

Hydrogeology of the Skadar Lake Basin



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Abstract The Skadar Lake basin belongs to the Dinarides mountain chain, which is well-known for classical karst terrains. In this area, we find a variety of karst phenomenon, from minor landforms (karren) to large karst depressions (poljes) on the surface, as well as networks of various karst conduits and caves underground. Also, almost all hydrogeological phenomena are present in this area (typical karst springs, sublacustrine springs, intermittent springs, swallow holes and estavelles). In addition to the inflow of surface water, Skadar Lake is also recharged directly by groundwater. It flows out through numerous sublacustrine springs distributed along the littoral zone. The assessed inflow of groundwater to the lake amounts to around 55 m³/s (17% of the total water budget). If we take the mean specific yield as a comparison parameter, the Skadar Lake basin represents one of the richest basins of fresh water in the world (54 l/s/km²). However, because of the karst regime of flow characterized by large fluctuations, in summer numerous karst springs dry up, and the inflow from rivers decreases significantly. At this time of year, the importance of the lake is particularly evident, because it still retains a considerable amount of fresh water. Special attention should be paid to the protection of this water as it represents one of the most valuable natural resources in the region.

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1 Introduction

The Skadar Lake basin represents a typical karst terrain with very interesting hydrogeology. There are cases where one stream sinks into the ground and appears again on the surface several times along its course. Some sinking waters never see the light of day again, but flow out only from the lake floor in the form of cold sublacustrine springs, which are precious for the aquatic biota.

The karst terrains of the Skadar Lake basin belong to the Dinaric system (Dinarides), more precisely to its south-eastern part. The whole basin covers 5,631 km², of which 81% belongs to Montenegro and the rest to the Albania [1] (Fig. 1). The largest amount of water comes to the lake by the Morača River. The lake water flows out by the Bojana River which connects the Skadar Lake and the Adriatic Sea.

This chapter gives an overview of the geology, geomorphology, tectonics and hydrogeology of the Skadar Lake basin, with special emphasis on the sublacustrine springs which recharge the lake with a significant amount of groundwater.

2 Geology

The geological characteristics of this area have been researched by many authors since the end of the nineteenth century [2–12].

2.1 Geomorphology

The Skadar Lake basin represents the classic karst of the Dinarides (Fig. 2) where almost all karst landforms are developed, but the following are particularly widespread: karren fields, sinkholes (dolines), uvalas, poljes and caves.

According to Radulović [13], there are three regional geomorphological units in the Skadar Lake basin, i.e. two karst plateaus and one system of karst depressions between them (Figs. 1 and 3).

Karst plateaus represent the highland with an average altitude of around 1,000 m asl. Some mountain peaks rising from the plateaus reach over 2,000 m asl (Vojnik, Žurim and Žijovo mountains). The plateaus are elongated along two regional anticlines (Fig. 1). There are numerous surface and subsurface karst landforms in these areas. Dolines are often densely arranged in the form of *polygonal karst*. There are two karst poljes, Nikšić and Cetinje, with fully developed hydrography (springs are located along the northern and western edges of the poljes and ponors along the southern and eastern edges). There is a well-developed system of caves in the area from Lovćen Mountain to Skadar Lake, consisting of three main caves: Cetinjska, Lipska and Obodska caves [14]. The deepest

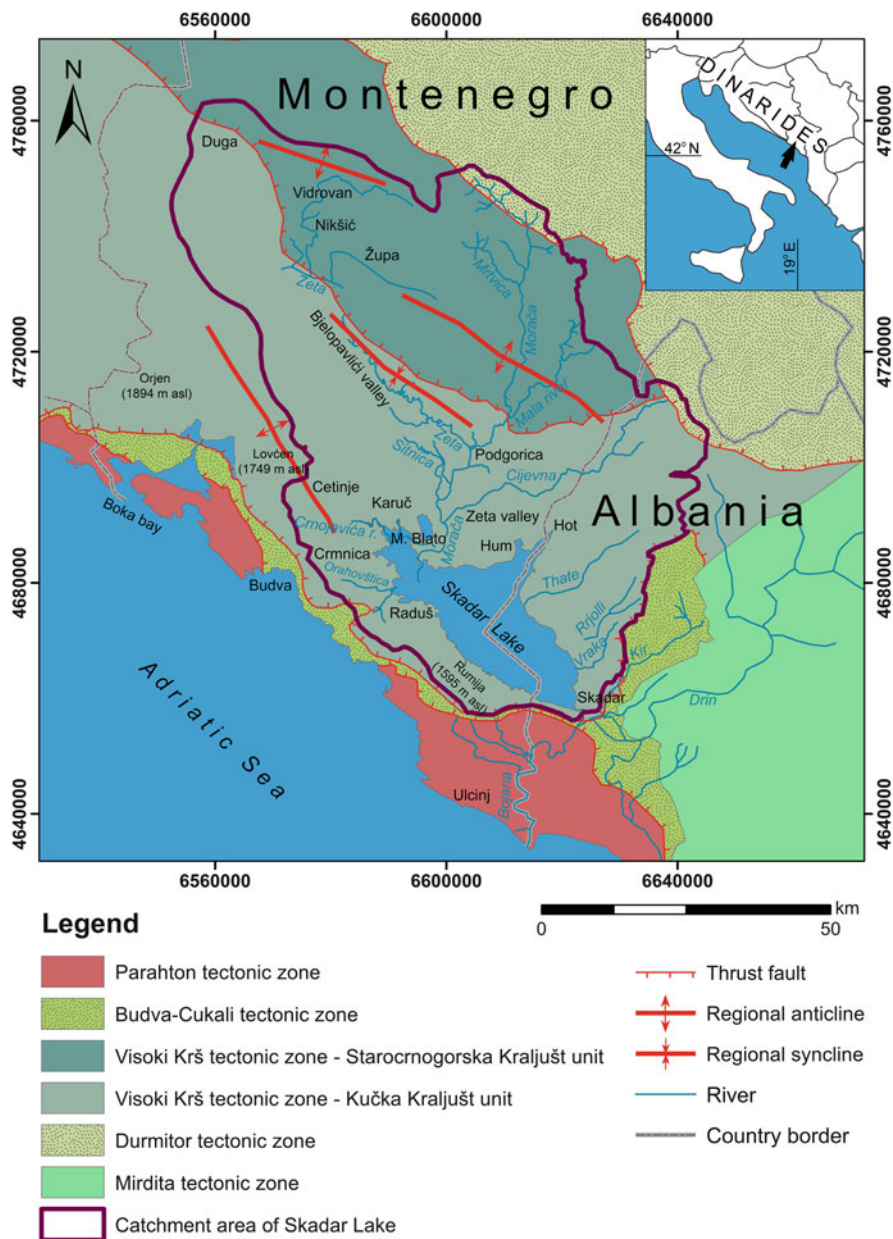


Fig. 1 Position of the Skadar Lake catchment area on the regional tectonic map [1]. Environmental Earth Sciences, 74, 2015, 71–82, Radulović et al., Hydrogeology of the Skadar Lake basin (South-east Dinarides) with an assessment of considerable subterranean inflow, Fig. 1, Copyright 2015. With permission of Springer



Fig. 2 Typical karst terrains of the Skadar Lake basin (photo by Milan Radulović)

cave of the Skadar Lake basin is the Iron Cave (1,162 m deep) located on Maganik Mountain [15]. The north-eastern plateau is cut by the deep canyons of the Morača River, Mrtvica River, Mala Rijeka River and Cijevna River, which represent the discharge zone in this part of the Skadar Lake basin (Figs. 1 and 3).

The system of karst depressions, consisting of Nikšić, Bjelopavlići, Zeta and Skadar Valley, is elongated along the regional syncline (Fig. 1). The altitudes of the valleys generally decrease from north to south, so the southernmost part represents a cryptodepression. This lowest part is flooded by lake water. The lake floor in the south-western part is around 2 m below sea level, and at the locations of the sublacustrine springs, it reaches several tens of metres lower (with an average depth of 72.5 m).

2.2 *Geology and Tectonics*

Karstified carbonate rocks (limestone and dolomite) have dominant distribution in the Skadar Lake basin. The flysch (claystone, marlstone, sandstone) has just a limited distribution in the northern part of the basin, but due to the low hydraulic conductivity of the flysch, it has a very important hydrological role. In contrast to the permeable karst areas, which are generally characterized by the absence of surface water, there are many streams in the flysch terrains.

Valleys and karst depressions are mainly covered by fluvioglacial and lacustrine sediments, the thickness of which ranges up to 100 m.

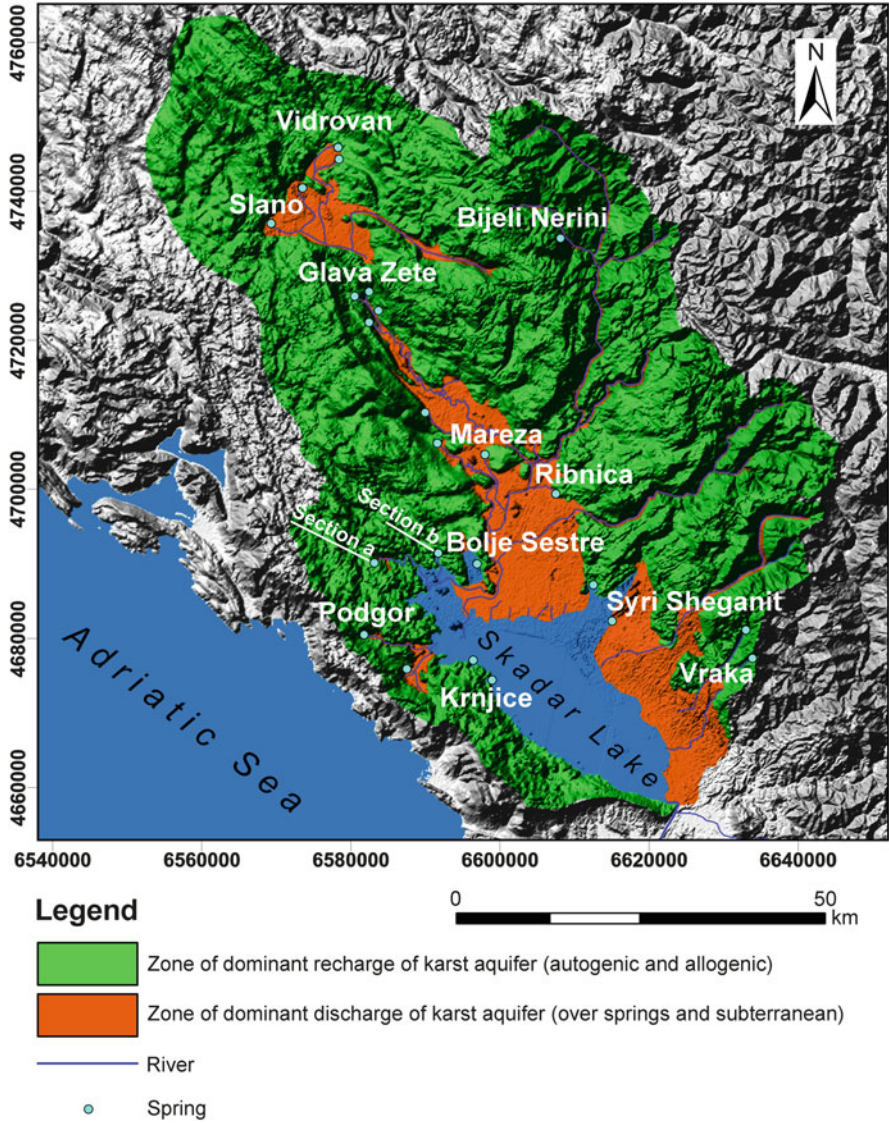


Fig. 3 Map of recharge and discharge areas of the karst aquifer in the Skadar Lake catchment area [1]. Environmental Earth Sciences, 74, 2015, 71–82, Radulović et al., Hydrogeology of the Skadar Lake basin (Southeast Dinarides) with an assessment of considerable subterranean inflow, Fig. 2, Copyright 2015. With permission of Springer

According to the authors of the Geological Map of Montenegro 1:200,000 [12], there are four tectonic zones in the wider area of the Skadar Lake basin (Fig. 1):

- *Paraautohton* (Adriatic-Ionian)
- *Budva-Cukali*
- *Visoki Krš*
- *Durmitor*

The Skadar Lake basin is mainly distributed within the Visoki Krš tectonic zone. Two tectonic units are distinguished in this zone: *Starocrnogorska Kraljušt* and *Kučka Kraljušt*. These two units are separated by a system of reverse faults.

The *Starocrnogorska Kraljušt* unit is mostly represented by limestone and dolomite, but along its northern boundary, a narrow flysch zone is present. It is distributed from the Budva-Cukali zone to the northern edge of the Nikšić, Bjelopavlići, Zeta and Skadar depressions. This unit contains one regional anticline and one regional syncline (Fig. 1) with Dinaric orientation (NW-SE).

The *Kučka Kraljušt* unit consists of carbonate rocks and flysch sediments. There is one regional anticline elongated along this tectonic unit from which high mountains rise, such as Golija, Vojnik, Žurim, Lola, Maganik, Prekornica, Vjeternik and Žijovo.

According to dating represented on the Geological Map of Montenegro 1:200,000 [12], the rocks are mainly from Mesozoic (limestone and dolomite), Paleogene (flysch sediments) and Quaternary (gravel, sand, conglomerate, debris and clay).

2.3 *Genesis of Skadar Lake and the Surrounding Area*

Geologists and geographers have long been drawn to Skadar Lake, lying as it does in the lowest part of one of the largest karst depressions in the Dinarides. Numerous explanations regarding the genesis of Skadar Lake have been put forward, but to date, the issue has not been solved.

One world-famous geomorphologist (recognized as the father of karstology), Jovan Cvijić [5], believed that the Zeta-Skadar depression represents a polje (large karst depression). According to him, this polje is created by merging dolines and uvalas which were previously formed by the dissolving action of rainwater.

Bešić [16] did not believe that the Zeta-Skadar depression represents a polje. He stated (1983) that the area was initially lowered by tectonics, followed by strong glacial and fluvial erosion. According to him, that erosion shaped the sides of the depression. Today, the depression is filled by thick glacial-fluvial, alluvial and lacustrine deposits.

Radulović [13] stated: “At the end of the Pliocene, finally the sea withdrew from the area that today belongs to the Skadar Lake basin. . . During the Quaternary the north-eastern part of the Zeta-Skadar depression was uplifted, and at the same time the south-western and western part was lowered”. Today, that lower part of the Zeta-Skadar depression is filled by the fresh water of Skadar Lake.

Miladinović [17] stated that Skadar Lake represents the relict of a sea from the Pliocene epoch.

A new view on karst genesis [18] allows the possibility that the karst depressions were formed under the sea. According to the same author [18], the Zeta-Skadar depression represents a large karst polje, the genesis of which was just initiated by tectonics. The depression was formed at great depths beneath sea level (below the lysocline), where the dissolution of carbonates was dramatically increased. Thereafter, rapid seawater regression and the action of strong fluvial and glacial erosion shaped the sides of the depression and broke a south-eastern crest of the polje, which had divided this area from the sea. The current geomorphological and hydrological characteristics of the area have influenced fresh water accumulation in the south-western part of the depression, i.e. the formation of Skadar Lake.

In order to clarify this issue, extensive future geological and geomorphological research should be carried out.

3 Hydrogeology

The hydrogeology of the Skadar Lake basin has been studied by many researchers, especially after World War II [1, 13, 19–31].

3.1 *Hydrogeological Characteristics of the Basin*

Since carbonate rocks (limestone and dolomite) have a dominant distribution on the Skadar Lake basin, most groundwater resources are accumulated within the *karst aquifer*. Also, the shallow *intergranular aquifer* of the Zeta and Skadar Valleys plays a very important role, especially during the dry season when karst spring discharge decreases significantly. *Impervious rocks* have limited distribution on the Skadar Lake basin. Mostly they are represented by impervious flysch sediments, volcano-sedimentary formations and lacustrine sediments.

3.1.1 Karst Aquifer

Permeable limestone and dolomite occupy around 73% of the basin surface. They are also distributed below the other rocks, i.e. below the impermeable flysch and clastic sediments of the karst depressions.

The karst aquifer mostly receives water from precipitation reaching permeable karst plateaus (Fig. 3). The mean annual precipitation rate for the recharge zone is relatively high (around 2,500 mm/year), but in spite of that, there is no surface water on this area. Almost all rainwater infiltrates rapidly into the permeable ground. Infiltrated water percolates vertically down until it reaches the water table. The average depth to the saturated zone of the karst aquifer from which groundwater can be abstracted is around 800 m, so the settlements distributed along the karst

plateau remain “thirsty” throughout the year. Drilling wells and pumping groundwater from such a depth are not sustainable.

From the recharge zones, the groundwater flows to karst depressions and canyons mainly through karst conduits and caves. Subsurface karst landforms are generally developed along the faults. Also, the orientation of the main folds (synclines and anticlines) has an influence on the direction of groundwater flow.

The karst aquifer has high hydraulic conductivity, especially along karstified zones. According to the results of tracer tests performed in the Skadar Lake basin, the average tracer velocity amounts to 3.41 cm/s (3 km/day). Uranine (fluorescein sodium salt) was used as the tracer. The proven hydraulic connections between shallow holes and springs [13, 20, 28, 29] are presented in Table 1 and Fig. 4. The results of the tests contributed to the delineating of the groundwater divides of Skadar Lake basin.

The groundwater of the karst aquifer flows out through numerous springs, mostly distributed along the edges of karst depressions and canyons (Fig. 3). Some springs appear at contact points between permeable carbonate rocks and impermeable flysch sediments. There are around 200 known karst springs within the Skadar Lake basin. The following springs have the highest yields (from southeast to the northwest; Fig. 3): Krnjice Spring, Raduš Spring, Velji Spring, Podgor Spring, Vitoja Spring, Crnojevića Spring (Fig. 5a), Karuč Spring (Fig. 5b), Bolje Sestre Spring, Ribnica Spring, Mareza Spring, Vučji Studenci Spring, Bijeli Nerini Spring, Oraš Spring, Milojevći Spring, Dobropolje Spring, Glava Zete Spring, Obošnica Spring, Slano Spring, Poklonci Spring, Rastovac Spring, Vidrovan Spring (located on Montenegrin territory), Vraka Spring, Rrjolti Spring and Syri i Sheganit Spring (located on Albanian territory) [1].

The karst aquifer also discharges directly to surface flows such as the Morača River, Zeta River, Cijevna River, Mala Rijeka River and Sitnica River. At the beginning of the dry season, the groundwater level of the karst aquifer descends below the beds of the rivers, so that the rivers then start to sink and feed the karst aquifer. Due to intensive sinking, the smaller rivers (the Cijevna, Mala Rijeka and Sitnica) dry up during the summer.

Besides the typical karst springs distributed within the discharge zone (Fig. 3), there are also other hydrogeological phenomena such as estavelles, intermittent springs and sublacustrine springs (*vrulja* or *oko*). Estavelles are hydrogeological phenomena with a dual role. In the rainy season, they function as springs and during the dry season as swallow holes (ponors). There are many sublacustrine springs distributed along the Skadar Lake coast through which the karst aquifer discharges below lake level. They are represented by underwater dolines (depressions) whose bottoms descend deep below the general lake floor. The deepest such doline is located in Raduš Bay. Its bottom descends as low as 66 m below sea level, i.e. 72.5 m below the average lake level. The largest sublacustrine springs are described in the next section (see Sect. 3.2).

Also, groundwater from the karst aquifer partly feeds the intergranular aquifer of Zeta-Skadar Valley. This transfer of groundwater between aquifers is very useful because the intergranular aquifer can store water longer than the karst aquifer. Therefore, a significant

Table 1 Hydraulic connections between swallow holes and springs confirmed by artificial tracer tests [13, 20, 22–24, 28, 29]

Tracer injection point	Date of tracer injection	Tracer appearance point	Date of tracer appearance	Difference in elevation (m)	Distance (m)	Tracer velocity (cm/s)
Swallow hole in Ljevačko (Sozina)	16.12.1971	Pod Kapom Spring (Sozina)	02.12.1971	600	3,000	0.82
Swallow hole in Bijelo Polje	23.09.1969	Modro Spring, Velji Spring, Okrugli Spring	06.11.1969	592.5	4,000	0.11
Swallow hole in Obzovica	07.01.1970	Podgor Spring	08.01.1970	657	6,965	13.82
Swallow hole in Seoštik (Seoca)	24.01.1969	Podgor Spring	26.11.1969	632	7,000	5.21
Swallow hole in Ugnji	16.09.1969	Cmojevića Spring	19.09.1969	640	6,990	2.75
Swallow hole in Cetinje	15.03.1934	Cmojevića Spring	17.03.1934	598	7,000	4.05
Swallow hole in Cetinje	23.10.1935	Cmojevića Spring	25.10.1935	598	7,000	4.74
Borehole C-4 (Cetinje)	09.07.1973	Cmojevića Spring	28.07.1973	614.98	8,550	0.52
Borehole C-2 (Cetinje)	15.03.1970	Cmojevića Spring	29.06.1970	622.5	8,850	0.25
Swallow hole in Cetinje	02.10.1987	Cmojevića Spring	05.10.1987	598	7,000	5.50
Swallow hole in Cetinje	18.11.1987	Cmojevića Spring	21.11.1987	598	7,000	4.50
Swallow hole in Cetinje	20.01.1988	Cmojevića Spring	23.01.1988	598	7,000	4.20
Swallow hole below Grabova Glavica (Šitart)	02.12.1977	Volač Spring (Karuč Bay)	05.12.1977	510	12,875	5.40
Swallow hole Lainje (Župa Dobska)	10.12.1977	Djurov Spring, Karuč Spring, Volač Spring (Karuč Bay)	29.12.1997	300	6,200	0.65–0.67
Swallow hole Brežine (Lješanska Nahija)	18.12.1978	Kaluderov Spring (Malo Blato)	20.12.1978	230	3,950	2.30
Borehole IBG-2 (Grbavci)	07.03.2007	Čkanjak Spring (Malo Blato)	08.03.2007	5.5	1,522	2.50
Cijevna River (Dinoši)	16.09.1965	Mileš Spring, Krvenica Spring, Vitoja Spring	17.09.1965–21.09.1965	33–80	2,755–8,500	2.05–3.07
Cijevna River (Dinoši)	06.11.1965	Ribnica Spring	13.11.1965	37	5,125	0.87
Swallow hole in Ostros (Rumija)	–	Van I Šitart Spring	–	215	1,818	0.42

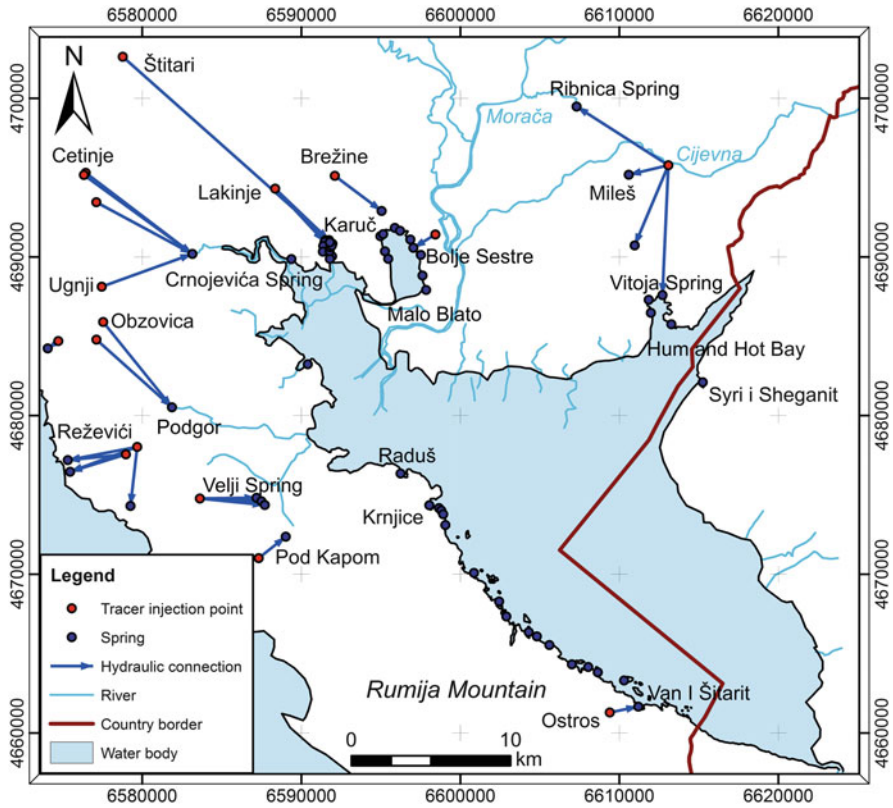


Fig. 4 Map of hydraulic connections between swallow holes and springs confirmed by artificial tracer tests

amount of groundwater is available from the intergranular aquifer, even in the driest period of the year.

The karst springs react rapidly to rainfall impulses. That is manifested by pronounced fluctuations in the water table and discharge. Fluctuations of the water table on the area of karst poljes can amount to as much as 200 m [20, 32]. Such karst aquifer behaviour can be seen clearly from the hydrograph on Fig. 6.

Groundwater from the karst aquifer is of good quality throughout the year, except after extreme rainfall events when turbidity increases. Water has low TDS (generally around 300 mg/l), with a higher concentration of HCO_3^{2-} , Ca^{2+} and Mg^{2+} ions. The pH value of groundwater amounts to 6.95–7.80 [30].

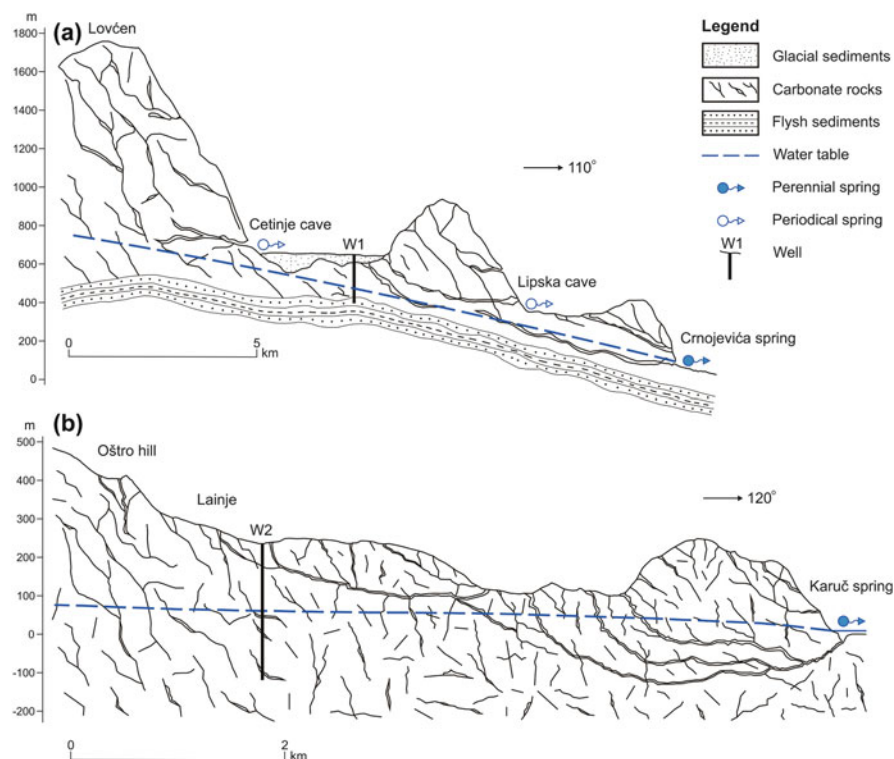


Fig. 5 (a) Hydrogeological section Lovćen-Crnojevića spring, (b) hydrogeological section Oštro hill-Karuč [1]. Environmental Earth Sciences, 74, 2015, 71–82, Radulović et al., Hydrogeology of the Skadar Lake basin (Southeast Dinarides) with an assessment of considerable subterranean inflow, Fig. 3, Copyright 2015. With permission of Springer

3.1.2 Intergranular Aquifer

The main intergranular aquifer is distributed along Zeta Valley. Also, this type of aquifer is presented in Skadar Valley, Crmnica Valley, Cetinje and Nikšić.

The shallow intergranular aquifer of Zeta Valley is represented by alluvial and fluvio-glacial sediments. These sediments consist of gravel, sand and conglomerates. The thickness of the sediments is up to 100 m. They lie over the limestone and dolomite in the northern and central part of the valley and over impermeable claystone and siltstone in the southern part.

Recharge of the intergranular aquifer of Zeta Valley occurs through the infiltration of atmospheric water and surface water, as well as by subterranean inflow from the bottom karst aquifer. The general direction of groundwater flow is north-south. The hydraulic conductivity of the intergranular aquifer is relatively high ($K \approx 0.005$ m/s) except for the southern part, where lacustrine sediments (clay, mud and silt) are present.

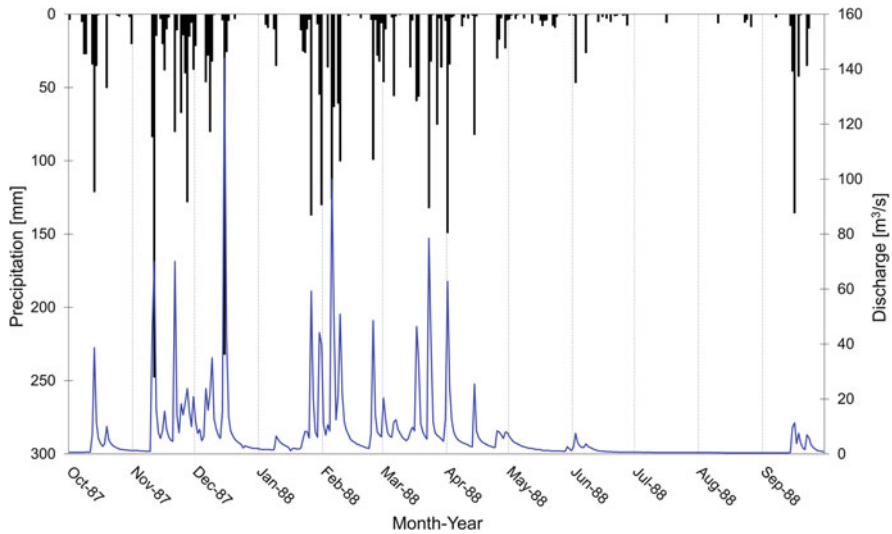


Fig. 6 Hydrograph of Crojevića spring discharge (hydrometric station “Brodska Njiva”) with precipitation bar graph (climatological station “Cetinje”) (after Živaljević [33]) [1]. Environmental Earth Sciences, 74, 2015, 71–82, Radulović et al., Hydrogeology of the Skadar Lake basin (Southeast Dinarides) with an assessment of considerable subterranean inflow, Fig. 4, Copyright 2015. With permission of Springer

The northern littoral belt of Skadar Lake represents the discharge zone of the Zeta Valley intergranular aquifer. In that zone, there are numerous diffuse springs and short streams through which groundwater from the intergranular aquifer flows out. In that zone, the following short streams flow into Skadar Lake: Plavnica, Zetica, Gostiljska River, Svinješ, Pjavnik, Velika Mrka, Mala Mrka and many other nameless streams (Figs. 1 and 4). According to the numerical groundwater flow model (MODFLOW), the outflow of groundwater from the Zeta Valley intergranular aquifer amounts to $11.62 \text{ m}^3/\text{s}$ [1].

Also, artificial discharge of the intergranular aquifer takes place by means of abstraction wells distributed along the valley. The pumped groundwater is used for the water supply, irrigation and industry (Aluminium Plant Podgorica). The drawdown of the water table in the wells is very limited (just a few metres) despite the fact that over 100 l/s is pumped from some wells.

The quality of groundwater is satisfactory in the northern part of Zeta Valley, but it is often disturbed in the area south of Aluminium Plant Podgorica, as well as south of some larger settlements and agricultural areas. The front of pollution spreads south from the polluters, but pollutant concentrations decrease after a few kilometres. Given that a contaminant transport through porous media (affected by dispersion, sorption, biodegradation and dissolution) decreases concentrations, Skadar Lake ultimately receives good-quality water from the intergranular aquifer.

The Skadar Valley intergranular aquifer behaves in a similar way to the Zeta Valley aquifer, but it has a lesser distribution. It consists of gravel and sand. This

intergranular aquifer receives water from precipitation, the bottom karst aquifer and surface water (Thate River, Rrjoli River and Vraka River), and it discharges into Skadar Lake. The groundwater is mostly used for the water supply and irrigation.

3.2 *Sublacustrine Springs of Skadar Lake*

There are numerous sublacustrine springs in Skadar Lake, but most of them are located in the following areas: south-western coast, Karuč Bay, Malo Blato Bay, Hum Bay and Hot Bay (Fig. 4).

3.2.1 **Sublacustrine Springs of the South-Western Coast**

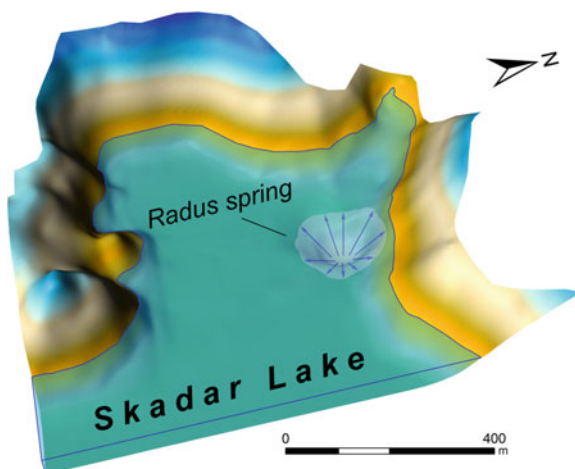
The karst aquifer of the south-western edge of Skadar Lake is discharged by sublacustrine springs distributed along the coast (Fig. 4). There are around twenty known springs, but besides the concentrated outflows of groundwater, there are also zones where diffuse discharge of the karst aquifer occurs. The main sublacustrine springs in this area are Raduš Spring and Krnjice Spring.

Raduš Spring

This is a spring on the south-western coast that first emerges on the line from the north-west to the south-east. It is located in Raduš Bay, where there is a small fishing village. The spring is positioned near the south-western edge of Raduš Bay (Fig. 7). The discharge of groundwater occurs through the bottom of a 70-m-deep underwater doline. The diameter of the funnel-shaped doline is around 130 m. The discharge point is also defined according to tectonics, i.e. according to the fault which transmits groundwater towards the spring (the orientation of this fault is north-south).

At the end of the 1980s, this spring was a potential source for the regional water supply system of the Adriatic coast, and a detailed investigation of the spring area was carried out [34]. The conclusion of the investigations was that the yield of the spring in the driest period of the year ($Q_{\min} = 60$ l/s) could not meet the demands of the water supply system. According to findings, the average yield of Raduš Spring amounts to $1.27 \text{ m}^3/\text{s}$, and the maximum is around $50 \text{ m}^3/\text{s}$. Therefore, the maximum yield is almost a thousand times greater than the minimum yield. This indicates that a well-developed network of karst conduits is present, so that the retention capabilities of the karst aquifer are very low within the catchment area of Raduš Spring. The highly fractured and karstified limestone of the spring background cannot accumulate water for long periods, but almost all of the infiltrated water transmits rapidly to the discharge point. The assessed size of this catchment area is around 25 km^2 [34].

Fig. 7 Morphology of the lake floor in the area of Raduš Bay



The spring water has low TDS, with an increased concentration of hydrocarbonate and calcium ions. According to systematic measurements [34], quality parameters were within threshold limits.

Krnjice Spring

Moving south-east, the next spring to appear after Raduš is Krnjice Spring. It is located in Luke Bay, where there is another fishing village, named Krnjice. This sublacustrine spring is also represented by an underwater doline. The depth of the lake at this location is 24.6 m [13]. Aquifer discharge occurs from the bottom of the doline. Since the catchment area of Krnjice Spring also consists of highly karstified limestone and dolomite, the discharge regime is similar to that at Raduš Spring. After intensive rainfall events, the spring reacts quickly with a high yield, but in the dry season, the discharge decreases significantly. In the immediate backdrop to Krnjice Spring, there is a fault with orientation north-south. The groundwater probably flows along this fault towards the bottom of the underwater doline, where it flows out to the lake.

Other Sublacustrine Springs on the South-Western Coast

Further to the south-east, there are many nameless sublacustrine springs. Their locations are presented on Fig. 4. Many of these springs dry up during the summer. According to a performed tracer test (Table 1), a hydraulic connection between a swallow hole in Ostros and the sublacustrine spring in Van I Šitarit Bay was established. The detected tracer velocity was 0.36 km/day [23, 24].

3.2.2 Sublacustrine Springs of Karuč Bay

Karuč Bay also represents one of the discharge zones where karst aquifer groundwater flows directly out to the lake. There are numerous sublacustrine springs in Karuč Bay (Fig. 4), such as Karuč Spring, Volač Spring, Đurov Spring, Studenac Spring, Radišev Spring, Žabin Spring, Grivo Spring and Bazagurska Spring.

The main discharge point is Karuč Spring. The minimum yield of this spring is around $1 \text{ m}^3/\text{s}$ [25]. At the location of the spring, there is an underwater doline, the bottom of which is around 20 m below lake level. Measured spring water temperature at the discharge point is 11.7°C [25], which is much lower than the temperature of lake water in summer. This temperature anomaly (the zone of colder water) is detected by thermal infrared camera, which is a very useful tool for the detection of sublacustrine springs (Fig. 8).

Right next to Karuč Spring is Volač Spring, which flows out from the cave. The channels of the cave descend deep below spring level (around 50 m lower), so there is an ascending outflow of groundwater to the spring (Fig. 5b).

The size of the Karuč Bay catchment area covers around 116 km^2 [21, 35]. Results of tracer tests represented the main base for the delineation of the groundwater divides in these highly karstified terrains (Fig. 4, Table 1), because surface topography plays no role in water separation. One of the most interesting facts is that sinking water from the Lainje swallow hole flows towards three different springs. Therefore, there is an underground water bifurcation through the branched network of karst channels. Other tracer tests helped in the delimitation of this catchment area, from the catchment areas of the Crnojevića River, Malo Blato Springs and springs along the south-western edge of Bjelopavlići Valley (Fig. 4, Table 1).

When planners ruled out Raduš Spring as the source for the regional water supply system, detailed investigations of Karuč Spring were conducted, but the spring was not selected.

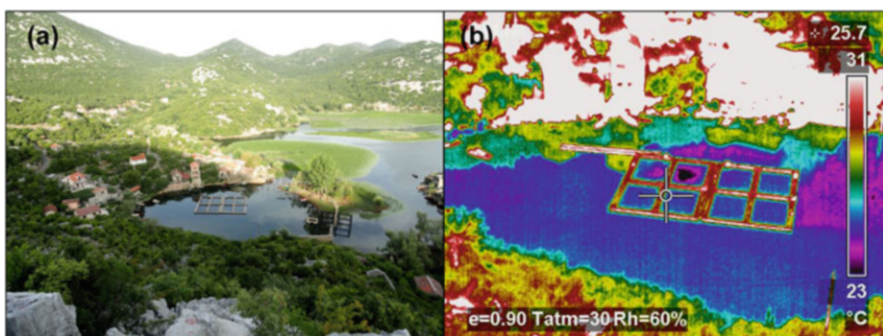


Fig. 8 (a) Photo of Karuč Bay captured in the visible spectrum; (b) photo of Karuč Bay captured in thermal infrared spectrum, from which a temperature anomaly can be seen (purple tones), i.e. the main location of groundwater discharge [1]. Environmental Earth Sciences, 74, 2015, 71–82, Radulović et al., Hydrogeology of the Skadar Lake basin (Southeast Dinarides) with an assessment of considerable subterranean inflow, Fig. 6, Copyright 2015. With permission of Springer

3.2.3 Sublacustrine Springs of Malo Blato Bay

Malo Blato Bay is located at the north-western part of Skadar Lake, between Karuč Bay and Zeta Valley. Water flows into Malo Blato by way of the Sinjačka River and numerous sublacustrine springs (Fig. 4), such as Velja Suica Spring, Mala Suica Spring, Krakala Spring, Bivo Spring, Crni Spring, Bolje Sestre Spring, Brodić Spring, Biot Spring, Bobovine Spring and Krstat Spring. The stream of the Sinjačka River begins with the Kaludjerovo Spring in the northern edge of Malo Blato Bay and flows just 1 km to the lake. Outflow of water from Malo Blato Bay occurs through the Biševina River, which connects this bay to the main body of Skadar Lake. The mean annual discharge of the Biševina River is $11.75 \text{ m}^3/\text{s}$ [22].

The main point of groundwater discharge is the Bolje Sestre Spring. It is located in the eastern part of Malo Blato Bay, at the foot of Kolozub Hill. The groundwater discharges at two points, one at the level of the lake and another at the lake floor a few metres away from the coast (Fig. 9). The depth of the lake at the location of the sublacustrine spring is around 7–8 m [22]. The spring background consists of bedded limestone and dolomite. Groundwater flow direction is predisposed according to faults and bedding planes. The general orientation of faults is southeast-northwest. The bedding planes dip towards the northwest at an angle of 28° [36]. The minimum yield of the Bolje Sestre Spring is around $2 \text{ m}^3/\text{s}$. The temperature of spring water in summer is 14.8°C [37].



Fig. 9 Water source “Bolje Sestre” during construction (photo by Milan Radulović)

When Raduš Spring and then Karuč Spring were rejected as potential water sources for the regional water supply system, detailed hydrogeological investigations were conducted in the area of Bolje Sestre Spring [28, 36, 38–40]. Numerous hydrogeological methods were applied at this area (geophysical investigations, remote sensing, drilling, pumping tests, tracer tests, hydrological and hydrochemical methods), and based on all obtained results, Bolje Sestre Spring was chosen as the best source for the regional water supply system. Nowadays, water from this source is tapped and transported by means of a 150-km-long pipeline to almost every settlement along the Montenegrin part of the Adriatic coast.

In Malo Blato Bay, there are also springs which discharge from the bottom of underwater dolines. Typical of such springs are Kaludjerovo Spring and Biot Spring.

3.2.4 Springs of Hum and Hot Bay

Hum Bay and Hot Bay represent another important zone of groundwater discharge. There are a few karst springs here, such as Ploče Spring, Vitoja Spring, Funija Spring and Syri i Sheganit Spring.

When it goes along Hum Bay towards the Montenegro-Albania border, the *zone of minor springs* first appears at the very beginning of the bay. There are some small springs which discharge at the level of the lake.

The next spring that comes up is *Ploče Spring*, which is located in Sunji Ploč Cove. It is a sublacustrine spring that flows out from a depth of around 6 m.

The main discharge point at Hum Bay is *Vitoja Spring* (Fig. 10) located in the northern part. In fact, it is a discharge zone that consists of two land springs and three sublacustrine springs. The land springs are located just below the limestone slope. They are around 30 m away from each other. At hydrological maximum, these springs are also flooded by lake water. There is another group of sublacustrine springs around 30–50 m away from the terrestrial springs. They flow out from a depth of around 5 m. The temperature of spring water in summertime was 11°C [41]. According to tracer test results [13], there is a connection between the swallow holes of the Cijevna riverbed (near the Trgaj Village) and Vitoja Spring. It was very interesting that tracer injected into the sinking zone of the Cijevna River (at the exit of the limestone canyon) appeared at four different springs: Ribnica Spring, Mileš Spring, Krvenica Spring and Vitoja Spring. So, there is an underground bifurcation of sinking water in four directions (Fig. 4).

At the bend between Hum and Hot Bays, there is one typical sublacustrine spring (*Funija Spring*) that flows out from a depth of 10 m. It is located around 300 m from the lake coast.

Syri i Sheganit is one of the largest springs in the Skadar Lake area. It is located at the south-eastern part of Hot Bay, near Gashaj Village. The minimum yield of the Syri i Sheganit Spring amounts to around 300 l/s, and the maximal yield is around 6.9 m³/s [42]. The mean annual yield is around 1.4 m³/s [31]. Groundwater flows out from the cave, the channels of which have been explored up to a depth of 52 m and up to 160 m in length [43]. This karst spring probably drains the south-western slopes of Prokletije Mountain. The catchment area of the spring covers around 30 km².



Fig. 10 Vitoja Spring (photo by Milan Radulović)

The assessed groundwater inflow to the Montenegrin side of Hum and Hot Bays is $2.5 \text{ m}^3/\text{s}$ [44]. The total inflow into the bay (Montenegrin and Albanian sides) is around $4 \text{ m}^3/\text{s}$.

3.2.5 Other Springs

Besides the mentioned groups of sublacustrine springs, there are also individual discharge points such as Modro Spring (western coast), Grab Spring and Vranjina Spring (north-western coast) and many other nameless sublacustrine springs.

4 Conclusion

The Skadar Lake basin represents one of the richest basins of fresh water in the world, measured by mean specific yield, which amounts to as much as 54 l/s/km^2 [1]. On this karst area, almost all natural factors (precipitation, land cover, the permeability of rocks, geomorphology) have a favourable effect on such a large outflow of water. However, problems with insufficient quantity of water can be expected in summer, a fact which is characteristic of such karst terrains. The minimum yield from springs might be as much as a thousand times lower than the maximum yield (e.g. Raduš Spring). Some springs with high yields in the rainy period dry up completely in

summer (e.g. Ribnica Spring). With this in mind, the significance of the lake is seen as even greater, because it plays the role of reservoir, where a considerable amount of fresh water is gathered, even in the driest period of the year.

The inflow of groundwater represents a very important constituent of the lake water budget. The assessed groundwater inflow amounts to around 55 m³/s, accounting for 17% of the total lake budget [1].

Bearing in mind the significance of sublacustrine springs at Skadar Lake, additional efforts are needed in order to establish adequate groundwater protection, since it represents one of the most valuable natural resources in the area.

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