulating surface consisting three "synclines" separated by two "anticlines". This is probably the result of non-uniform overthrusting energy of the massif, or of the different strength of the basement rocks. It seems that in the "syncline" axes the over-thrusting rocks energy has been high, or the strength of basement rocks has been low, or both assumptions were at work simultaneously. Concerning the eastern part of the massif the basement of the karst massif deeps normally in one direction, south-north, to the Mat River. The contact between limestone and the basement rocks in the southern periphery of the eastern massif is at the elevation about 1300-1400 m a.s.l.; and in the deeply incised Mat River Valley the carbonate rocks outcrop at elevations of about 400-500 m a.s.l. (cross-section B-B, Figure 3).

2.3 GEOMORPHOLOGY

The MMG massif is very famous for its outstanding karstification. Favourable hypsometric and geomorphological character, structural (high fissure permeability of limestones), lithological (chemical purity of carbonate rocks) and climatic conditions (high annual precipitation) favour the active development of karst throughout the MMG karst massif (Andreychouk et al., 2022; Kalinina, 1951; Kessler, 1958; Parise et al., 2004; Qiriazi, 2019; Doka and Qiriazi, P. 2022).

In terms of geomorphology, in contrast to its geological and geographical characteristics, three large units can be distinguished within it: a) the Western Plateau is developed at an elevation of about 1500-1600 m a.s.l, with its highest peak being Miceku Shenmerise reaching 1827 m a.s.l.; b) the Central Plateau is developed at elevations of about 1300-1450 m a.s.l. with some peaks reaching elevations of about 1600 m a.s.l.; and c) the Eastern Plateau is developed at an elevation of about 1300-1600 m a.s.l with its highest peak, Shen-Noi Math, reaching 1846 m a.s.l. These units are separated by deeply incised valleys, the Linos valley separates the Western and Central Plateaus, and the Vali valley separates the Central Plateau from the Eastern one (Figure 3 and 4). At each plateau, two basic geomorphological environments can be distinguished: high elevation peaks and the plateau itself, and steep peripherical slopes related to the valleys (Figure 2).

The study area is characterized by high frequency and morphogenetic diversity of surface karst features both in terms of karst forms and karst terrains (Figure 4a, 4b). According to their size, they can be divided into small (microforms like karren, karren fields), medium (mesoforms like swallow holes and vertical shafts) and large (macroforms like uvalas, caves and dry valleys). The density of dolines within the MMG karst plateaus varies from 96 to about 328 per km^2, being in average about 200 per km^2 (Andreychouk et al., 2022). Most of the dolines have circular morphology with diameters of about 15-40 m, maximum depth about 10 to more than 30 m with flattened bottom filled with residual and soil material (Figure 4b). Sometimes, from the confluence of several dolines, uvalas are formed that reach more than 300 m in width and more than 80 m in depth (Figure 4c).

The closed depressions, mostly of solutional origin (Guitierrez et al., 2014) are located adjacent to each other and are separated by narrow ridges or bare rocks, forming a typical polygonal karst. Locally, at the bottoms of larger dolines, artificially created ponds occur, which collect rain and serve for watering sheep grazing on the plateau. One of the most important landforms of the studied karst massif is the Vali dry valley about 12 km long (Figure 5a). It is formed by the Biza River, which at early Pleistocene flowed to the Mat River. As the result of the intensive lowering of the Mat River valley after Middle Pleistocene (Aliaj et al., 2018), the karst corrosion was more active than the surface erosion of the Vali River. This resulted in the formation of the deep Mat River canyon and Biza River valley becoming a blind one; its flow disappeared underground in the Vali cave (Figure 5b), length 330 m (Denneborg, 1993).

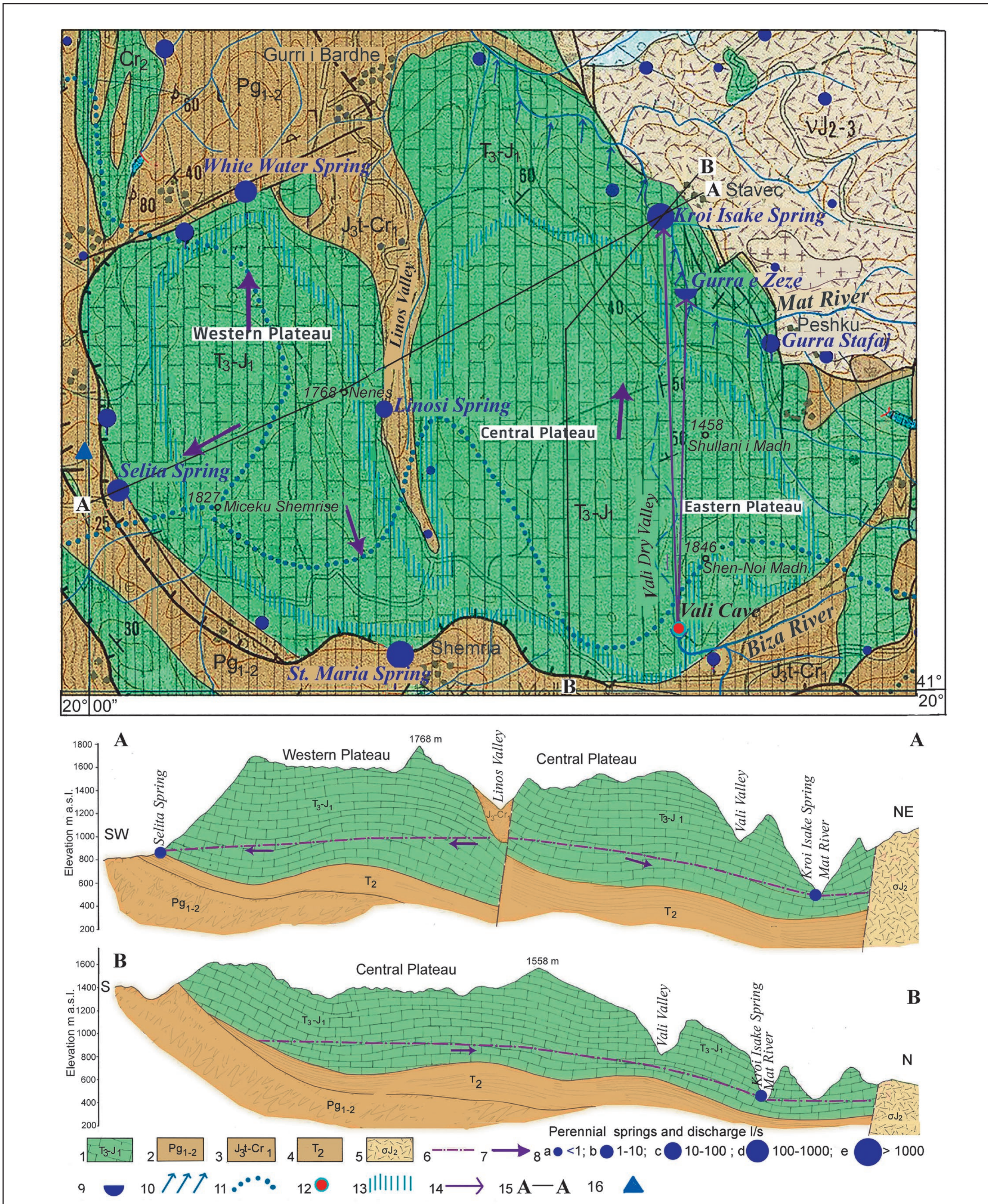

Figure 3: Hydrogeological map of the MMG karst massif and cross-sections A-A and B-B: 1 - High permeable karst aquifer, massive limestone; Low permeable rocks: 2 – Siltstone, shale (Krasta flysch); 3 - Ophiolitic conglomerate-breccias; 4 - Effusive-sedimentary rocks; 5 - Intrusive ultrabasic rocks; 6 – Groundwater level (supposed); 7 – Direction of groundwater flow; 8 – Springs and discharge in l/s; 9 – Temporary karst spring; 10 Karst groundwater drains in the river; 11 – Surface water divide; 12 – Artificial trace injection point; 13 - Limit of highly karstified area; 14 – Proved underground connection; 15 – Hydrogeological cross-section; 16 – Meteostation Selita (modified from Eftimi et al., 1985).

Figure 4: Some karst phenomena of the MMG karst massif: A Southern part of Western plateau. B Cultivated doline in Central Plateau; C Uvala, length about 300 m, in Central plateau (photos R. Eftimi and V. Andreychouk).

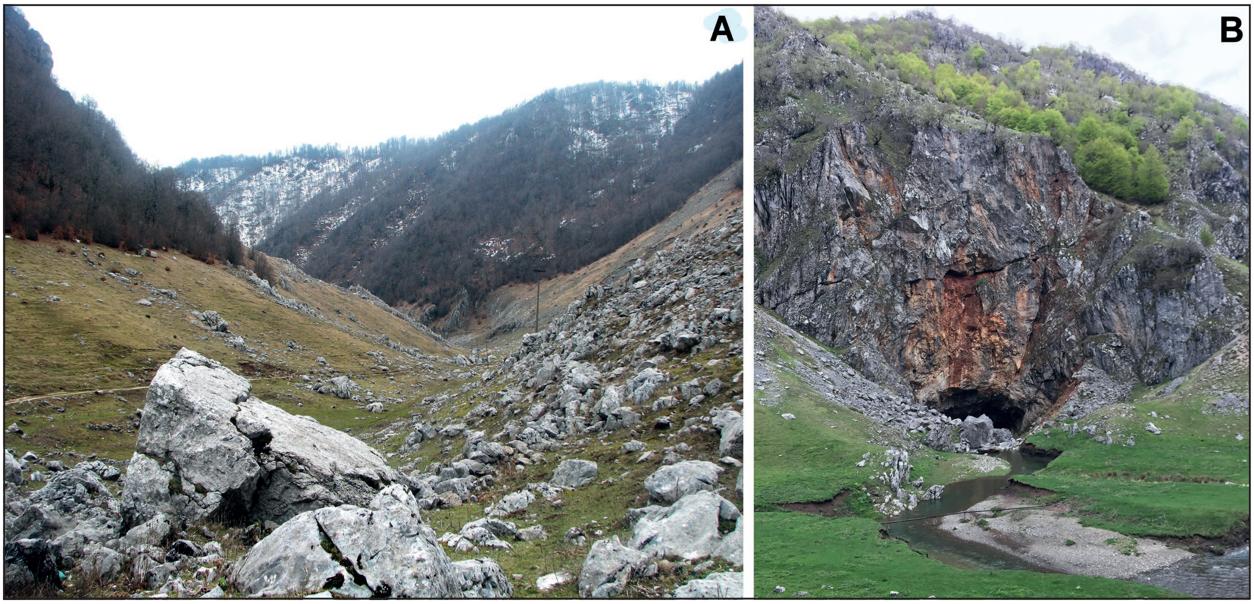

Figure 5: Karst phenomenon in the border area between Central and Eastern Plateau of the MMG karst massif: A Vali dry (blind) valley: B Vali cave serves as swallow hole for small Biza River (Photo R. Eftimi).

3. MATERIAL AND METHODS

Due to its special natural features, the MMG karst massif has attracted the attention of specialists in various fields, like geologists, geomorphologists, environmentalists, hydrogeologists, etc. However, a complex multidisciplinary study of this area has never been performed until now. Desio (1960) was first to describe the karst of the MMG in the well-known book "Manual di Geologia Applicata". The geology of this massif is described in detail as part of the geological map of the area on a scale 1:50,000 (Liko, 1962) and its tectonic character is treated also by some regional geological studies (Xhomo et al., 2002; Aliaj at al., 2018; Liko, 1962). Karst of Albania is mainly described by geographers (Kristo 1973; Kristo et al., 1987; Qiriazi ,2019; Parise at al., 2004), who generally characterise it as a typical Mediterranean karst (Bakalowicz, 2015). The geomorphological Map of Albania on a scale 1:500,000 (Anonymous, 1992) characterises the MMG as a very intensively karstified area with innumerable sinkholes at the surface.

The first important hydrogeological survey of the MMG was performed in 1950-1951 at the Selita karst spring (Figure 3) as a water supply source for the city of Tirana (Kalinina, 1951). In this study, the intake structure of this spring was proposed as a long drainage gallery receiving groundwater flowing from the karstified limestone. During the investigation of the Selita Spring, Kalinina described also the karst of the Western plateau. She observed that the basement of the western karst platform of the MMG was an undulating surface, which was confirmed later also by the other specialists (Liko 1962; Pali, 1973). Another hydrogeological investigation is performed also at the St Maria karst spring, which in 1964 was diverted for the water supply of Tirana, also. Total supplied population by the springs Selita and St Maria is about 500,000 inhabitants.

The hydrogeological map of Albania, scale 1:200,000 (Eftimi et al., 1985), was the first starting point for understanding the hydrogeology of the MMG as a whole. To realize the map, all springs of the area have been identified, measured and analysed at the Laboratory of Albanian Hydrogeological Service (AHS). The major ion composition was determined by ion chromatography, colorimetry, and end-point titration. The water supply board of Tirana along a period of some tens of years has systematically measured the discharge of the Selita and St Maria springs, as well as has performed water chemical analyses. Beside this for characterising the hydrogeology of the MMG, different investigation methods were applied such as detailed geomorphological investigations (Andreychouk et al., 2022), and an experiment with artificial tracer with injection in Vali Cave swallow hole (Amataj, 2002). For determining the water balance of the MMG, beside the Turc (1954) empirical method, the recently developed software WaterbalANce (Mammoliti et al., 2021) was used. An important investigation is also performed for the assessment of the regional flow type and groundwater sensitivity to pollution of the MMG karst massif using the hydrograph analyses and hydrochemical data of the Selita Spring (Eftimi & Malík, 2019).

4. HYDROGEOLOGY

The most important hydrogeological features of MMG are shown on the 1:200,000 scale Hydrogeological Map (Figure 3). This massif consists of a karst aquifer lying mainly on impermeable effusive-sedimentary rocks with siliceous rocks. Generally, the recharge area of the karst aquifer overlaps with wide karst plateaus, while the discharge extends along the lower elevation outcrops of karst rocks and at deep Mati River canyon. The elevation difference between the recharge and discharge areas of the springs varies about 450 m to 600-700 m. The most common recharge process of the MMG is the areal infiltration of precipitation directly to the carbonate rocks (autogenic, or diffuse recharge), but the allogenic recharge is also present in one case. It happens in the Vali Cave where the small Biza River disappears (Figure 3) and flows to Mat River canyon (Eftimi, 2020; Eftimi et al., 1985).

From the hydrogeological point of view, the MMG karst massif consists of two water bodies; the western one overlaps with the Western Plateau and the eastern one which comprises the Central and the Eastern Plateaus. Probably both water bodies are connected in the highest, southernmost part of Linos Valley, but it is not known how intensive this connection is in terms of groundwater flow and water mass exchange. The discharge of karst water resources occurs along the periphery of the aquifer. Each of the large springs of the Western karst plateau, namely White Water, Selita and St Maria, emerges at the lowest points of three respective syncline undulations of the impermeable basement rocks. The Eastern water body overlapping with the Central and Eastern plateaus drains in the deep Mat River canyon. The most important springs here are the Kroi Isake, Gurra Zeze and Gurra Stafaj Spring (Figure 3).

4.1 REGIME OF THE SPRINGS

Table 1 summarizes the water flow data of all large springs of the MMG karst massif. For the springs of the MMG, Selita and St Maria, daily long-term discharge measurements are available for the first spring since 1953 and for the second spring since 1961. For the White-Water Spring exist only long-term, but non-systematic measurements. For the springs of the eastern water body the discharge measurements are missing. For analysing the discharge data of Selita Spring and their relation to the precipitation, the data for the period 1981-1996, which are more reliable, were used. Figure 6 shows some hydrographs of Selita Spring.

The discharge regime of Selita Spring has two well defined periods (Figure 6A), one high flow period during October or November to the beginning of May, and one recession period usually lasting from May to the end of October or November with significant decrease of the spring discharge. Both discharge regimes are very different depending on the precipitation regime. The absolute minimum daily discharge is 215 l/s while the absolute maximum is 1200 l/s and the mean annual discharge is of 515 l/s.

In Figure 6B, the mean monthly yields of Selita Spring and precipitation rates are plotted. The minimum monthly discharge of 320 l/s is measured during September, and the maximum one of 731 l/s is measured during May. The graph in Figure 6C shows that the correlation between mean monthly yields of this spring and the respective values of precipitation is very weak. The regime of the mean annual discharge and the corresponding amount of precipitation is shown in Figure 6D. The minimum annual yield of Selita Spring of 409 l/s is registered during 1975 and largest one of 600 l/s is registered during 1970. Between the mean annual discharge and mean annual precipitation values there is a relatively good correlation, $R^2 = 0.70$ (Figure 6E). It has been established that the yearly recharge of the karst springs does not depend mainly on the annual precipitation but also on the annual distribution of precipitation (Kessler 1958, 1967).

As established by detailed observation of the karst waters (Kessler, 1958), rainfall in autumn and partially of winter remain mainly at the channel-ways and narrow capillaries of the aeration zone, thus, in a certain way preparing the conditions for the development of infiltration in the first part of the next year. The amount of precipitation falling in the first four months of the year, preceding the development of the vegetation, and prior to the large losses due to evapotranspiration, is determinative for the karst water recharge (Kessler, 1967).

The discharge of St Maria Spring is the sum of the discharge values of six intake structures, whose water is used for Tirana water supply (Table 1). It is also established that in addition to the used amount of water, about 200-300 l/s is the ungauged flow of St Maria Spring. As described above the groundwater of the Eastern waterbody (central and eastern plateaus) totally drains into the Mat Canyon where recharges the springs Kroi Isake, Gurra Zeze and Gurra Stafaj (Figure 3, Table 1). Measuring the Mat River flow in the beginning and in the end of limestone part of the canyon, is established that the total discharge of the Eastern waterbody in summer time varies about 5 to 6 m³/s. The most important springs of the canyon are the perennial spring Kroi Isake and temporary spring Gurra Zeze (Figure 7). Beside this the contribution of the Biza River disappearing in Vali Cave (Figure 3), to the karst water of the eastern karst-waterbody, according to some non-systematic measurements, varies about 100 to 1500 l/s, with a mean of about 300 l/s.

Table 1: Some hydrogeological data of the springs of MMG karst massif.

Karst massif	Springs	Elevation m a.s.l.	Water Temp. °C	Q_{mean} l/s	Q_{min} l/s	Q_{max} l/s	Investigation period	Use
Western	White Water	1050	6.0-7.0	523	160	>2000	1966-1981	No use
	Selita	881	6.0-6.5	515	215	1200	1966-1981	Tirana water supply
	St. Maria	830	6.9-7.2	894	380	2700	1966-1981	Tirana water supply
	St Maria	830	6.9-7.2	≈300	-	-	-	Unused part of the spring
	Linos	1010	6.0-6.5	150	20	600	-	No use
Eastern	Kroi Isake	≈650	7.8-8.1	≈3.0	≈1.5	≈6.0	-	No use
	Gurra Zezë	≈680	-	-	0	some m³/s	-	No use
	Gurra Stafaj	≈720	8.3	≈50	-	-	-	No use
	Vali Cave	1300	-	≈300	100	≈100-1500	1976-2008	Allogenic recharge

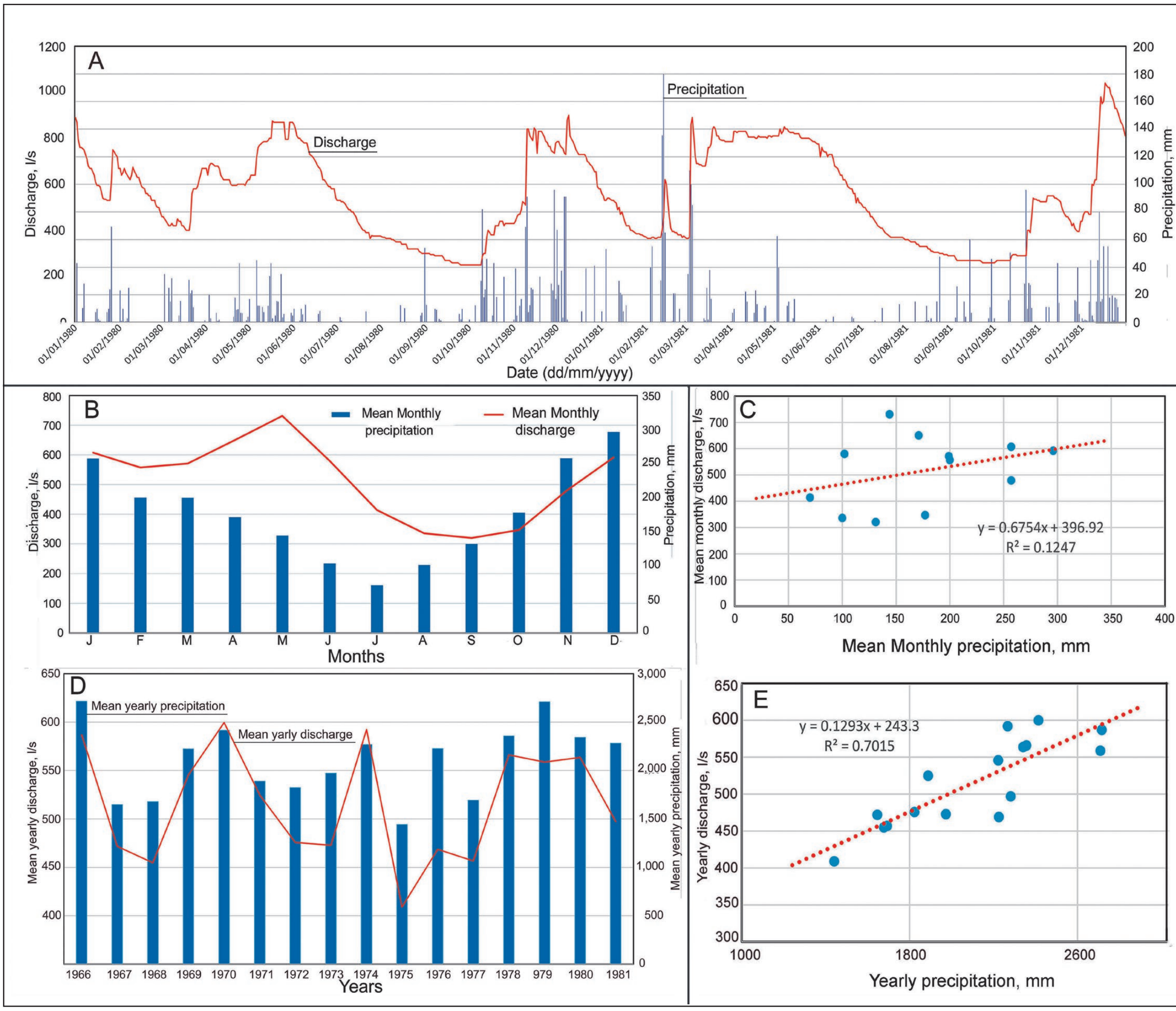

Figure 6: Selita Spring discharge characteristics. A Daily discharges and precipitations 1980-1981; B Mean monthly discharges vs monthly precipitations; C Correlation between mean monthly discharges and precipitations; D Mean yearly discharges vs yearly precipitations; E Correlation between yearly discharges and precipitations, 1966-1981.

Figure 7: Kroi Isake Spring issues in Mat River canyon (Photo: R. Eftimi).

Table 2: The calculated groundwater flow velocity using the artificial tracer introduced in Vali Cave.

Sampling spring	Elevation m a.s.l.	Air distance m	Mean hydraulic gradient I	Trace travel time of first appearance hours	Maximum velocity m/h	Trace travel time of max. concentration hours	Mean groundwater flow velocity m/h
Kroi Isake	680	10,000	0.062	192	52.0	288	34.7
Gurra Zeze	720	8,800	0.066	216	40.7	264	33.3

The Institute of Nuclear Physics of Tirana and Hydrogeological Service of Albanian in cooperation with Johanneum Research Institute of Graz, organised on the 15th and 16th of May 2002 a tracer experiment (Amataj, 2002, pers. comm.) with the injection of 4 tracers. As an example, we report on the main results for the tracer Rhodamine WT, which was injected into the swallow hole of Vali Cave at elevation 1300 m a.s.l. (Figure 3). Water samples taken in the Kroi Isake Spring and Gurra Zeza Spring located respectively at distances 10 km and 8.8 km respective resulted in the data given in Table 2.

The maximal groundwater flow, which is related to the first tracer appearance results 40.7-52.0 m/h and the average velocity, which is related to the time arrival of maximal tracer concentration, results about 33.3-34.7 m/h. The values of the karst water flow velocity in MMG are comparable with the velocities measured in other karst massifs, for example, in some experiments realised in Slovenia where the results were from 25 to 165.6 m/h (Kogovšek & Petrič, 2003).

4.2 WATER BALANCE OF MMG KARST MASSIF

The most reliable method to determine the water balance of a karst aquifer is based on discharge measurements of all springs as well as in water balance calculations (Kresić & Stevanović, 2010). As for the case of the MMG massif there are relatively good data about the discharge of the springs of the Western Plateau, but for the springs of the Central and Eastern Plateaus the data are very scarce. For the estimation of the water balance of both areas are used two methods: (a) Turc method, and (b) WaterbalANce software (Mammoliti et al., 2021).

Turc (1954) method

The most important parameter for the estimation of the karst water resources is the rate of infiltration of the precipitation in the karst aquifers. Usually in the hydrogeological practice is used the concept of *effective infiltration* which represents that portion of precipitation, which reaches the aquifer and recharges the groundwater resources.

The mean annual water balance of a karst massif is expressed by the following formula:

$$P = Ie + E + F \quad (1)$$

Where: P – precipitation, mm;
Ie – effective infiltration, mm;
E – evapotranspiration, mm.

If the surface flow is missing (F = 0), formula (1) is simplified to:

$$P = Ie + E \quad (2)$$

$$\text{Coefficient of infiltration} = \text{Infiltration} / P \quad (3)$$

So, the estimation of the water balance of a karst aquifer often consists in the estimation of the effective infiltration, or of the evapotranspiration. The direct determination of this parameter through the discharge of the springs is more real, but often it is very difficult or expensive to organize.

According to the Turc empirical method of the mean yearly precipitations and the mean air temperature of the recharge area of the karst massif are taken into consideration. The empiric methods are quite applicable in engineering practice (Boni et al., 1982; Bonacci & Ljubenkov, 2005). In Table 3, the results of the calculation for the Western block and for the Eastern block are shown separately.

WaterbalANce software method

The recently developed software WaterbalANce (Mammoliti et al., 2021) is an attractive, easy-to-use research tool for calculating monthly water balance, as demonstrated by its developers based on two case studies from Italy and Slovenia. Later, the software was successfully applied for hydrogeological studies in several regions of

Table 3: The results of the water balance calculation of MMG karst massif applying the Turc method.

Block	Surface km^2	Mean elevation m a.s.l.	Mean air temperature °C	Mean yearly precipitation mm/year	Infiltration mm/year	Coefficient of infiltration %	Renewable resources m^3/s	Module of underground flow $l/s/km^2$
Western	55	1500	6.5	2100	1630	78	2.86	52
Eastern	102	1350	8.0	1900	1230	65	4.59	45

Bulgaria (Orehova et al., 2021a; 2021b; 2024). This method is used for calculations of water balance of the Western Plateau only. For this purpose, WaterbalANce software is used, which is based on the Thornthwaite & Mather (1957) method. This software provides monthly time series (in mm) for potential and actual evapotranspiration (PET, AET), soil moisture content (ST), and total monthly runoff (TOT RO), including monthly snowmelt runoff (SMRO).

The meteorological data used for the calculations for the western waterbody (block), refer to the closest station Selita (Lat = 42° N). The study period covers several decades: 1966–1981. Monthly precipitation sums for the station Selita are available for the whole study period. As for the air temperature, only mean values averaged for each month are available, valid for the entire study period. In the calculations, the average monthly air temperature for the Western Plateau with mean elevation of 1500 m a.s.l. is extrapolated by the data of Selita and Lena meteostations located accordingly at elevation 810 m a.s.l. and 1600 m a.s.l. This is based on the recommendation that air temperature in the mountainous areas of Albania decreases 0.7 °C for 100 m of elevation (Jaho et al., 1984, Kolaneci 2021). WaterbalANce software with monthly meteorological data from the Selita meteorological station is used to identify the elements of the water balance. The input data are presented in Table 4.

Table 4: Input data for WaterbalANce software for Selita meteorological station, period 1966–1981.

Parameter	Value
Latitude (Lat, ºN)	42
Soil moisture storage capacity (SM, mm)	50
Runoff coefficient (beta, %)	30
Snowfall-rainfall temperature threshold (SRT, ºC)	−3
Average precipitation 1966–1981 (P_{av}, mm/year)	2106.2
[1)]Average air temperature 1966–1981 (Tm_{av}, ºC)	6.5

Considering the typical shallow soils on the karst terrain, a low value of soil moisture storage capacity (SM = 50 mm) was set. In order to eliminate the accumulation and melting processes of the snow cover, the value of SRT is set to −3 °C, which is lower than the lower average monthly temperature for each winter month. The outputs of the software are presented in Table 5. The coefficient of correlation between the simulated monthly time series of total runoff and the Selita Spring runoff is R^2 = 0.74. The results of the software application for the period 1978–1981 are presented in Figure 8, which shows the nearly synchronous behaviour of the simulated runoff and spring discharge.

Table 5: Summarized output data for the period 1966–1981 for Selita meteorological station.

Parameter	Value
Potential evapotranspiration (PET, mm/year)	533.7
Actual evapotranspiration (AET, mm/year)	473.9
Total runoff (TOT_RO, mm/year)	1600.8
Runoff modulus (M, l/s/km^2)	50.8
Mean soil moisture content (ST, mm)	43.0

Effective infiltration, defined as the difference (P – AET) for the annual averages, is 1632.3 mm/year and the coefficient of infiltration = 77.5% in the western plateau. The average annual discharge of the spring for the period 1966–1981 is Q = 515.3 l/s. With a runoff modulus value of M = 50.8 l/s/km^2, the resulting spring-shed area is 10.1 km^2. The values of the calculated parameters are practically similar with that benefited from Turc method (compare the values of Table 3 and 5).

The calculated values of the coefficient of infiltration and of the underground runoff modules seems to be very high, but they are comparable with the results for some karst massifs of the Mediterranean area. For the southern edge of the Skadar Lake in Montenegro, the average effective infiltration varies from 60 to 80 % (Radulovic et al., 2012). For the Camposecco

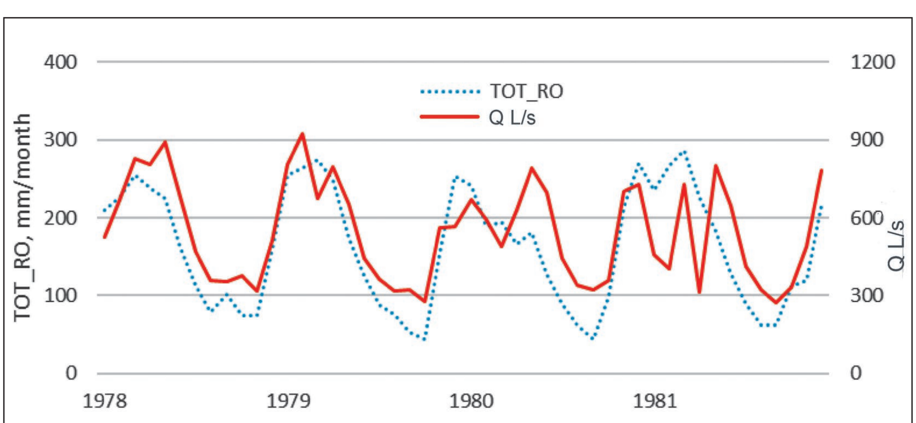

Figure 8: Comparison of mean monthly modelled runoff and measured discharge of spring Selita.

Basin in Central Italia the effective infiltration is calculated at 68 % (Boni et al. 1982), for two karst massifs in Picentini mountains this coefficient is calculated as 66 % and 67 % (Fiorillo 2014; Fiorillo et al. 2012), and for the karst region of Gradole ranges about 35.6 % to 76.3 % (Bonacci 2001). According to Bayari et al. 2011 in southwestern coast of Turkey the effective infiltration is estimated at about 80-75 %.

5 DETERMINATION OF PHYSICAL ASPECTS OF MMG KARST AQUIFER

5.1 EVALUATION OF THE FLOW WATER SYSTEM OF SELITA SPRINGS

Karst aquifers are characterized by their high heterogeneity, created and organized by groundwater flow (Ford & Williams, 2007; Bakalowicz, 2005; Worthington & Ford, 2009; Stevanović ed., 2015). There are at least two end-member types of groundwater flow in karst aquifers: conduit flow related to integrated systems of solutionally enlarged openings or conduits, and diffuse flow related to flow through primary pore spaces or small-scale secondary pore spaces (White, 1969). To identify the flow system, chemical and isotopic monitoring of springs is used (Krothe & Libra, 1983; Lakey & Krothe, 1996; Perrin et al., 2007). In general, greater hydrochemical variability of a spring during the hydrological year is indicative of a higher development of karstification.

Spring water chemistry is not only a function of conduit size but also a reflection of recharge type and particularly of the volume of allogenic recharge (Newson, 1971); however, a spring can be fed by a common diffuse type system although it shows a rather high coefficient of variation. This is the case of studied springs Selita which have only autogenic recharge; the allogenic recharge is totally missing in the western karst plateau recharging this spring.

Based on variation in water hardness, the springs are classified into diffuse flow and conduit flow (Shuster & White, 1971). Some more chemical parameters are used also to classify flow water systems of karst springs (Jacobson & Langmuir, 1974). In this study, as they are more trustful, the parameters used are water temperature, hardness, electrical conductivity, concentrations of SO_4^{2-} and Cl^-, as well as rMg/rCa and rSO_4/rCl ratios. Indexes of saturation with calcite (Sic) and dolomite (Sid) are used to find a correlation between chemical and physical attributes of karst systems (Eftimi & Malík, 2019).

The coefficient of variation, CV [%], which is 100 times the standard deviation divided by the mean, is used to describe changes in water chemistry. This coefficient shows higher values for the conduit flow springs than these for diffuse flow springs. The values of coefficient of variation of selected physical and chemical parameters of the Selita Spring are presented in Table 6. Simple comparison of data presented here with the data of already studied springs suggests that Selita Spring should be a conduit flow spring. The same conclusion can be reached when comparing the values of saturation indexes of calcite (Sic) and dolomite (Sid). Less saturation of the karst groundwater with respect to calcite and dolomite is typical for springs with prevailing conduit flow; the opposite is evident with the increased participation of diffuse flow (Jacobson & Langmuir, 1974). The values of saturated indexes of calcite and dolomite for Selita Spring are -2.9 and -0.9, which are smaller than those of Blue Eye Spring, respectively +2.28 and +0.11, which is determined as a diffuse flow spring (Eftimi, 2005; Eftimi & Malík, 2019).

5.2 SENSITIVITY OF THE KARST GROUNDWATER OF MMG TO POLLUTION

The classification of karst aquifer systems with a diffuse recharge, based on the variation of hydrochemical com-

Table 6: Coefficient of variation (CV%) of water physico-chemical parameters of Selita Spring in comparison with Blue Eye springs (Eftimi & Malík, 2019), Rock Spring (Shuster & White, 1971), Thomson Spring (Jacobson & Longmuir, 1974), Iskrets Spring (Eftimi & Benderev, 2007) and Al-Dhaher Spring (Abboud, 2016).

Spring	Type of flow	Temperature (°C)	Hardness (mev/l)	Conductivity (µS/cm)	SO_4^{2-} (mg/l)	Cl- (mg/l)	rCa/rMg	rSO_4/rCl
Selita	Conduit	11	13	8.3	28	25	22	32
Rock	Conduit	26.9	26.0	23	12.7	17.7	-	-
Iskrets	Conduit	10.3	13.6	-	43.7	24.4	-	-
Al-Dhaher	Conduit	14.5	14.3	-	26.2	40.8	-	-
Thomson	Diffuse	1.4	4.8	6.2	17.8	29	-	-
Blue Eye	Diffuse	0.6	5.5	5.0	9.0	17.0	12	16

ponents, becomes much more realistic if the classification is validated also by the results of hydrograph analysis, as is demonstrated in the following. Springs draining integrated conduit systems have the potential for transmitting different type of pollutants including clastic particles (clays, silt) and sometimes coarser materials. The small-sized particles are easily mobilised by quick (storm) flow and are responsible for many karst springs becoming turbid after storm events (Drew & Hötzl, 1999; Goldscheider et al., 2010; White, 2010). This phenomenon occurs particularly when intensive human activities are present in the recharge area.

Discharge variability can be used to estimate regional processes and hydraulic properties of aquifers. Springs with high discharge variability can indicate a high degree of groundwater transport. Discharge recession was dealt by many authors, starting with Boussinesq (1877) who was the first to mathematically describe discharge recession, ending with later applications in karst hydrogeology (Kullman, 1990; Király, 2003; Kovács et al., 2005; Kresic & Bonacci, 2010; Fiorillo, 2014; Giacopetti et al., 2017). Hydrograph analysis of springs discharge data can be successfully used for identifying and separation of fast-flow and slow-flow regimes. Computer techniques of master curve construction (Gregor & Malík, 2012; 2014) can help a lot in discharge time-series analysis and subsequent estimation of groundwater vulnerability to potential pollution (Kullman, 1990; 2000; Malík & Vojtková, 2012; Malík, 2015). This method was successfully applied in the case of Selita and Blue Eye springs in Albania (Eftimi & Malík, 2019).

Selita spring discharge ranges from 215 to 1,200 l/s with the average of 515 l/s and median discharge of 480 l/s. The ratio of maximal and minimal discharge is 5.6 and the discharge standard deviation 191 l/s. The HydroOffice RC4 software tool (Gregor & Malík, 2014) was applied here to analyse recession curves for obtaining recession coefficients. Available discharge data were covering 21 calendar years for the period 1966 – 1986 by daily discharge averages.

Time series data record of Selita Spring enabled construction of a master recession curve based on 20 individual hydrograph recessional parts (Figure 9 and 10) using normal and logarithmical plots of discharge values. Two flow components were identified in the Selita Spring master recession curve; both of them were fast-flow components (Malík, 2015) described by linear equation (1) respectively (2):

$$Q_t = \left(\frac{1}{2} + \frac{|1-\beta_1 t|}{2(1-\beta_1 t)}\right) Q_{01}(1-\beta_1 t) + \left(\frac{1}{2} + \frac{|1-\beta_2 t|}{2(1-\beta_2 t)}\right) Q_{02}(1-\beta_2 t) \qquad (1)$$

$$Q_t = \left(\frac{1}{2} + \frac{|1-0.00330\cdot t|}{2(1-0.00330\cdot t)}\right) \cdot 485 \cdot (1-0{,}00330\cdot t) + \left(\frac{1}{2} + \frac{|1-0.0170\cdot t|}{2(1-0.0170\cdot t)}\right) \cdot 715 \cdot (1-0.0170\cdot t) \qquad (2)$$

were

Q_t – discharge at time t [l/s]
t – time elapsed from initial (maximal) discharge [day]
Q_{0x} – x-th partial initial discharge [l/s]; maximal spring discharge Q_0 is equal to the sum of all partial initial discharges
β_x – recession coefficient of the x-th linear (quick) flow component [1/d]

The total volume of water discharged in pure recession of the Selita Spring, starting from 1200 l/s and finishing in zero discharge is 3,376,078 m^3. Nearly one half of this volume (44 %) is discharged by the higher quick flow component with a relatively high recessional coefficient β_2 (0.0170 d^{-1}). The remaining discharged volume (56 %) belongs to the first quick flow component with a lower recessional coefficient β_1 (0.00330 d^{1}). If not recharged, the total spring discharge should drop down to zero in 303 days. In other words, as a result of equation (2) parameters, during this time the whole karstic aquifer should be emptied out, although being of maximal discharge at the beginning.

The very high sensitivity degree of Selita Spring's catchment area to potential groundwater contamination is caused by the many existing possible sources of contaminant entry (karst pits, sinkholes, swallow holes) into the karstic aquifer, and the high potential for quick contamination spreading within the catchment because very limited retention and dispersion capabilities can be found. Potential pollutants can be quickly transported in high concentrations from quite distant places. The role of quick flow components, favoured also by the prevailing conduit groundwater flow is usually manifested in a quick increase of high pollutant concentrations in the groundwater resource, followed by their rapid removal (short duration of contamination event). The high sensitivity to pollution of Selita Spring was demonstrated in autumn 1975 when the spring water became turbid as a result of the soil cover removal in karst poljes in the spring recharge area when an attempt of their conversion to cultivated land started (Eftimi & Zojer 2015). The high sensitivity of the karst water to pollution asks for the well-organised protection policies (Ravbar & Šebela, 2015), as well as for increase the public education and awareness regarding the karst water management.

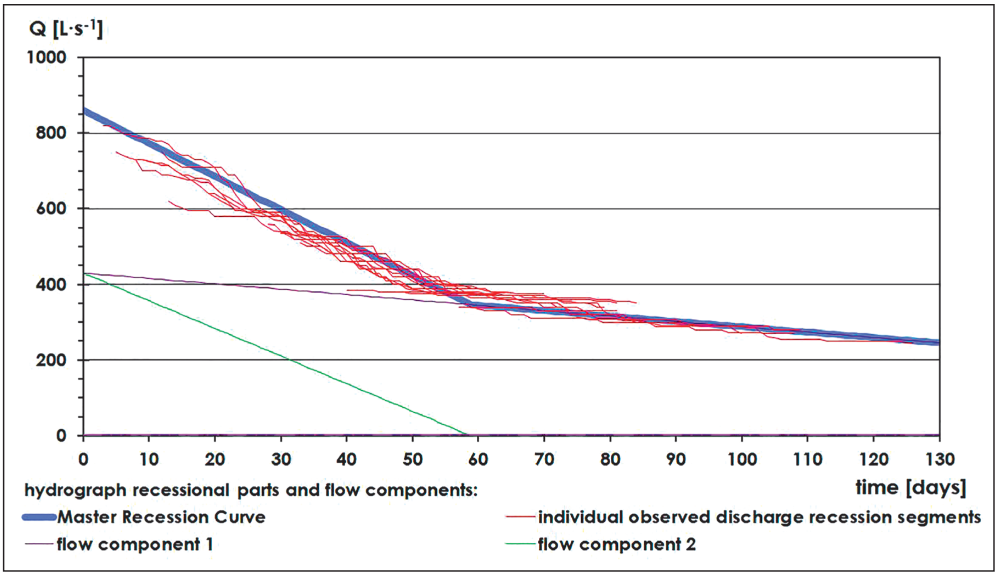

Figure 10: Master recession curve of Selita Spring, with individual recessional parts of the hydrograph used for its construction and partial flow components: logarithmical plot.

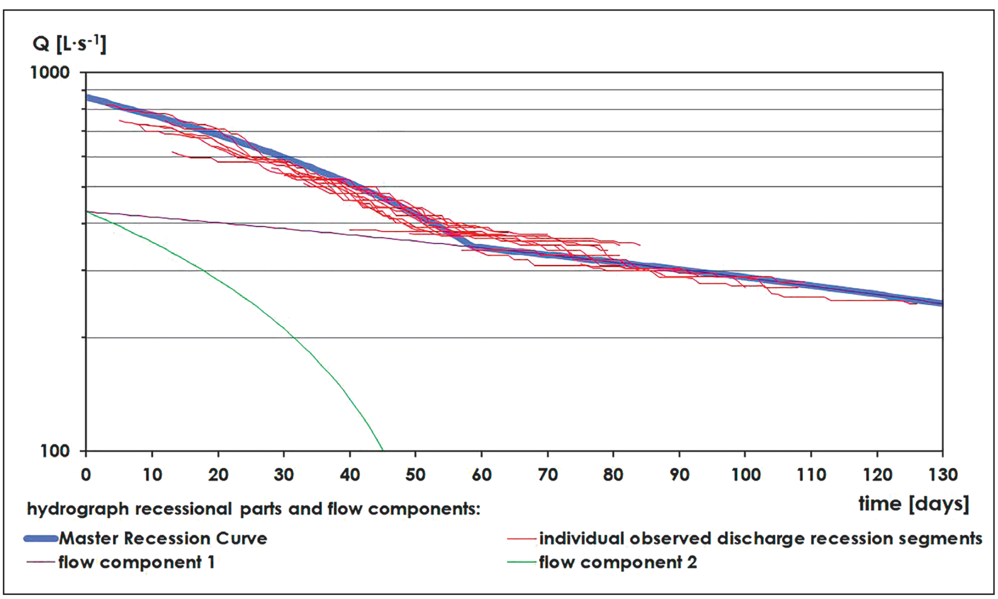

Figure 9:Master recession curve of Selita Spring, with individual recessional parts of the hydrograph used for its construction and partial flow components: normal plot.

6. CONCLUSIONS

Although the MMG karst massif it has attracted the attention of people and specialists due to the exceptional development of surface karst landforms and its large and high-quality groundwater resources, it has not been the subject of comprehensive study so far. This karst massif as a highly heterogeneous environment can only be explained by applying and combining various methods, such as geomorphological and water balance studies, analysis of the groundwater regime and its relationship with meteorological data, assessment of groundwater quality and its variability, and the use of hydrochemistry and runoff data to determine groundwater flow patterns and the sensitivity of spring waters to pollution. Furthermore, investigation becomes incomplete when individual research methods are applied in localized areas. In this paper, for the first time are summarized the results of the multi-method investigations of the MMG karst massif.

The main findings of the paper are the following: (i) the location of karst springs is mainly controlled by the structure of the impermeable basement of the carbonate aquifer; (ii) based on the long term and runoff data for the Selita Spring, their high variability is confirmed, as well as their correlation to precipitation is established; (iii) using the recently developed WaterbalANce software, a fairly high value of the mean effective infiltration (1632.3 mm/year) is obtained corresponding to an infiltration coefficient of 77.5%; (iv) when performing statistical processing of the hydrochemical data, it is found that the Selita Spring is a conduit-flow dominated karst spring; (v) the analysis of the master recession curve for the Selita Spring shows a predominance of fast-flowing components, which is a prerequisite for the rapid passage of potential pollutants through the karst system. The high sensitivity to potential groundwater contamination of Selita Spring was confirmed when high water turbidity followed the removal of soil cover from newly cultivated karst poljes in the recharge area in 1975.

Overall, there is no doubt that the hydrogeological characteristics of the MMG karst massif are in good agreement with its geomorphological features (development of karst landforms). The results of the multi-method studies conducted on the MMG karst massif should be useful for future studies of the numerous carbonate karst regions in Albania. The importance of studying the groundwater resources of the MMG massif also lies in the detailed study of two large karst springs of the massif: Selita and St Maria, used for water supply of the city of Tirana, as well as a third one, Uji Bardhe, which is also planned to be used in the near future for the same purpose.

Despite the research conducted on the MMG massif, there are many phenomena that have not been discovered or scientifically explained. This particularly concerns the circulation of water and its temporal variability, as well as its relationship to the current and changing climate. Systematic interdisciplinary and detailed studies that use modern research technologies should be applied to the poorly understood processes associated with the sustainable development of this vulnerable environment.

Author contributions RE: conceptualization, methodology, data analyses and writing-original draft. WA: conceptualization, writing the geomorphology and geology. PM: conceptualization, writing sensitivity of karst groundwater to pollution. TO: applying and writing WaterbalANce software method for calculation of the groundwater balance, corrections of Abstract and Conclusions. MN: writing the geomorphology and some statistical calculations; PQ: writing the geology and geomorphology.

Funding The authors declare that no funds, grants, or other supports were received during the preparation of this manuscript.

DECLARATIONS

Conflict of interest No conflict of interest is declared for this article.

Ethical approval All authors kept the "Ethical Responsibilities of Authors".

Consent to participate All the authors gave explicit consent to participate in this study

Consent to publish All the authors gave explicit consent to publish manuscript.

REFERENCES

Abboud, I., 2016. Describe and statistical Evaluation of Hydrochemical data of Karst phenomena in Jordan: Al-Dhaher Cave Karst. Researcher 2014, 5(3): 56-76. https://www.sciencepub.net/researcher.

Amataj, S., 2002. Tracer experiment in MMG karst massif – personal communications. Institute of Nuclear Physics of Tirana.

Anonymous, 1992. Geomorphologic map of Albania. Centre of Geographical Studies, Academy of Science of Albania. Printed in Topographic Institute, Tirana.

Aliaj, Sh., 2012. Neotectonics Map of Albania, Printing House KLEAN, Tirana. 292.

Aliaj, Sh., Bushati, S., 2019. Look for the roots of the Mirdita ophiolites (Albania). Journal of Natural & Technical Sciences 2019, 49: 3-47.

Andreychouk, V., Eftimi, R., Nita, J., Klimchouk, A., 2022. Karst relief of the Mali me Gropa Massif, Central Albania. Geological Quarterly, 2022, 66, 6. DOI: http://dx.doi.org/10.7306/gq.1638

Bayari, C.S., Ozyurt, N.N., Ozatan, M., Bastanlar, Y., Varinlioglu, G., Koyuncu, H., Ulkenli, H., Hamarat, S., 2011. Submarine and coastal karstic groundwater discharges along the southwestern Mediterranean coast of Turkey. Hydrogeology Journal (2011) 19: 399-414. DOI 10.1007/s10040-010-0677-y

Bakalowicz, M., 2005. Karst groundwater: a challenge for new resources. Hydrogeology Journal, 13: 148-160. DOI 10.1007/s10040-004-0402-9

Bakalowicz, M., 2015. Karst and karst groundwater resources in the Mediterranean. Environmental Earth Sciences, 74, 5-14.

Bonacci, O., 2001. Monthly and annual effective infiltration coefficients in Dinaric karst: example of the Gradole karst spring catchment. - Hydrological Science Journal, 46, 2, 287-299, DOI: 10.1080/02626660109492822

Bonacci, O. & Ljubenkov., J. 2005. Karst river Keka hydrology. Proceedings of the International Conference and Field Seminars, Belgrade and Kotor, Eds. Zoran Stevanović and Petar Milanović, 13-22 September 2005, 397-404.

Boni, C., Bono, P., Capelli, G., 1982. Valutazione Quantitta tiva dell'infiltrazione efficace in un bacino carsico dell'Italia Centrale: Confronto con analoghi bacini representativi di diversa litologia. Estrato da:Atti del II° Simposio Internazionale sulla «Utilizzazione delle aree carsiche» Bari – Castellane Grotte, 20-22 Maggio 1982.

Boussinesq, J., 1877. Essai sur la theorie des eaux courantes (Essay on the theory of running waters). Memoires presentes par divers savants a l'Academie des Sciences de l'Institut National de France XXIII. 1, 252-260.

Chen, Z., Auler, A.S., Bakalowicz, M., Drew, D., Griger, F., Hartmann, J., Jiang, G., Moosdorf, N., Richts, A., Stevanović, Z., Veni, G. & Goldscheider, N., 2017. The World Karst Aquifer Mapping project: concept, mapping procedure and map of Europe. Hydrogeology Journal, 25, 3, 771-785. DOI 10.1007/s10040-016-1519-3

Desio, A., 1960. Manual della Geologia Applicata. Hoepli, Milano.

Denneborg, M., 1993. Albanien expedition 1992 und 1993. Mitteilungen des Verbades der detschen Höflen und Karsifrscher. 39, 4, 64-73.

Doka Dh. Qiriazi P., 2022. The Geography of Albania – Problems and Perspectives. Springer. ISSN 2363-908, ISSN 2363-9091 (electronic).

Drew, D., Hötzl, H., 1999. Karst hydrogeology and human activities: impact, consequences and implications. International Contributions to Hydrogeology, 20, IAH, Balkema, Rotterdam, The Netherlands, pp. 322.

Eftimi, R., 2005. Hydrochemical characteristics of some lithologicaly different karst massifs of Albania. In: Water Resources & Environmental Problems in Karst. In: Stevanovi,ć Z., Milanović, P. Proceedings of the International Conference and Field Seminars 13-19 September, Belgrade 2005, 499-504.

Eftimi, R., 2010. Hydrogeological characteristics of Albania. AQUAmundi Am01012, 79-92. DOI 10.4409/Am-007-10-0012

Eftimi, R., 2020. Karst and karst water resources of Albania and their management. Carbonates and Evaporites, 35, 1-14, DOI 10.1007/s13146-020-00599-0

Eftimi, R., Bisha, G., Tafilaj, I. Sheganaku, Xh., 1985. Hydrogeological Map of Albania, sc. 1:200 000, Tirana. Printed in Nd, Mjeteve Mësimore H. Shijaku, Tirana-Albania.

Eftimi, R., Malík, P., 2019. Assessment of regional flow type and groundwater sensitivity to pollution using hydrograph analyses and hydrochemical data of the Selita and Blue Eye karst springs, Albania. Hydrogeology Journal, 27, 6, 2045-2059; DOI: 10.1007/s10040-019-01974-5

Eftimi, R., Zojer, H., 2015. Human impact on karst aquifers of Albania. Environmental Earth Sciences, 74, 57-70. DOI 10.1007/s/12665-015-4309-7.

Eftimi. R., Benderev, A., 2007. Utilization of hydrochemical data for characterization of the karst system: example of Iskrets spring. Bulgaria Review of the Bulgarian Geological Institute, vol. 68, 1-3, 167-174.

Fiorillo, F., 2014. The recession of spring hydrographs, focused on karst aquifers. Water Resour Manag 28: 1781-1805. https://doi.org/10.1007/s11269-014-0597-z

Fiorillo, F., Revellino, P.,Ventafridda, G., 2012. Karst aquifer draining during dry periods. J Cave Karst Stud 74, 2, 148-156. https://doi.org/10.4311/2011JCKS0207

Ford, D., Williams, P., 2007. Karst Hydrogeology and Geomorphology. John Wiley & Sons, Ltd., Chichester, England.

Giacopetti, M., Materazzi, M., Pambianchi, G., Posavec, K., 2017. Analysis of mountain springs discharge time series in the Tennacola stream catchment (Central Apennine, Italy). Environ Earth Sci, 76, 20, https://doi.org/10.1007/s12665-016-6339-1

Gjata, K., Kodra, A., 1999. Albanian ophiolites: from rift to ocean formation. EUG 10: Abstracts. Symp, F04, Petrologic, 405, Strasbourg.

Goldscheider, N., Pronk, M. & Zopfi, J., 2010. New insight into the transport of sediments and microorganisms in karst groundwater by continuous monitoring of particle-size distribution. Geol Croat 63, 2, 157-166.

Gregor, M., Malík, P., 2012. Construction of master recession curve using genetic algorithms. Journal of

Hydrology & Hydromechanics, 60, 1, 3-15. DOI 10.2478/v10098-012-0001-8

Gregor, M., Malík, P., 2014. RC 4.0 User's manual. 36 pp. http://www. Hydro office.org. Accessed April 2019.

Gutierrez, F., Parise, M., De Waele J, and Jourde H., 2014. A review of natural and human-induced geohazards and impacts in karst. Earth Science Reviews 138, 61-88

Günay, G. & Ekmekci, M., 1997. Importance of public awareness in groundwater pollution. In: Günai, G., Johnson, K., (eds) Proc. 5th Int Symposium and field seminars on Karst Water & Environmental, Antalya-Turkey, Balkema, Rotterdam, pp 3–10.

Jacobson, R.L., Langmuir, D., 1974. Controls on the quality variations of some carbonate spring water. Journal of Hydrology, 23.

Jaho, S., Mici, A., Boriç, M., Mukeli, R. & R. Naçi, 1984. Climate of Albania (in Albanian), Institute of Hydrometeorology, Tirana.

Hartmann, A., Goldscheider, N., Wagner, T., Lange, J., Weiler, M., 2014. Karst water resources in a changing world: Review of hydrogeological modelling approaches. Review Geophysics, 2014, 52. DOI: 10.1002 / 2013RG000443.

Kalinina, P., 1951. Geotechnical conditions of Selita Spring area (in Russian). Vodokanalproekt, Leningrad.

Kessler, K., 1958. About the possibility increase the water supply capacity of Tirana (in Hungarian). Water Supply Directory, Ministry of Construction, Tirana-Albania.

Kessler, H., 1967. Water balance investigations in the karst regions of Hungary. Act Coll Dubrovnik. AIHS-UNESCO, Paris, 91-105.

Király, L., 2003. Karstification and groundwater flow/ speleogenesis and evolution of karst aquifers. In: Gabrovšek F (ed) Evolution of karst: from prekarst to cessation. Zalozba ZRC, Postojna-Ljubljana, Slovenia, pp 155–190.

Kolaneci M., 2021. Possibility of the use of White Water Spring for increasing the capacity of Tirana water supply system; hydrometeorological study. Archive of Tirana Water Board.

Kovács, A., Perrochet. P., Király, L., Jeannin, P-Y., 2005. A quantitative method for the characterisation of karst aquifers based on spring hydrograph analysis. Journal of Hydrology 303:152–164. https://doi.org/10.1016/j.jhydrol.2004.08.023

Kogovšek, J., Petrić, M., 2003. Tracing tests as a tool for the estimation of possible impacts of human activities on karst waters – examples from Slovenia. ICGGE Bled 2003.

Kresić, N., Bonacci, O., 2010. Spring discharge hydrograph. chap 4. In: Groundwater hydrology of springs: engineering, theory, management and sustainability. Elsevier, Amsterdam, pp 129–163.

Kresić, N. & Z. Stevanović, Z., 2010. (Eds) Hydrology of Springs: engineering, theory, management and sustainability. Elsevier Inc. BH, Burlington, New York, pp. 736. ISBN: 978-1-85617-502-9

Kristo, V., 1973. Some aspects of karst in Albania (in Albanian). Collection of Studies, 1, 67-79.

Kristo, V., Krutaj, F., Mezini, B., 1987. Karst landscape of Albania and the problems of its rational exploitation (in Albanian). Studime Gjeografike, 2, 257-268.

Krothe, N.C., Libra, R.D., 1983. Sulphur isotopes and hydrochemical variation in spring waters of southern Indiana, U.S.A.- Journal of Hydrology 61, 1, 267-283.

Kullman, E., 1990. Krasovo-puklinové vody. Karst Fissure waters. Geologický ústav Dionýza Štúra, Bratislava, pp. 184.

Kullman, E., 2000. Nové metodické prístupy k riešeniu ochrany a ochranných pásiem zdrojov podzemných vôd v horninových prostrediach s krasovo-puklinovou priepustnosťou [New methods in groundwater protection and delineation of protection zones in fissure-karst rock environment; in Slovak with English summary]. Podzemná voda, 6, 2, 31-41.

Lakey, B., Krothe, N.C., 1996. Stable isotopic variation of storm discharge from a perennial karst spring, Indiana. Water Resource Research 32, 3, 721-731.

Liko, V., 1962. Tectonics and characteristics of the development of Mali me Gropa Region (in Albanian). Bulletin of Tirana University, Natural Sciences, 3, 37-47.

Liso, I.S., Parise, M., 2020. Apulian karst springs: a review. J Environ Science and Engin Technology, 2020, 8, 63-83.

Malík, P., Vojtková, S., 2012. Use of recession-curve analysis for estimation of karstification degree and its application in assessing overflow/underflow conditions in closely spaced karstic springs. Environmental Earth Sciences 2012, 65, 2245–2257. DOI 10.1007/s12665-012-1596-0

Malík, P., 2015. Evaluating discharge regime of karst aquifers, chap 7. 205-250. In: Stevanović Z (ed) (2015) Karst aquifers: characterization and engineering. Professional Practice in Earth Sciences series, Springer, Cham, Switzerland, 687 pp. https://doi.org/10.1007/978-3-319-12850-4

Mammoliti, E., Fronzi, D., Mancini, A., Valigi, D., Tazioli, A., 2021. WaterbalANCe, a WebApp for Thornthwaite–Mather Water Balance Computation: Comparison of Applications in Two European Watersheds. Hydrology, 8, 1, pp. 34.

Margat, J., 1998. Les eaux souterraines dans le bassin méditerranéen. Ressources et utilisations. Documents BRGM 282, BRGM, Orléans, France.

Meco, S. & Sh. Aliaj, 2000. Geology of Albania. Gebrüder Borntraeger, Berlin-Stuttgart. 246. ISBN 3-443-11028-2

Newson, M.D., 1971. A model of subterranean limestone erosion in the British Isles based on hydrology. Trans Inst Br Geogr 54, 55-70

Orehova, T., Gerginov, P., 2021a. Analysis of water regime and balance of springs from the Lovech-Tarnovo basin, Bulgaria. International Multidisciplinary Scientific GeoConference: SGEM 2021, 27-34

Orehova, T., Gerginov, P., 2021b. Model study of the regime and balance of karst spring Iskrets, NW Bulgaria. "Climate, atmosphere and water resources in the face of climate change", vol. 3, 23–29. ISSN 2683-0558

Orehova, T., Toteva, A., Gerginov, P., 2024. Application of Water balance software in the upper Mesta River basin. In: Proc. of the 6-th International scientific "Global Warming's Imprints on the Elements of the Climatic System", Hisarya, 24-28 September, 2024. 102-108. ISBN 978-619-92989-0-9

Pali, N., 1973. About the possibility to modify the discharge of the Selita and Shen Maria springs. Ndertuesi, Nr. 2, Tirana, April 1973. 15-22.

Parise, M., Qiriazi, P., Sala, S., 2004. Natural and anthropogenic hazards in karst areas of Albania- Nat. Hazards Earth Syst Sci, 4, 560-581.

Perrin, J., Jeannin, P-Y., Cornaton, F., 2007. The role of tributary mixing in chemical variation at karst springs, Milandre, Switzerland. Journal of Hydrology, 332, 1-2, 158-173.

Radulovic, M., Stevanovic, Z., Radulovic, M., 2012. A new approach in assessing recharge of highly karstified terrains–Montenegro case studies. Environmental Earth Sciences, 65, 2221-2230.

Ravbar, N., Šebela, 2015. S., The effectiveness of protection policies and legislation framework with special regard to karst landscapes: Insights from Slovenia. Environ. Sci. Policy 2015, 51, 106-116.

Qiriazi, P., 2019. Physical Geography of Albania (in Albanian). Mediaprint, Tirana. 580. ISBN: 978-9928-08-415-6

Stevanović, Z., 2015. Ed. Karst aquifers – Characterization and engineering. Professional practice in earth sciences Springer: Heidelberg, Germany, 2015. ISBN 978-3-319-12849-8.

Stevanović, Z., 2019. Kast water in potable water supply: a global scale overview. Environmental Earth Sciences, 2019, 78, 662. https://doi.org/10.1007/s12665-019-8670-9

Stevanović, Z., Eftimi, R., 2010. Karstic sources of water supply for large consumers in south-eastern Europe—sustainability, disputes and advantages. In Proceedings International Interdisciplinary Scientific Conference "Sustainability of the Karst Environment. Dinaric Karst and Other Karst Regions", September 2009, Plitvice Lakes, Croatia, 23–26. DOI: 104154/gc.2010.15

Shuster, E.T., White, W.B., 1971. Seasonal fluctuations in the chemistry of limestone springs: a possible mean for characterizing carbonate aquifers. Journal of Hydrology, 14, 93-128.

Thornthwaite, C.W., Mather, J.R., 1957. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, Johns Hopkins Univ., Laboratory in Climatology, Baltimore, MD, USA, 10, 181–311.

Turc, L., 1954. The soil balance: relations between rainfall, evaporation and flow (in French). Geography Rev 38, 36-44

White, W.B., 1969. Conceptual models for carbonate aquifers. Ground Water, 7.

White, W.B., 2010. Springwater geochemistry. In: Groundwater hydrology of springs. Kresić, N. & Stevanović, Z., Eds.; Butterworth-Heinemann: Burlington, VT, USA, 2010; pp. 231-268.

Worthington, S.R.H., Ford, D.C. 2009. Self-Organization Permeability in Carbonate Aquifers. Ground Water, 47, 3, 326-336.

Xhomo, A., Kodra, A., Xhafa, Z., Shallo, M., 2002. Geology of Albania, Notes of Geological Map of Albania, sc. 1:200.000 (in Albanian). Albanian Geological Service, Tirana. 410.