

Hydrogeological characteristics of the Trebeshinë-Dhëmbel-Nëmërçkë (TDN) karst massif and groundwater drainage through the Këlcyra Gorge, Albania

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Abstract. This study focuses on the Trebeshinë-Dhëmbel-Nëmërçkë (TDN) karst massif, one of Albania's largest karst regions. The study integrates field investigations, geological and hydrogeological mapping and observations, groundwater balance calculations, and hydrochemical and stable-isotope evidence. The main contribution of this study is explaining the karst massif's functioning by identifying the recharge area, calculating renewable groundwater resources, and determining groundwater discharge. The value of the study also lies in identifying the dominant hydrochemical processes and the role of the Permian evaporite formation underlying the Mesozoic carbonate rock in the hydrogeochemistry of karst water in the TDN massif. A better understanding of the massif, especially the Këlcyra Gorge (canyon), where many important karst springs emerge, is valuable because the Vjosa River catchment basin was designated a National Park in 2024 and holds international significance. In this context, knowing the quantity and quality of karst waters draining into the Këlcyra Gorge is essential, as they affect the overall quality of the Vjosa River. The TDN massif is a transboundary karst massif shared with Greece (UNECE, 2007), but no coordinated investigations have been conducted by either country to date. The massif's total renewable karst water resources are nearly 12.0 m³/s, most of which drain into the Këlcyra Gorge, with the remainder flowing into Greece. The results provide the first comprehensive hydrogeological synthesis of the TDN karst massif and establish a scientific basis for future sustainable management of the Vjosa National Park in general, which is also a transboundary aquifer shared between Albania and Greece. The study finds that the TDN massif is a typical Mediterranean karst area characterized by large hypsometric differences, which favor the formation of significant karst flows that recharge large karst springs with highly variable regimes.

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INTRODUCTION

Karst waters are widely recognized as vital resources in Europe, including the Mediterranean region (Margat, 1998; Bakalowicz, 2005; Stevanović, 2019; Stevanović and Eftimi, 2010; Liso and Parise, 2020; Xanke *et al.*, 2024) and Southeast Europe (Stevanović and Eftimi, 2010). Karst aquifers are among the richest in groundwater on Earth (Hart-

mann *et al.*, 2014; Stevanović, 2015, 2018) and, globally, provide drinking water to almost a quarter of the world's population (Goldscheider *et al.*, 2020). In Albania, carbonate karst rocks are widespread, covering about 24% of the territory (6440 km²). They form 23 carbonate water reservoirs that contain approximately 227 m³/sec (7.15×10⁹ m³/year) of renewable karst water resources, accounting for about 78% of the country's groundwater reserves

(Eftimi, 2010, 2020). These resources supply about 80% of Albania's urban population (Eftimi and Zojer, 2015; Eftimi, 2024). This study focuses on the Trebeshinë-Dhëmbel-Nëmërçkë (TDN) karst massif, one of Albania's largest. Although the hydrogeology of Albanian karst has been studied for several decades, the TDN massif has never been evaluated as an integrated hydrogeological system. The main goal of this paper is to identify and analyze the key elements of the karst massif, such as geological structure, hydrogeological system, groundwater recharge and drainage, hydrochemistry, and sustainability. A better understanding of this massif in general, and the Këlcyra Gorge in particular, is especially valuable, given that the Vjosa River catchment basin has been designated a "National Park"

starting in 2024. In this context, deeper knowledge of the water resources of the Vjosa River, the last wild river in Europe, is of particular scientific importance, given its status as a protected environment in Europe and its international interest. Field observations carried out by the author over several decades have been an essential source of information for interpreting groundwater resource formation.

STUDY AREA AND PHYSIOGRAPHIC CONDITIONS

From a geological perspective, the TDN massif (Fig. 1) forms a ridge that extends approximately 60 km and reaches widths of up to 7 km, trending

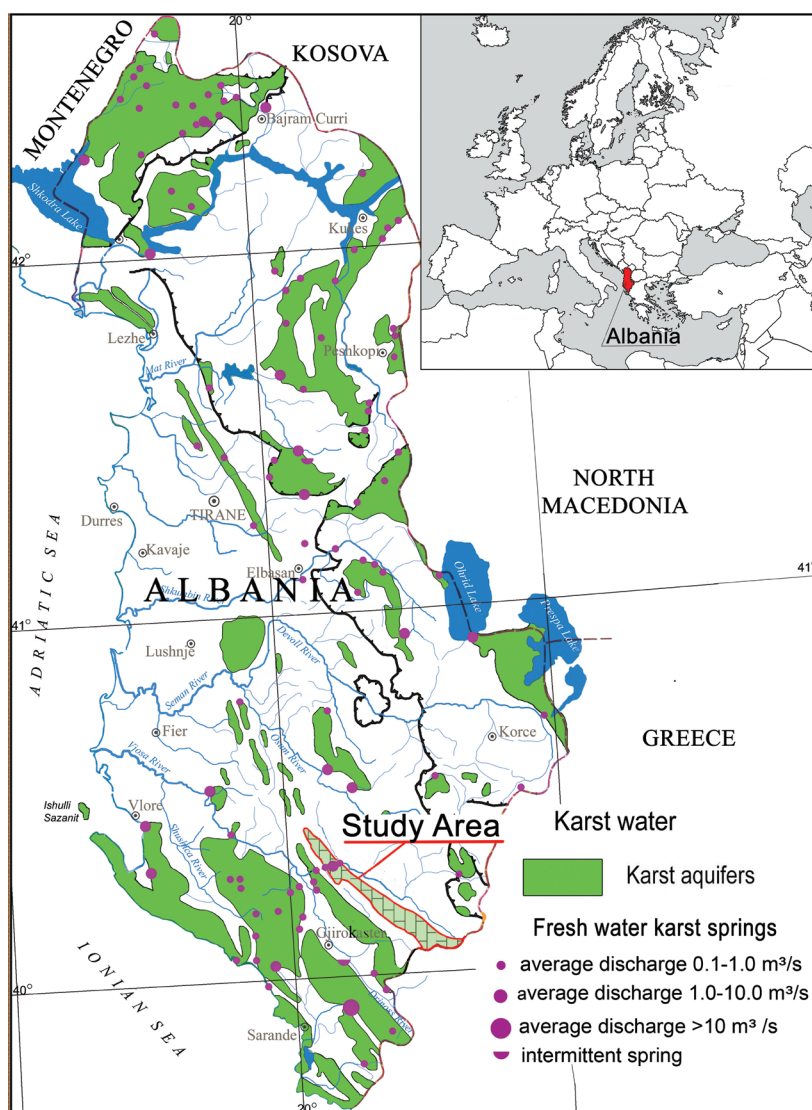


Fig. 1. Location of the study area: Trebeshina-Dhëmbel-Nëmërçka karst massif (TDN).

northwest-southeast. In Albania, the massif covers about 275 km². The TDN structure features several high peaks from north to south, namely Trebeshina 1992 m above sea level (a.s.l.), Dhëmbel 2138 m a.s.l., and the southernmost peak, Papingj 2485 m a.s.l. Annual precipitation, as across Albania (Jaho *et al.*, 1984), decreases toward the east. The Leskovik station, at an elevation of 920 m a.s.l., best represents the climate of the study area (Table 1). The average annual temperature at Leskovik is 11.4 °C, and the average annual rainfall is 1207 mm, with about 70% falling from November to April. These apparent climatic anomalies, characteristic of Medi-

terranean countries, favor intensive recharge during the wet season, explaining both the abundance of groundwater resources in the massif and the large seasonal variation in spring discharge.

As is generally the case in karst areas, the TDN massif also lacks permanent surface runoff (Bakalowicz, 2005; Ford and Williams, 2007; Eftimi, 2010). The only river associated with the TDN massif is the Vjosa, which, for about 40 km, flows parallel to the massif on the eastern side and, in Këlcyra, turns westward and crosses the limestone massif, forming the Këlcyra Gorge (Fig. 2), about 10 km long. Opinions differ on the origin of this gorge, but the

Table 1

Basic data of meteorological stations located on the outskirts of the TDN karst massif

Meteo-station	Elevation m a.s.l	Mean air temperature, °C			Precipitation, mm		
		May–October	November–April	Yearly	May–October	November–April	Yearly
Këlcyra	182	19.7	8.4	14.1	395.0	961.0	1356
Përmeti	240	20.7	8.8	14.8	361.3	946.3	1308
Leskovik	920	17.45	5.3	11.4	362.3	844.4	1207

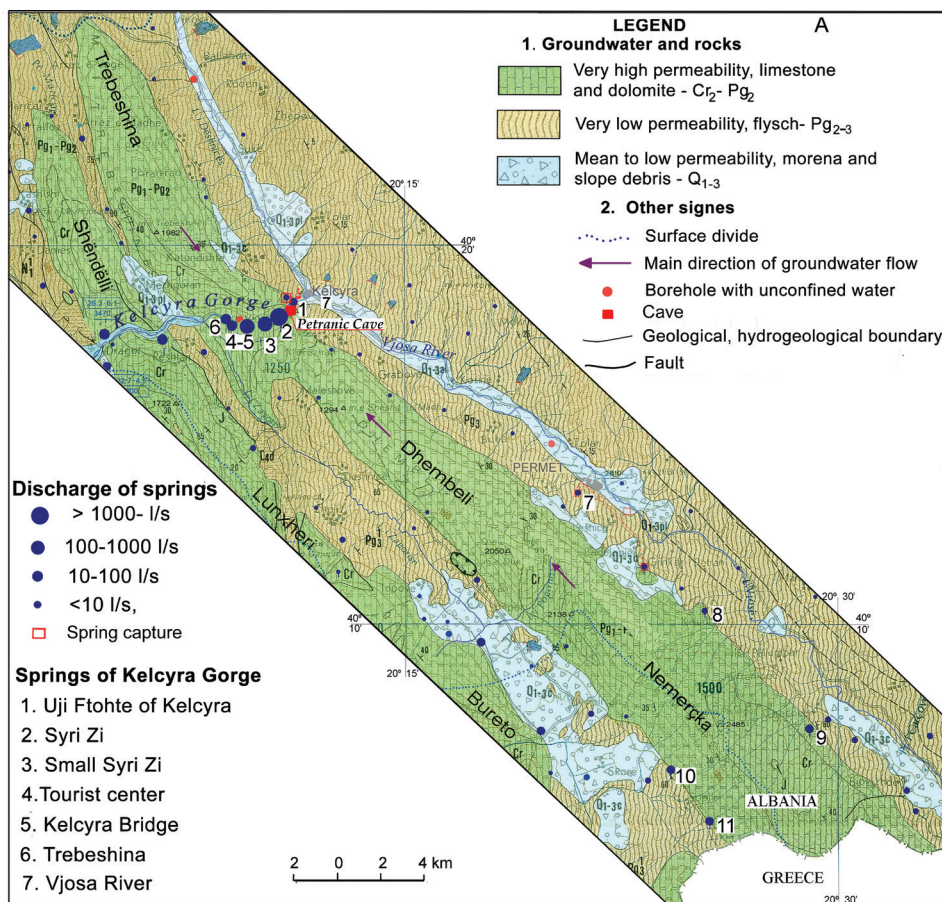


Fig. 2. Hydrogeological map of the study area, the TDN karst massif (after Eftimi *et al.*, 1985).

prevailing view is that it is erosional, resulting from the Vjosa River's erosion of the limestone massif (Qirjazi, 2019). According to data in "Hydrology of Albania" (Pano, 1984), the average multi-year flow of the Vjosa River along the gorge increases by $10.6 \text{ m}^3/\text{s}$, and during the dry season, it increases by $4.5 \text{ m}^3/\text{s}$. This increase mainly reflects the drainage of karstic water in the Këlcyra Gorge. In the high-mountain setting, abundant rainfall and its highly unstable regime in a highly karstified environment create conditions for the formation of groundwater flow with a steep hydraulic gradient, feeding karst springs with variable discharges.

GEOLOGY

The TDN karst massif defines an anticline within the Ionian Zone (Xhomo *et al.*, 2002; Aliaj, 1987,

2018), which is characterized by anticlinal and synclinal ranges trending SE-NW toward the Adriatic Sea. The TDN massif comprises two anticlines: Trebeshina and Dhëmbel-Nëmërçka (Aliaj, 2018), which coalesce into a single large structure (Fig. 2). It consists of carbonate formations (Fig. 3A) that overlie Permian evaporitic formations, constituting the deep basement of the Kruja and Ionian tectonic zones (Meço *et al.*, 2000). The underlying Permian evaporites play a major role in controlling karst groundwater chemistry. The carbonate rocks of the TDN karst massif consist of Mesozoic Upper Jurassic radiolarian siliceous rocks and limestones (Figs 2, 3B), and thin interbedded Lower and Upper Cretaceous clayey limestones, phosphate limestones, and siliceous layers. The carbonate section is completed by Paleocene and Eocene deposits, mainly located on the structure's wings (Fig. 2). Stratification and tectonic fractures in carbonate



Fig. 3. A) Eastern view of Mount Nemerçkë; B) limestone with thin siliceous layers, Upper Jurassic (J_3); C) Paleocene-Eocene flysch formations (Pg_1 – Pg_2); D) Pleistocene conglomerates (Q_{1-3}). Photos by R. Eftimi.

rocks constitute the principal groundwater pathways and are often widened by karstification. Both slopes of the TDN carbonate structure, on the eastern and western sides, are covered by Oligocene flysch formations (Fig. 3C), which act as an aquiclude, limiting the karst aquifer, modulating karst water flow, and concentrating groundwater discharge into the Këlcyra Gorge. The youngest deposits in Këlcyra Gorge are Pleistocene and consist mainly of well-cemented, coarse-grained conglomerates with variable grain sizes (Fig. 3D). Surface karst features are not highly developed on the TDN massif, unlike many other karst massifs in Albania. However, numerous important karst springs attest to well-developed karst features within the massif.

MATERIALS AND METHODS

Although the hydrogeology of Albanian karst has been studied for several decades, no comprehensive synthesis of hydrogeological information of the TDN massif has been published. Small-scale maps, such as geological maps (Xhomo *et al.*, 2002) and neotectonics maps (Aliaj, 2018), were initially used. During the investigation conducted as part of the hydrogeological map of Albania at a scale of 1:200 000 (Eftimi *et al.*, 1985), particular attention was given to the numerous springs in Këlcyra Gorge. As the largest springs emerge at or below the Vjosa River level, measuring their flows is practically impossible.

Subsequently, special hydrogeological studies have been conducted on the spring that supplies local water (Lako, 1986, 1988) or is commercialized (Tafilaj, 2002). An important investigation was conducted during 1988–1990, when each spring in the Këlcyra Gorge was sampled four to five times across different seasons. Water samples were analyzed mainly for the major elements Mg^{2+} , Ca^{2+} , $N^{+}+K^{+}$, Cl^{-} , SO_4^{2-} , and HCO_3^{-} in the laboratory of

the Albanian Hydrogeological Service (AHS) using volumetric, spectrophotometric, and colorimetric methods. Some parameters, such as pH, temperature, and electrical conductivity (EC), were measured in the field. Major ions were interpreted using conventional hydrochemical methods, the Piper diagram, and other hydrochemical graphics. A special investigation applying environmental isotope analyses of oxygen-18 ($\delta^{18}O$) and deuterium (δD) was conducted. The isotopic analyses were carried out at the Isotopic Section Laboratory of the IEAE – Vienna, and the results were used to assess the elevation of the recharge areas of the karst springs and to characterize groundwater recharge and flow processes. The study integrates geological mapping, hydrogeological observations, hydrochemical analyses, stable-isotope data, and groundwater-balance calculations to characterize groundwater recharge, flow, and discharge.

HYDROGEOLOGY

The hydrogeological features of the TDN karst massif are shown on the Hydrogeological Map (Fig. 2), which demonstrates that the main hydrogeological feature of this karst massif is the concentration of springs in Këlcyra Gorge. Some smaller springs, with maximal inflows of up to 50 L/s, are also found in the southern part of the study area.

Springs of the southeastern part of the massif

These springs (Fig. 2) were documented during Albania's hydrogeological survey (1967–1975), and their key characteristics are summarized in Table 2. They occur at altitudes ranging from about 400 m to 1050 m above sea level, and their flows range from 1.2 to 20 L/s. Only the last two springs, near the village of Sopik, have flows of about 40–50 L/s. Spring no. 7, near Përmet, emerges from slope deb-

Table 2
Main data of the most important sources of the southern part of the TDN karst massif

Nr	Spring	Date [d/m/y]	Elevat. m a.s.l.	Q L/s	T °C	pH	TDS. mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Na ⁺ +K ⁺ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L	HCO ₃ ²⁻ mg/L	HC type	rCa ²⁺ / rMg ²⁺
7	Përmet	12.07.1968	385	4–15	12.0	7.5	161.3	48.7	3.0	10.8	7.1	14.0	155.5	HCO ₃ –Ca	10.1
8	Kaludh	13.07.1968	500	1.2	12.0	7.6	158.6	52.7	1.2	9.6	7.1	4.1	167.7	HCO ₃ –Ca	26.3
9	Draçovë	13.07.1968	575	20.0	–	7.1	126	41.8	1.2	9.0	5.3	3.3	131.1	HCO ₃ –Ca	20.2
10	Sopik	21.07.1968	?	40	12.0	–	–	–	–	–	–	–	–	–	–
11	Sopik	21.07.1968	1050	50	12.0	–	–	–	–	–	–	–	–	–	–

Notes: Q – discharge; T – temperature; TDS – total dissolved solids; HC – hydrochemical.

ris, discharges approximately 4–15 L/s, and supplies the city's water. Chemical analyses (Table 2) indicate that the groundwater is very fresh, with TDS of 126–161 mg/L. Calcium and bicarbonate are the dominant ions (water facies is $\text{HCO}_3\text{-Ca}$). The high $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio is characteristic of karst waters derived primarily from limestones (Langmuir, 1984; Eftimi, 2005; White, 2010).

Springs of the Këlcyra Gorge

The Këlcyra Gorge is the primary drainage area for the karst waters of the TDN massif; the largest springs in the TDN karst massif emerge here (Fig. 4). In the Këlcyra Gorge, 11 sources with varying discharges and chemical compositions are present, of which 6 are the most important (Figs 2, 4). The largest springs emerge on the left bank of the Vjosa River, about 2 km from Këlcyra. Right-bank springs have lower flows and lower salt concentrations. Springs 1, 2, and 3 emerge at river level, whereas springs 4, 5, and 6 originate at elevations of roughly 8–10 meters above the first river terrace (Fig. 4). Many smaller outlets lie below river level and become visible only during low river flow. Outlet elevations, determined from topographic maps

at a scale of 1:25 000, with proximity range from 179 to 220 meters above sea level. Springs 1 and 6, which emerge on the right bank of the Vjosa River, appear to be fed by the Trebeshina anticline, whereas springs 2, 3, 4, and 5, which emerge on the left bank of the Vjosa River, originate from the Dhëmbel anticline. Table 3 presents the main physical data for the springs of Këlcyra Gorge.

Petranik Cave Spring. This spring emerges on the left side of the Vjosa River valley (Fig. 4), at the easternmost part of the Këlcyra Gorge, and is an artesian siphon. The cave's entrance is about 3 m above the Vjosa River valley and slopes gently eastward; the water inside is hydraulically connected to the Vjosa River (Fig. 5). During heavy rainfall, the groundwater level in the cave rises, overflows the barrier, and flows into the river valley, sometimes for several hours or, in rare cases, for several days (Fig. 5A). After these brief periods, the groundwater level in the cave drops and remains slightly above the Vjosa River level. The maximum discharge from Petranik Cave exceeds $5 \text{ m}^3/\text{s}$. The cave's siphon was explored by divers between 1994 and 1995 (Touloumdjian, 2005). The maximum depth explored was –63 m, but the cave appears to continue; its section becomes too



Fig. 4. Këlcyra Gorge and the location of the springs (elaborated from Google Maps).

narrow and difficult to pass through. Initially, the discharge elevation of this spring may have been the lowest point of a limestone outcrop in the Këlcyra Gorge.

Cold Water Spring (no. 1), also known as Ali Pasha Tepelena's spring, is located on the eastern outskirts of Këlcyra Gorge, on the right bank of the

Vjosa River. This spring is recharged by the northern part of the TDN karst massif, the Trebeshina anticline (Fig. 2). The spring emerges where Paleocene-Eocene limestone formations meet Paleogene formations. During the wet season, the spring discharge is about 1 m³/s (Fig. 6A, 6B), but during the dry season it decreases to about 3 L/s.

Table 3
Main physical data of the springs of Këlcyra Canyon

Order No.	Spring's name	Coordinates, elevation m a.s.l.	Type of spring	Q _{min} m ³ /s	Q _{mean} m ³ /s	Q _{max} m ³ /s	Use	Literature
	Petranik Cave	40° 18' 21" N 20° 11' 01" E Z ≈ 184 m	Syphon artesian (ascending)	0.0	–	> 5.0	Not used	Touloumdjian (2005) Eftimi (2025)
1	Uji Ftohtë (Cold Water)	40° 18' 30" N 20° 11' 11" E Z ≈ 182 m	Free flow	≈0.003	–	≈ 1.0	Not used	Archive of AGS
2	Uji Zi (Black Water)	40° 18' 20" N 20° 10' 57" E Z ≈ 180 m	Syphon artesian (ascending)	1.8	3.5	≈ 8.0	Not used	Eftimi (2025)
3	Small Black Water (Syri Zi I Vogel)	40° 18' 26" N 20° 10' 49" E Z ≈ 179 m	Syphon artesian (ascending)	0.020	–	≈ 2.0	Not used	Archive of AGS
4	Tourist Centre	40° 17' 45" N 20° 09' 45" E Z ≈ 220 m	Free flow	0.020	0.07–0.08	≈ 1.0	Used as a tourist attraction	Archive of AGS
5	Bridge Spring	40° 17' 47" N 20° 17' 47" E Z ≈ 206 m	Free flow (epigenic)	0.002	≈ 0.020	≈ 0.1		Archive of AGS
6	Trebeshina Spring	40° 17' 55" N 20° 09' 18" E Z ≈ 204 m	Free flow (epigenic)	0.0	–	≈ 0.35		Tafilaj (2002)

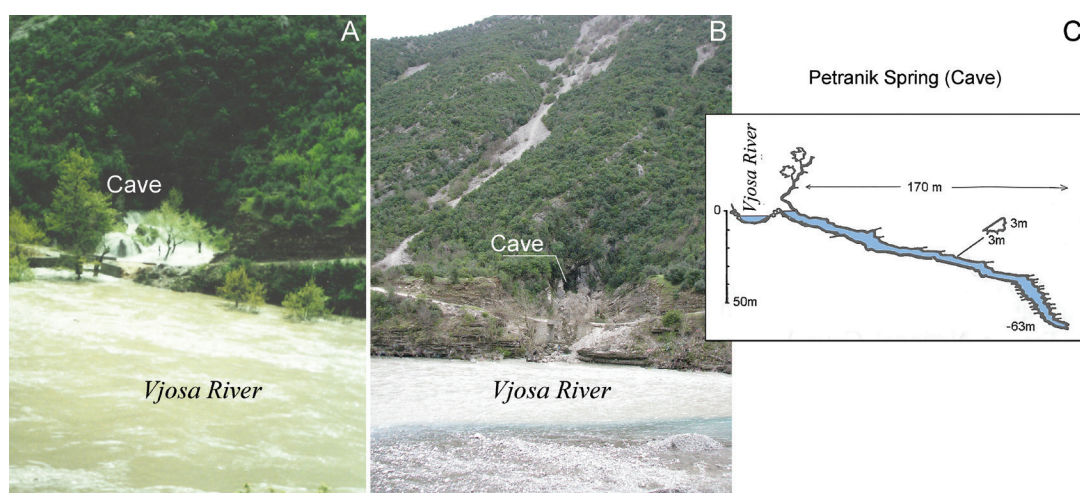


Fig. 5. Petranik Cave Spring: A) The spring flowing at high groundwater level; B) Petranik Cave at low groundwater level; C) Vertical profile of the spring siphon.

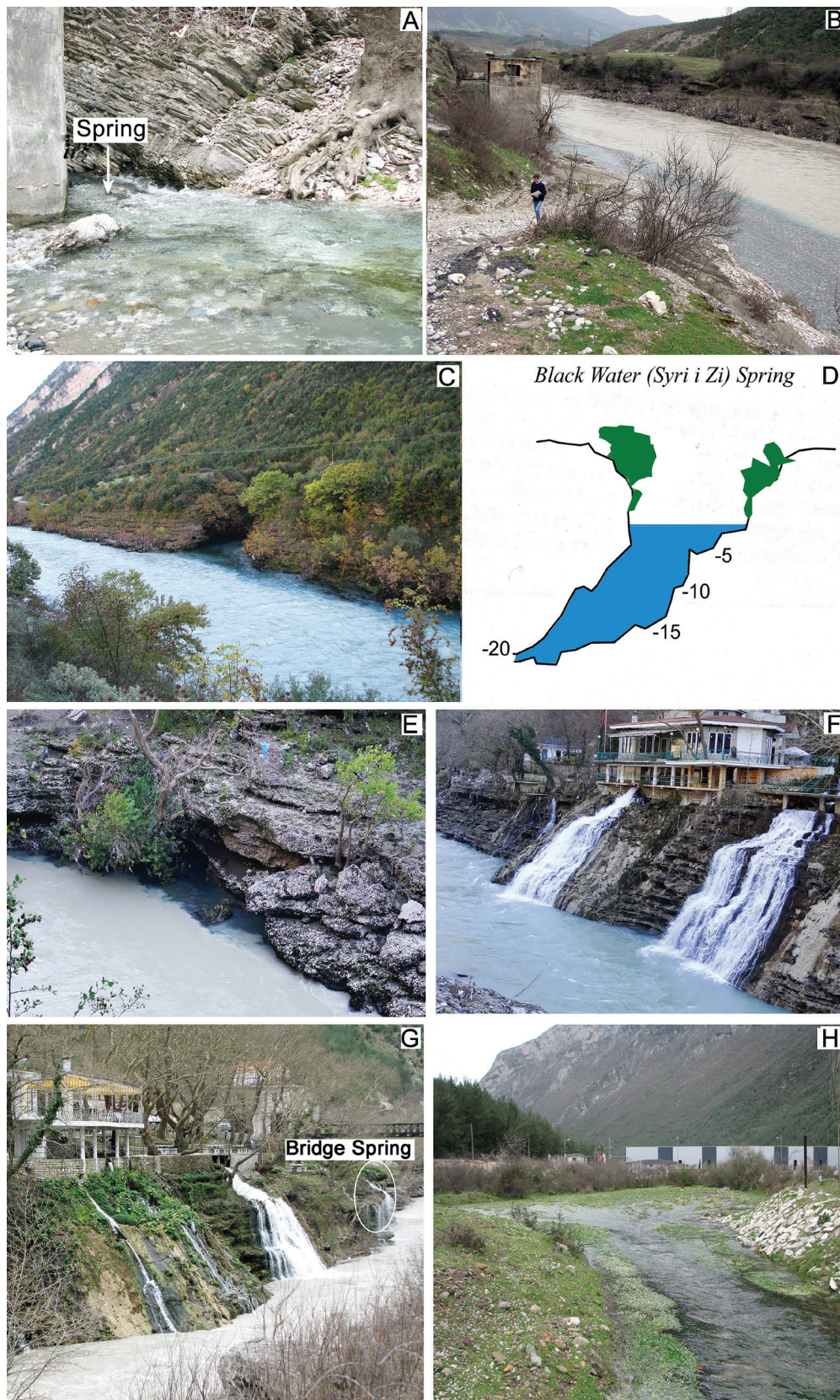


Fig. 6. Springs of Këlcyra Gorge: (A and B) Uji Ftohte (Cold Water) Spring; (C) Uji Zi (Black Water) Spring; (D) cross-section of the Syri Zi Spring syphon; (E) Syri Zi Spring; (F) Tourist Center Spring; (G) Bridge Spring (near the Tourist Center Spring); (H) Trebeshina Spring during the wet season (October 31, 2010).

Uji Zi (Black Water) spring (no. 2). This spring is located in the easternmost part of the Gorge, near the small town of Këlcyra, and is the largest in the Këlcyra Gorge. Its orifice resembles a small lake about 12 m in diameter, located on the left bank of the Vjosa River valley (Fig. 6C). Based on irregular measurements, its minimum flow is approximately 0.7–1.8 m³/s, its average is approximately 3.5 m³/s, and its maximum exceeds 8 m³/s. An Italian team conducted the first diving exploration of the Syri Zi siphon in 2005 (Eusebio, 2005). According to the dive reports, the siphon has strong vertical water currents and a narrowing section. Below –20 m, it was impossible to continue (Fig. 6D). Uji Zi emerges at an elevation of about 180 m, which represents the lower karst water discharge point in Këlcyra Gorge. This indicates that the intensity of underground flow is mainly conditioned by the elevation of the spring discharge point. Syphon springs are a distinct group within the artesian springs and are classified as ascending springs (Kresic and Stevanovic, 2010; Eftimi, 2025). The formation of limestone caverns (syphons) at some depth below the water table occurs because, near the point of discharge, equivalent potential surfaces require higher groundwater velocity. Groundwater circulation here is much more active, and rock dissolution is at a maximum, so the largest caverns should form near the discharge point (Fig. 7). The syphonal geometry of the Uji Zi spring and of Petranik Cave confirms that groundwater circulation recharging both springs occurs under confined conditions close to river level. This spring is recognized as a Monument of Nature (Jashiku et al., 2025).

Small Uji Zi Spring (no. 3) is another large spring located about 400 meters downstream of the Black Water Spring on the left bank of the Vjosa River (Fig. 6E). This is also an ascending spring that emerges from a widened karstic fissure, but no siphon is visible at the surface. The spring issues through well-cemented Pleistocene conglomerate formations and is also recharged by the TDN karst aquifer. Its flow ranges from about 20 L/s to more than 2 m³/s. Downstream of this spring, over about 1 km of river, many temporary springs occur along the left bank at or below river level.

Spring of the Tourist Center (no. 4). This spring is located on the left bank of the river, in the central part of the Këlcyra Gorge, near the Tourist Center. It emerges above the cemented conglomerate layers, about 25 m above the Vjosa riverbed (Fig. 6F). The spring's flow varies widely, from about 20–30 L/s to more than 1 m³/s. The outlet location also shifts by 7–8 m depending on the season. The spring has a

beautiful waterfall that flows from the terrace level down to the Vjosa River.

Bridge Spring (no. 5) emerges on the river's left bank in the central part of the Këlcyra Gorge, near a metal bridge leading to the tourist center (Fig. 6G). It is free-flowing. The water flows at the level of the Vjosa River's terrace and shows highly variable seasonal flows, ranging from about 2 L/s in the dry season to more than 100 L/s in the wet season. The Bridge Spring is neither captured nor used.

Trebeshinë Spring (No. 6) is located in the center of the Këlcyra Gorge and is the second spring on the right bank of the Vjosa River valley (Fig. 6H). It flows from the Quaternary conglomerates of the Vjosa valley at an elevation of about 174 m a.s.l. The spring is primarily fed by the karst massif of Mount Trebeshina. Its flow varies considerably with the seasons, from nearly 0 L/s to over 350 L/s, and its temperature ranges from 10.3 to 11.6 °C (Table 3). The spring is recharged by the karst waters of Mount Trebeshina. This spring is industrialized and recommended for use as table water (Tafilaj, 2002). In June 2009, a bottling plant was established (Fig. 6H).

After the source description, the hydrogeological model of the TDN karst massif becomes clear. Infiltrated atmospheric precipitation within the massif feeds the karst waters intensively but unevenly. In addition, resource inflows are structurally controlled by hypsometry (Table 3). Because the TDN karst massif is blocked on both the western and eastern sides up to high elevations by impermeable flysch deposits, its karst water resources drain into the Këlcyra Gorge, where carbonate deposits outcrop at the lowest levels.

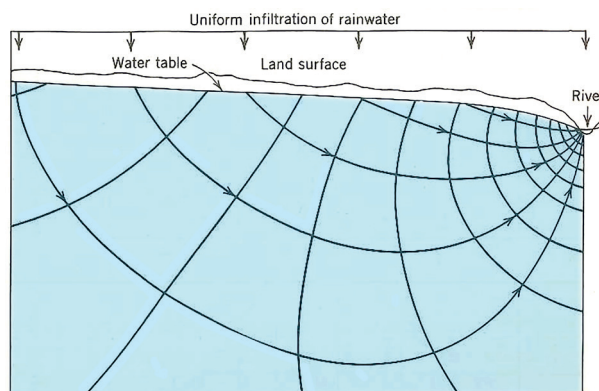


Fig. 7. Hypothetical circulation of groundwater in a homogeneous and isotropic medium with recharge (after Davis and De Wiest, 1966).

GROUNDWATER BALANCE OF THE TDN KARST MASSIF

Direct estimation of groundwater recharge into a karst massif from spring discharge is more accurate and reliable (Kresic and Stevanovic, 2010), but it is often difficult or costly to implement. Therefore, the groundwater recharge of TDN was estimated using the Turc (1955) empirical approach, which has proven reliable in Mediterranean karst environments (Boni *et al.*, 1982; Bonacci and Ljubenkovic, 2005; Eftimi *et al.*, 2025). The following formula expresses the average annual water balance of a karst massif:

$$p = I_e + E + F \quad (1)$$

where: P – precipitation, mm; I_e – effective infiltration, mm/year; E – evapotranspiration, mm/year.

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

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

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

Applying Turc's empirical formula implies that meteorological stations should be located at elevations roughly equal to those of the massif's recharge zone. Therefore, even data from the highest-elevation meteorological station, Leskovik, cannot be used to determine effective infiltration in this massif.

To estimate the elevation of the recharge area, we also used the relationship between spring elevation and the isotope $\delta^{18}\text{O}$ content (Gat and Dansgaard, 1972; Gat and Gontfiantini, 1981; Davis, 1989; Clark and Fritz, 1997; IAEA, 2004; Eftimi *et al.*, 2017). Table 4 presents the isotopic measurements of the springs. As shown in this table, the measured $\delta^{18}\text{O}$ and δD values for the springs in Kelcyra Gorge and the Vjosa River are quite similar. This indicates that the recharge areas of the studied springs and

the Vjosa River watershed have approximately the same elevation. Because data on so-called local springs are lacking, it is impossible to determine the recharge elevation of the springs (Gat and Gontfiantini, 1981; Davis, 1989). However, compared with the isotope data from the Tomorri karst massif (Eftimi *et al.*, 2026), located about 25 km north of the TDN massif, the recharge elevation of the major springs in Këlcyra Gorge is estimated at 1200 m a.s.l.

To calculate the water balance of the study area, interpolated meteorological station data for temperature and precipitation are used (Jaho *et al.*, 1984). Based on relief characteristics, the TDN karst massif is divided into two areas: the southern area has a surface area of 140 km² and an average elevation of about 1500 m a.s.l., while the northern area has a surface area of 135 km² and an average elevation of about 1200 m a.s.l. Table 5 presents the water balance values for the TDN karst massif. The estimated renewable water reserves of karst waters are nearly 12 m³/s; the average groundwater flow modulus is 41.1 L/s/km²; and calculated infiltration accounts for 71–77% of precipitation. These values are comparable to those for the karst massifs Mali me Gropa (Eftimi *et al.*, 2025) and Tomorri (Eftimi *et al.*, 2026). During the rainy season, rising groundwater levels and saturation often prevent the aquifer from fully absorbing and retaining infiltrated water. As a result, it is widely accepted that about 10% of annual rainfall flows as runoff along the edges of karst massifs. For the TDN massif, 10% of annual rainfall is 130 mm, corresponding to a flow of 1.2 m³/s across the entire area of 275 km². In summary, renewable water resources are estimated at 10.8 m³/s (12.0 m³/s – 1.2 m³/s), of which approximately 6–8 m³/s drain into Këlcyra Gorge.

The TDN massif is a transboundary karst massif shared with Greece (UNECE, 2007), but neither country has conducted a coordinated investigation. Within Greek territory, there are large

Table 4
Isotopic values measured in the springs draining into the Këlcyra Gorge

Nr	Water point	Elevation m a.s.l.	Nr of analyses	$\delta^{18}\text{O}$ -mean ‰	δD -mean ‰
1	Syri Zi Spring	165	4	–8.75	–51.33
2	Small Syri Zi Spring	164	4	–8.76	–50.45
3	Tourist Center Spring	185	4	–8.36	–48.23
4	Bridge Spring	172	3	–8.46	–49.6
5	Vjosa River	166	3	–8.63	–50.4

Note: the elevations are determined using a topographic map at a scale of 1:25 000

Table 5
Results of calculating the TDN karst water balance using the Turc method

Zone	Area km ²	Mean altitude m a.s.l.	Mean air temperature °C	Yearly precipitation mm/year	Infiltration mm/year	Coef. of Infiltration %	Renewable resources m ³ /s	Module of groundwater flow L/s/km ²
Northern	140	1200	8.0	1750	1250	71	5.55	39.7
Southern	135	1600	7.2	1950	1500	77	6.42	47.5

$11.97 \approx 12.0 \text{ m}^3/\text{s}$

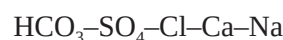
sulfur springs such as Rogozi and Manu Nerou, with discharges exceeding 1 m³/s and high SO₄ concentrations of about 250–900 mg/L (Nikolau *et al.*, 2011). It appears that part of the karst water from the southern TDN karst massif flows from Albanian territory into Greek territory, but the flow rates are unknown.

HYDROGEOCHEMICAL CHARACTERISTICS

The results of the general physico-chemical analyses of the springs (Table 6), along with the Piper diagram (Fig. 8) and other hydrochemical graphs (Fig. 9), have been used to characterize the hydrochemical evolution of the studied springs. The correlation coefficients among the chemical parameters Ca²⁺, Mg²⁺, Na⁺, Cl⁻, and SO₄²⁻ are also listed in Table 7. Each spring is sampled 4 or 5 times across different seasons. As shown in the Piper diagram (Fig. 8), all the analyzed springs cluster closely together, indicating that their chemical compositions are very similar

and that they formed under the same geochemical processes. The very high correlation coefficients among the hydrochemical parameters, which mostly cluster around 0.9, also suggest a common geochemical environment throughout the evolution of the waters.

Approximate values for EC and TDS are 420–720 µS/cm and 240–500 mg/L, respectively. The hydrochemical facies of the karst springs in the Këlcyra Gorge are similar and are as follows:



Two hydrochemical processes determine the chemical composition. The first is carbonate dissolution. In the epikarst area, infiltrating water enriched with CO₂ dissolves limestone through water-rock interaction to an extent proportional to the partial pressure of CO₂ (Shuster and White, 1971; Jacobson and Longmuir, 1974; Trček, 2005; Raimann and Birke, 2010):



Table 6
Chemical analysis with minimal and maximal concentrations of karst springs draining into the Këlcyra Gorge. Names of springs: K – Këlcyra; BW – Black water; SBW – Small black water; TC – touristic Center; BS – bridge Spring; Trb – Trebeshinë; VR – Vjosa River.

Nr	Spring	Date [d/m/y]	Q L/s	T °C	pH	EC µS/cm	TDS mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Na ⁺ + K ⁺ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L	HCO ₃ ²⁻ mg/L	Hydrochemical type
1	K	30.03.2009	70	9.3			277	61.7	4.2	19.8	51.5	23.0	125.0	HCO ₃ –Cl–Ca–Na
2	BW	03.11.1988	700	10.2	7.47	1247	792	124.0	17.5	121.7	196.8	224.3	164.7	Cl–SO ₄ –Ca–Na
		11.05.1989	1300	10.1	7.40	597	382	73.2	8.2	46.2	69.2	88.5	155.0	HCO ₃ –Cl–SO ₄ –Ca–Na
3	SBW	03.11.1988	5	10.2	7.47	1245	805	124.0	16.5	121.4	196.8	225.1	157.4	Cl–SO ₄ –Ca–Na
		11.05.1989	13	10.1	7.55	594	365	73.23	5.84	48.5	67.4	88.0	152.5	HCO ₃ –Cl–SO ₄ –Ca–Na
4	TC	30.05.1989	10	10.9	7.70	425	278	65.5	6.4	21.8	55.0	60.9	117.1	HCO ₃ –SO ₄ –Ca–Na
		08.08.1990	2	12.2	7.62	720	500	98.2	11.6	51.7	72.7	146.9	182.0	HCO ₃ –SO ₄ –Cl–Ca–Na
5	BS	03.11.1988	50	10.8	7.74	529	370	95.2	14.4	4.4	12.4	130.9	187.0	HCO ₃ –SO ₄ –Ca
		30.05.1989	250	10.8	7.65	419	238	64.5	4.68	23.9	24.8	57.6	167.1	HCO ₃ –SO ₄ –Ca–Na
6	Trb	29.12.1988		10.9	8.8	523	336	76.6	7.2	27.6	35.5	78.2	171.3	HCO ₃ –SO ₄ –Ca–Na
		24.11.1989		10.6	7.76	497	336	76.6	7.2	27.6	33.7	81.9	178.1	HCO ₃ –SO ₄ –Ca–Na
7	VR	29.12.1988		9.8	7.48	685	423	84.5	9.5	45.3	74.5	109.0	158.6	HCO ₃ –SO ₄ –Cl–Ca–Na
		24.11.1989		10.6	7.90	539	343	66.8	10.7	39.1	53.2	82.3	164.7	HCO ₃ –SO ₄ –Cl–Ca–Na

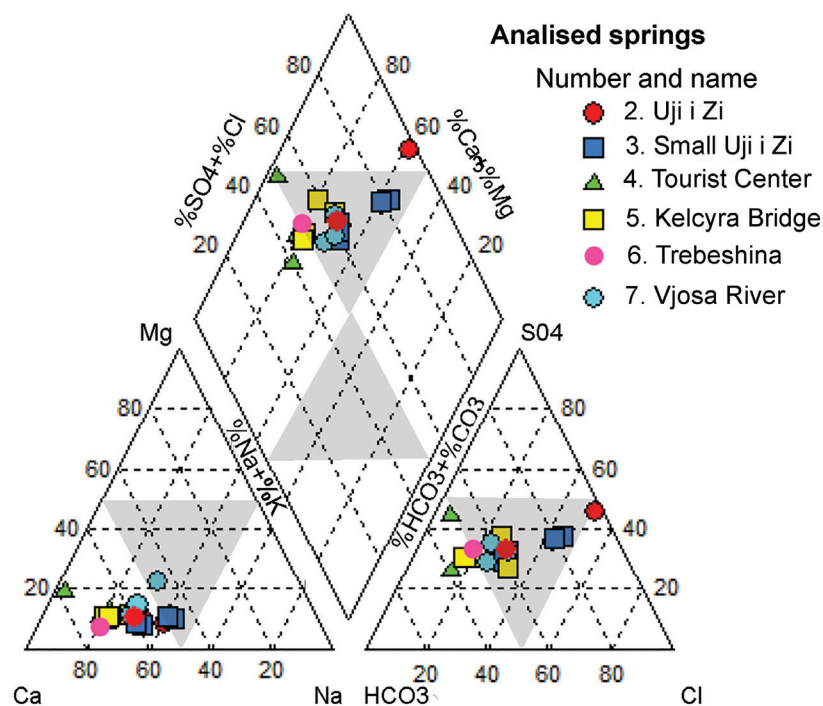


Fig. 8. Piper's graph of the karst springs in the Këlcyra Gorge and the Vjosa River.

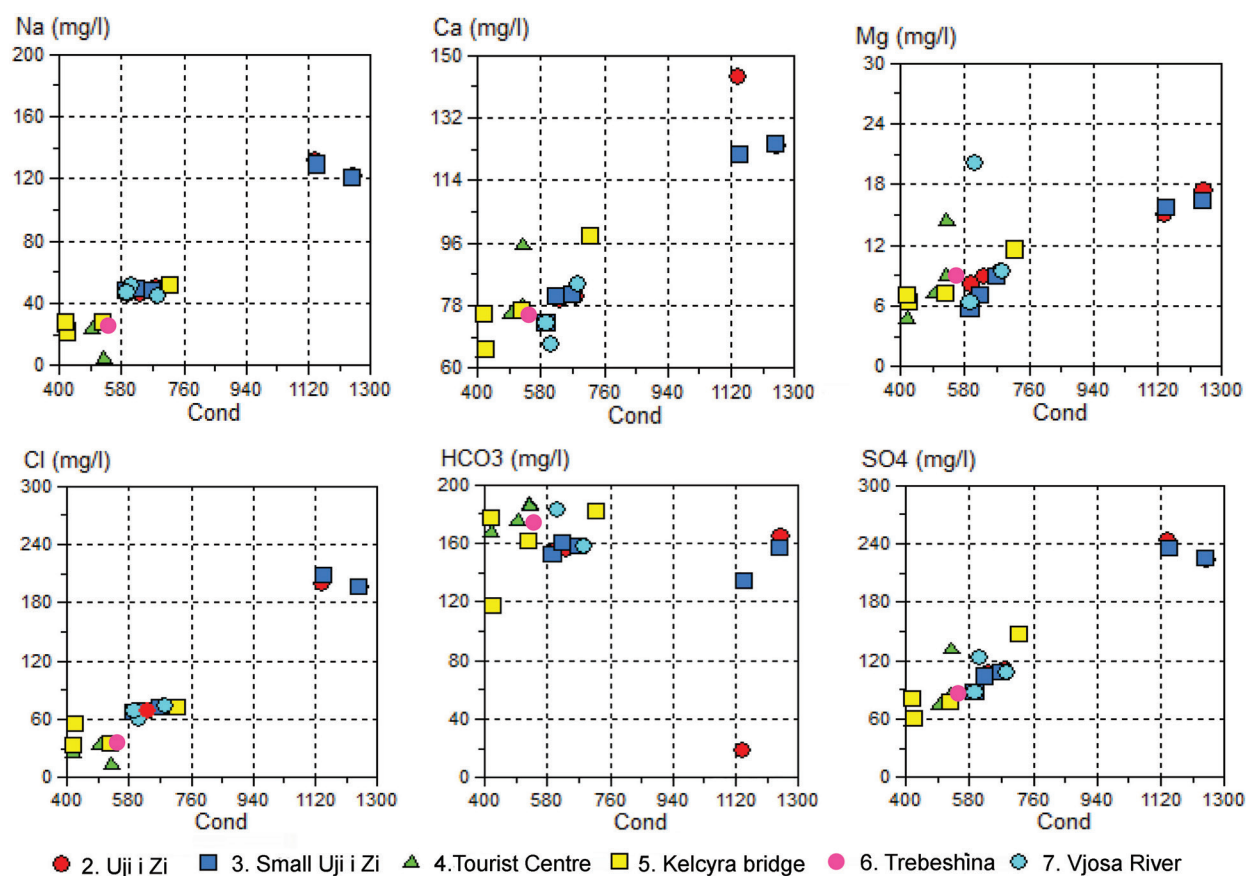


Fig. 9. Hydrochemical graphs of the springs of the Këlcyra Gorge and the Vjosa River: ions vs EC.

Table 7
Correlation coefficients of the main chemical elements

	Na	Ca	Mg	Cl	SO ₄	TDS
Na	1.0	0.88	0.752	0.992	0.924	0.961
Ca		1.0	0.893	0.882	0.982	0.954
Mg			1.0	0.776	0.916	0.896
Cl				1.0	0.029	0.968
SO ₄					1.0	0.982

The second hydrogeochemical process shaping the chemical composition of the springs in the Këlcyra Gorge area is mixing with sulfate-rich waters from evaporitic formations forming the basement of the Ionian Zone's anticlines (Velaj, 2001; Nikolau *et al.*, 2011).

Additionally, geological studies indicate that evaporitic deposits in Albania's outer tectonic zones often contain high levels of NaCl (Eftimi, 1998), resulting in elevated concentrations of Na⁺ and Cl⁻ (Bakalowicz, 2015). In the analyzed springs, concentrations of these parameters range from 30–130 mg/L to 25–200 mg/L (Table 6). Increased seasonal variability is important for understanding karstification processes, as greater hydrochemical and discharge variability over the hydrological year generally indicates greater karstification (Sánchez *et al.*, 2015; Eftimi and Malík, 2019).

Compared with other karst springs in Albania, those of the TDN massif generally have significantly higher concentrations of chemical parameters, particularly sulfate (Eftimi 2005, 2010). The groundwater of two other karst massifs in Albania, Dajti and Mali Gjere, also have relatively high sulfate concentrations. In the Dajti massif in central Albania, the SO₄²⁻ concentration averages about 83 mg/L (Eftimi, 1998), while in Mali Gjere in southern Albania it averages about 130 mg/L (Eftimi, 2009; Eftimi and Malík, 2019). The origin of SO₄²⁻ differs between the two karst massifs. In the Dajti massif, the SO₄²⁻ concentration results from the oxidation of trace pyrite, marcasite, and gypsum present in the dolomite that forms the karst aquifer (Hem, 1985; Eftimi, 2005). In the Mali Gjere massif, the increased SO₄²⁻ concentration is due to sulfate-rich water from the Drinos Valley partially recharging the karst aquifer (Eftimi, 2009; Eftimi and Malík, 2019; Eftimi *et al.*, 2017).

DISCUSSION AND CONCLUSIONS

The study highlights that, in several key characteristics, the TDN karst massif is very similar to other

karst massifs in Albania's outer tectonic zones. Along with other massifs, it forms a high mountain ridge that, structurally, is characterized by the Dhëmbel and Nëmërçka anticlines. Integrating geological, hydrogeological, hydrochemical, isotopic, and groundwater balance data yields a consistent interpretation of groundwater circulation within the TDN karst massif. The following are the main findings of this study. From a hydrogeological perspective, this structure represents a transboundary karst basin shared between Albania and Greece. The massif contains large reserves of renewable karst waters that are intensively replenished by highly uneven atmospheric precipitation. As in other structures in typical Mediterranean karst areas, the TDN high-elevation structure exhibits steep hydraulic gradients in the karst water, which are a precondition for rapid discharge through large springs. Karst waters mainly flow toward the Këlcyrë Gorge, their main drainage area; large karst springs emerge at the level of the Vjosa River and are characterized by highly unstable regimes. From a qualitative perspective, the chemical composition of the karst waters of the studied massif is determined by the presence of evaporitic deposits located beneath carbonate deposits that form the massif. However, the lack of systematic measurements of spring flows, the limited number of chemical and isotopic analyses, and the lack of data in the Greek territory represent serious limitations for this study.

The calculated infiltration coefficients for precipitation in the TDN karst massif range from 71% to 77%, and the karst underground flow module ranges from 39.7 to 47.5 L/s/km². The total renewable karst water resources of this massif within Albanian territory are estimated at about 12 m³/s. Some unknown karst water resources in the southern part of the massif drain into Greek territory. The groundwater from the springs is highly mineralized, primarily due to elevated sulfate concentrations, and is generally unsuitable for drinking. The groundwater's chemical composition shows distinct seasonal variations, particularly in the larger springs; the EC

and TDS range from 630 to 1200 $\mu\text{S}/\text{cm}$ and 370 to 800 mg/L , respectively. The key processes governing the hydrogeochemistry of karst water in the TDN massif are water-rock interactions and the mixing of groundwater of different origins. The first involves carbonate dissolution by CO_2 -enriched infiltrating water, and the second is the mixing of fresh karst water with sulfate-rich waters from evaporitic basement formations of the Ionian Zone. The increased variability in discharge and hydrogeochemical changes throughout the hydrological year generally indicate greater karstification, as observed in other karst massifs in Albania.

This study cannot be considered complete, as many phenomena remain poorly understood or scientifically unexplained. These include the formation and calculation of karst water reserves, their regime, and the development of their chemical properties.

To organize and explain these phenomena, detailed studies should be conducted using modern research methods. These requirements are even more crucial now that the Vjosa River Watershed has been declared a national park, thereby gaining international significance. Additionally, the TDN karst massif is a transboundary water body, which necessitates well-organized collaboration between Albanian and Greek scientific institutions and their involvement in these important joint studies.

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