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INTRODUCTION

The Serbian part of the Iron Gates (Serb. Đerdap) is located in South East Europe and the northeastern part of Serbia, on the very border with Romania. The Đerdap area extends for about 100 km along the right bank of the Danube River, from the town of Golubac to Karataš near Kladovo. It intersects diverse geologic formations, from Precambrian to contemporary (Fig. 1). The area formally became a national park in 1974.

The primary natural phenomenon in this area is the magnificent Đerdap gorge on the Danube River, comprised of four smaller gorges (Golubačka Klisura, Gospođin Vir, Kazan and Sipska Klisura) and three ravines (Ljupkovska, Donjomilanovačka and Oršavska). They abound in geomorphological features, such as canyons, escarpments, sinkholes, ponors, caves and the like).

Prior to the impoundment of the Danube, there were several powerful karst springs along the right bank, whose water drove watermills on several locations. Today, these springs are submerged in the Đerdap Reservoir and are visible only at extremely low river stages. They function as freshwater vruljas.

GEOLOGIC FRAMEWORK

The geologic framework of the Đerdap area is diverse and extremely complex. It is a product of geologic and tectonic processes from the Precambrian to the present day. From Golubac through to Karataš, Precambrian, Paleozoic and Mesozoic formations have been identified along the right bank of the Danube. They include the Golubac nappe, the Gethicum nappe (Gethicum), the Danubicum parachton (Danubicum), the Gethicum outliers, the Krajina nappes (Krainicum), and the Prebalkanic autochton (Prebalkanicum) (Grubić et al., 1997). On several locations, younger Neogene and contemporary Quaternary sediments overlie older geologic formations.

The Precambrian comprises highly-metamorphic crystalline schists – so called Gethic overthrusts, including amphibolites, migmatites & gneisses, gneiss-granites, and serpentinites (Žujović, 1893; Urošević, 1908; Kalenić et al., 1980; Kalenić et al., 1997).

The Paleozoic formations are represented by green schists and metamorphed sandstones of the Cambrian period and Carboniferous sedimentary rocks (conglomerates, sandstones and claystones), with seams of stone coal (Bogdanović, 1977; Kalenić et al., 1997). The

Mid-Carboniferous featured Hercynian granitic intrusions (granodiorites, granite-monzonites and granites) in the zone between Brnjica and Mt. Miroč, accompanied by veins of mostly aplites and pegmatites (Milovanović, 1953; Vasković and Matović, 1997). The youngest Paleozoic rocks in the Đerdap area are Permian red sandstones, conglomerates and claystones. The Permian also includes intrusions of quartz porphyries, riodacites, basalt and volcanogenic sedimentary rocks (Kalenić et al., 1980).

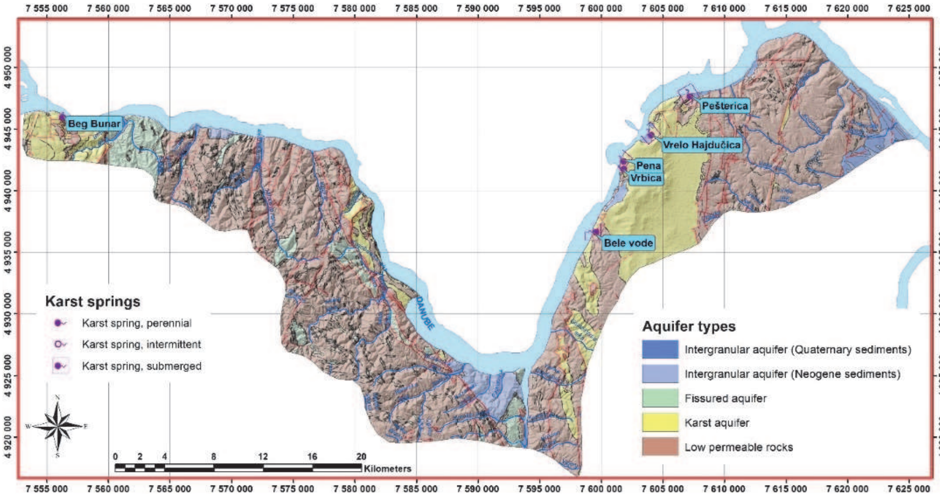

***Fig 1.** Geological and hydrogeological schematic*

The Mesozoic comprises Jurassic and Cretaceous sedimentary formations, with considerably different deposits west and east of the Poreč River.

The Jurassic is represented by three divisions: early, middle and late. The Liassic transgresses and discordantly overlies crystalline schists. It is comprised of quartz sandstones, in part conglomeratic and coarse-grained in the basal series, as well as clayey sandstones and coaly claystones. Parts of the lower reaches contain seams of stone coal in the quartz sandstones. The sedimentary rocks of the Mid-Jurassic (Doggerian) discordantly overlie Late Carboniferous schists, Hercynian granites and Cambrian schists. They are built up of sandstones, claystones and sandy limestones. The spread of the Late Jurassic carbonate rocks is much larger, and they are represented by various types of limestones (Milovanović, 1953; Bogdanović, 1977; Vasić et. al., 1997).

The Cretaceous is well developed in the Đerdap area. The Early Cretaceous is represented by Neocomian limestones transitioning into sandy limestones, sandstones and marls (non-carbonate rocks) in the upward direction. Sinaia beds are a special Neocomian development, of a flysch nature, which gradually give way to sedimentary rocks of the Barremian/Aptian. These sedimentary formations are represented by organogenic limestones, marls, claystones and sandstones. Albian/Cenomanian formations transgress the Barremian/Aptian or Late Jurassic in Mt. Miroč. They are represented by conglomerates, sandstones, claystones and sandy limestones. The biostratigraphy of the

Cenomanian, Turonian and Late Senonian in the eastern wing of the Miroč anticline and the Krajina syncline has been documented (Bogdanović, 1977; Bogdanović et al., 1980; Rabrenović, 1997).

The Tertiary. In addition to Paleogene dacite-andesite intrusions in the Golubac Mountains and small masses of Laramian plutons (granodiorites and diorites in Mt. Miroč, where they intrude into Precambrian schists of the Gethic overthrust), the Tertiary also includes Neogene sediments. The spread of these sediments is within isolated Neogene basins created in the Middle Miocene, within the very Đerdap gorge (near Donji Milanovac and Dobra on the Danube). They are built up of conglomerates with multiple interchanges of clayey sands and clays (Stevanović P, 1977).

The Quaternary. The Quaternary comprises alluvial sediments of small right-bank tributaries of the Danube (the Brnjička, the Dobranska and the Porečka) and small masses of debris beneath limestone escarpments in the Đerdap gorge. Recent sediments of the Danube have largely been flooded by the Đerdap Reservoir.

HYDROGEOLOGICAL CHARACTERISTICS

The complex geologic framework and the presence of different types of rocks and sediments in the Đerdap area have resulted in the formation of fractured, karst, Neogene and alluvial aquifers. In addition, there are zones poor in aquifers (Fig 1).

Fractured aquifers. They generally occur in granitic, dacite-andesitic and serpentinites. Their water-bearing capacity is relatively low.

Aquifer in granodiorites. A fractured aquifer poor in groundwater is formed above the local base levels of erosion. It is drained via springs whose capacity is less than 0.01 l/s. Within the Brnjica pluton, in a place called Brnjica on the Danube, there is only one artesian well that is 70 m deep (Q = 0.8 l/s). The chemical composition of the groundwater drained from shallow parts of the granitic rocks has a low mineral content and is of the HCO_3-Ca type, contrary to the subartesian aquifer where the groundwater is of the HCO_3-Na type.

The granitic rocks have hydrogeologically been investigated in any detail only at the dam of the Đerdap hydroelectric power plant on the Danube. Open fractures were detected while underground galleries were being built, from which groundwater flowed at a rate of 1.0 to 2.0 l/s. The water permeability of the granites near the dam is 5-12 lugeon units (Semiz, 1966).

Karst aquifers. They are formed in carbonate rocks, on several isolated locations, from Golubac (at the entrance to the gorge) to near Đerdap 1 HPP at the exit from the gorge (Golubac Mountains, Gospođin Vir gorge, and Mt. Miroč with the Golubinje, Gradašnica and Dževrinska Greda karst). The carbonate rocks are Mesozoic, represented by Doggerian sandy limestones; Oxfordian-Kimmeridgian limestones with chert and dolomite; massive and banked Tithonian limestones; Valendian-Hauterivian banked, sandy and marly limestones; and Urgonian massive and banked limestones of the Barremian-Aptian age. Despite tectonic damage, karstification is not uniform and depends on the type of carbonate rock. As a result, some areas are rather poor and other rich in surface and subsurface karst features.

Karst aquifer in the Golubac Mountains and the Gospođin Vir gorge. The Golubac mountains (especially their northern parts) are not as karstified as the neighboring areas and, consequently, the groundwater reserves are small (Stevanović Z, 1988, 1977). Very few speleological features in this zone, compared to the Miroč karst, support this finding (Mandić, 2015). There are several gravitational emergences of groundwater associated with the karst aquifer in the Golubac Mountains, which J. Petrović (1968) distinguishes as the "karst hinterland of the Upper Gorge". Downstream from a spring in the Golubac City Fort, several springs exist: Ridan, Stari Majdan (Beg Bunar) and Livadice, of which only Beg Bunar is not captured for local drinking water supply (Stevanović, 1988; 1997). The capacity of these springs varies considerably during the year and the minimum is always less than 5 l/s. The Beg Bunar karst spring is located at the apex of an abandoned quarry, at a distance of about 30 m from the Danube. In dry periods, its discharge capacity drops to less than 1.0 l/s, whereas at high groundwater levels of the karst aquifer in the hinterland its capacity exceeds 300 l/s (Fig. 2).

Fig. 2. *Beg Bunar (minimum, average and maximum discharges)*

Apart from the emergences in the Đerdap gorge, a small part of the karst groundwater is drained into the Brnjička River, upstream from the village of Brnjica. There are several small springs, the largest of which, called Jelenska Stena, is captured and delivers Q = 1.5 l/s. Downstream from the Golubac Mountains, in the Gospođin Vir gorge karst, where the spread of the carbonate rocks is smaller and the content of the sandy component larger, there are several karst springs of low capacity (Q < 0.3 l/s). These springs are located at Sokolovac.

*Karst aquifer of central Miroč***.** This aquifer is situated above the Đerdap Reservoir, in the hinterland of Kazan. The surface area of the exposed karstified rocks is 105.11 km^2 and that of non-karst, which gravitates towards the Miroč aquifer, is 41.04 km^2 (Prohaska et al., 2002). The karst comprises dolines and sinkholes, with no surface runoff for the most part. There are many surface and subsurface morphological features. The most distinct are fluvial relief elements, sinkholes, ponors, and dry and blind valleys (Cvijić, 1921; Milić, 1965; Ćalić, 2015).

Surface water which originates in a part of the terrain built up of impermeable non-carbonate rocks, sinks as it enters the limestone mass, along well-defined ponors and underground conduits, and gravitates towards the local base levels of erosion. Water balancing and hydrometric investigations of the Miroč karst revealed a total average subsurface runoff of Q_{av} = 1.396 m^3/s, of which 1.028 m^3/s is attributed to submerged springs and 0.268 m^3/s to the Blederije Spring (Prohaska et al., 2002).

Groundwater drainage in the Đerdap gorge is governed by the base level of the Danube and the positions of impermeable rock masses that underlie limestones. Following impoundment of the Danube at Đerdap, five large and several small karst springs ended up 15–25 m below the reservoir water level. It should be noted that some of the karst springs (Pena and Trajanova Tabla) had been partly drained below the pre-impoundment water level of the Danube.

Beginning with the most upstream spring of Bele Vode, the downstream springs in the Đerdap gorge include Pena, Hajdučka Vodenica (Hajdučica), Trajanova Tabla and Pešterica. Available discharge data are sparse. The discharge of Bele Vode is estimated at Q=10-2000 l/s*;* of Hajdučka Vodenica Q=20-1000 l/s, and Pešterica Q =20-1500 l/s (Petrović, 1968; Stevanović, 1996; 1997). According to C. Vasov (1974), prior to impoundment of the Danube at Đerdap, Trajanova Tabla Spring emerged from a vertical fracture at a rate of approximately 3.5 l/s, while part of the groundwater was drained below the water level of the Danube.

The Blederija Spring is in fact a cluster of springs comprised of two "cold" springs and one "subthermal" (T = 17.5 ºC) spring of the ascending type. Based on multiyear monitoring, its discharges are: Q_{min} = 17.0 l/s, Q_{max} = 2660.0 l/s, and Q_{av} = 210.0 l/s (Živanović et al., 2016).

The submerged springs can be observed only at low stages of the Đerdap Reservoir (Fig 3).

In the southwestern slopes of Mt. Miroč, there are small aquifers in the catchments of the Gradašnica and Golubinjska rivers. Streams that flow from the non-carbonate bedrock sink and emerge via cave-type springs (springs of the Gradašnica and the Golubinjska). Their minimum yield is less than 1 l/s.

Fig. 3 *Hajdučka Vodenica Spring*

East of central Miroč, there is a karst aquifer called Dževrinske Grede, formed in a narrow belt of Tithonian limestones. The rift extends to the south for about 18 km and its width varies from several meters to a maximum of 700 m. The limestones are squeezed between Proterozoic-Paleozoic schists to the west and Early Cretaceous marly sandstones to the east. They are extensively fractured and karstified, with a large number of karst features (Ćalić, 2008). The karst aquifer called Krečnjačke Grede gravitates towards the Đerdap gorge and is drained via several small springs, the largest of which is located in Matovića Krš and its discharge is 3.0 l/s (Ćalić, 2008)

Neogene aquifers. In the vicinity of the Đerdap gorge, the spread of these aquifers is small (areas surrounding Donji Milanovac and Dobra). They are formed in relatively thin strata and lenses of sands, sandstones and conglomerates. The groundwater level is subartesian and the capacity of a 100-120 m deep wells is relatively low (1.5 to 3.0 l/s). The spread of the aquifers is much greater to the west (Braničevo Neogene Basin) and east of the Đerdap gorge (Dacian Basin).

Alluvial aquifers. These aquifers are found in recent alluvial deposits of the Danube's right tributaries in the Đerdap gorge (the Porečka, the Dobranska and the Brnjička rivers). The sediments are of a dual-layer formation, with clayey-sandy deposits on top and coarse-grained sand and gravel below. The water tables of the alluvial aquifers closer to the Danube are under the influence of the Đerdap 1 HPP reservoir and necessitate protection of the riparian lands (at Donji Milanovac, Dobra, and Golubac) from groundwater. Despite good hydraulic conductivity of the aquifers, the groundwater is underutilized because of considerable pollution from municipal activities (Brnjica and Donji Milanovac) and mining operations (villages along the lower course of the Porečka River) (Dragišić et al., 1997). Far more significant alluvial aquifers are found east of the Đerdap gorge, especially in the first Danube terrace (Komatina and Dragišić, 1997).

Terrains poor in aquifers. A considerable part of the Đerdap area is occupied by terrains built up of rocks with low hydraulic conductivity which classifies them as terrains poor in aquifers. These are primarily the Precambrian highly-metamorphic crystalline rocks (gneisses, gneiss-granites and amphibolites), Paleozoic sandstones and green schists and Early/Middle Jurassic and Early/Late Cretaceous sandstones and clayey-and-marly rocks. These rocks are often extensively fractured, but the fractures are filled with clayey products from the weathering core, which prevent the formation of significant aquifers. Exceptionally, the formation of local aquifers is possible. Such aquifers are drained via weak, generally seasonal springs.

Permeability of crystalline schists. The spread of Precambrian crystalline schists in the Đerdap area is large. They build up parts of the Gethic overthrust. Above the Danube, there is a fractured aquifer poor in groundwater, which is drained via springs. The capacity of these springs is generally less than 0.01 l/s. While galleries were being built on the Đerdap 1 HPP dam site, minor occurrences of groundwater in the form of drops were detected, as well as very rare minor springs in the deeper reaches of the galleries. The rate of groundwater flow to well PS drilled to approximately 100 m below the water level of the Danube is only 2.0 l/min. In most cases, the permeability of the crystalline schists is less than 1 lugeon. A higher permeability has been detected only in several boreholes drilled in amphibolites, where it amounts up to 2 lugeon (Semiz, 1966; Kujundžić et al., 1969, 1966; Bančila et al. 1969).

Based on the chemical composition of the groundwater drained from the aquifers in the crystalline schists above the water level of the Danube, TDS is low and the groundwater type HCO_3-Ca, in places with elevated concentrations of Mg^{2+} and Na^{+} ions. Hydrochemical testing of the groundwater below the water level of the Danube revealed a considerably different chemical composition. In the tectonic zone near the dam, on Crkvište Island, the groundwater is aggressive, of the SO_4-Ca type, with SO_4^{2-} ion concentrations ranging from 1421.0 to 4208.0 mg/l. High sulfate concentrations in the groundwater, occurrence of Fe_2S and accumulation of sulfate minerals in borehole cores were attributed to the oxidation of H_2S gas from a deep fault zone (Semiz, 1966).

Thermal waters. Prior to impoundment and the creation of the Đerdap 1 HPP reservoir, at a place called Dževrin, on the very bank of the Danube, there used to be a subthermal spring where the water temperature was 18 ºC. The capacity of that spring was 0.58 l/s. The composition of the groundwater classified it as belonging to the sodium-chloride type, with a dry residue of 1.25 g/l (Leko et al., 1922). J. Žujović (1983) also mentions this spring, stating that cold sulfur water emerges below Dževrin. The position of the spring leads to the conclusion that the water comes from Precambrian crystalline schists.

There are several subthermal karst springs associated with the above aquifers, which extend beyond the Đerdap area (Dragišić et al., 1988: Dragišić and Ćalić-Ljubojević, 2003).

- Spring in the southern part of the Golubac Mountains, in a place called Krivača (T = 17.5 ºC),
- Blederija Spring 1 on the southeastern fringe of the central Miroč karst (T = 17.5 ºC), and
- The Banja Spring in the central part (T = 17-19 ºC) and the Banjica Spring on the southern fringe of the Dževrinska Greda karst (T = 17-19 ºC).

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