Hydrogeological characteristics of south hills, Ivanšćica Mountain

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ABSTRACT
This article presents results of hydrogeological and hydrogeochemical research conducted at south hills, Ivanšćica Mountain, situated in the northwestern part of the Republic of Croatia. Research was carried out in the summer of 2013, between July and September. Hydrogeological mapping was undertaken on approximately 20 km² (at a scale of 1:25000), with water samples taken from 10 springs. Rocks and deposits were classified into three hydrogeological units with respect to permeability. Two main aquifers were identified – the Triassic carbonate aquifer and the Badenian carbonate aquifer. The overall capacity of 41 registered springs (permanent and periodic) was estimated. According to their basic chemical composition, water from springs belong to Ca-HCO₃ (calcium-hydrogen carbonate), CaMg-HCO₃ (calcium magnesium-hydrogen carbonate) and to MgCa-HCO₃ (magnesium calcium-hydrogen carbonate) types.

1. Introduction

Ivanšćica Mountain is located in the northwestern part of the Republic of Croatia (Main map). It stretches in a west-east direction for ~26 km. The highest peak is located in the central part of the mountain at 1061 m above the sea level (asl). The area is characterised by a moderate continental climate (Zaninović, Gajić-Čapka, & Perčec Tadić, 2008). From 2004 to 2013, the average annual air temperature was 10.9°C while average annual rainfall was 920 mm. The research area was intensively faulted and fractured during the geological past which generated a complex structural setting (Šimunić, 1992; Šimunić & Hečinović, 1979; Šimunić, Pićija, Šimunić, Šikić, & Milanović, 1976; Šimunić, Šimunić, & Milanović, 1979). The northern slopes of the mountain are very steep reflecting rapid uplift along the faults. The southern slopes are less inclined with many hills (average altitude of hill peaks is 600 m asl). Ivanšćica Mountain is made of Mesozoic rocks and younger Neogene deposits. Carbonates of Middle and Upper Triassic and Badenian lithoamnium limestone are, in hydrogeological terms, defined as mountainous aquifers of the northern part of the Republic of Croatia (Dragičević, Blašković, Mayer, & Tomljenović, 1998). In order to see whether the study area contains significant groundwater reserves, the hydrogeological and hydrogeochemical investigations were made in the summer of 2013. The objective of hydrogeological investigations was to produce a hydrogeological map at a scale of 1:25,000 and to estimate the capacity of springs through water balance. The objective of the hydrogeochemical investigations was to define the groundwater origin.

2. Site conditions and methods

2.1. Map design

The hydrogeological map was produced on the basis of existing geological data and field hydrogeological mapping of approximately 20 km². The research area is composed of Triassic, Jurassic, Cretaceous, Paleogene and Neogene (Oligocene–Miocene and Miocene) rocks and deposits.

2.2. Geological settings

The Middle and Upper Triassic (T₂+t₃) deposits appear exclusively as carbonates and overlie the Lower Triassic clastic deposit complex (sandstones and siltstones). They are made from stromatolite dolomites, intraclastic dolomites, medium-grained dolomites, dolomite breccia and fine-grained limestones. Stromatolite dolomites mostly consist of a 90–97% of dolomite component. Intraclastic dolomites are made by the destruction and re-sedimentation of algae limestone sediments and subsequent dolomitisation. Medium-grained dolomites are the most common carbonates in the research area. Separation of the Middle and Upper Triassic deposits in this area is not possible due to continuous sedimentation, field coverage (i.e. lack of outcrops), folded and fractured rocks and most probably the lack of fossils due to the dolomitisation process (Šimunić, 1992). The Upper Triassic (T₃) deposits make carbonate reefs. They usually appear in the form of massive or layered, grey coloured fine-grained carbonates. These deposits are often intensively tectonised and transformed into...
tectonic breccias. They mark the major fault zones. Šimunić (1992) assumed that their thickness is about 400 m. In this area Jurassic deposits are represented by shallow-water fine-grained Lower Jurassic limestone (J). They rarely appear at the surface, except in the Mržljak area where their thickness is just a few meters (Šimunić, 1992).

Jurassic-Cretaceous (J, K) deposits appear on the surface in the western part of the research area. Prior to the deposition of these sediments an emersion event was noted during which older sediments were eroded. This is the reason why the border to the Triassic layers is erosional and discordant. They are made from thin, yellow and light grey laminated limestone. Some limestone layers are recrystallised or silicified and often alternate with radiolarian shale and cherts. Sandstones appear in the upper parts and present transition layers to the Cretaceous volcanogenic–sedimentary deposits (K1,2). The total thickness is usually between 10 and 25 m with the maximum of 50 m (Šimunić, 1992). The Cretaceous volcanogenic–sedimentary complex is characterised by a large number of lithological members, which can be seen in frequent and irregular changes of sandstones, shales, marl, chert, limestone, silicified limestone, tuffs and diabase. The most represented deposits are grey to grey-green coloured sandstones which are classified as greywacke. Lower Cretaceous basic eruptive rocks (ββ) are related to the volcano-sedimentary complex (Šimunić, Pikija, & Hečimović, 1983). Cenozoic sediments surround the Mesozoic core of the Ivanščica Mountain. These are clastic sediments which were deposited discordantly on the older surface at the turn of the Oligocene to Lower Miocene. They were created as a result of intense erosion of the uplifted relief. The base part OligoMiocene clastites are represented by coarse-grained breccias and conglomerates. They are followed by fine- to medium-grained clastic sediments, clays, silts, sands and marls with sporadic occurrences of brown coal. These sediments are primarily transgressive on the older rocks. Subsequently, due to tectonic movements, they are in tectonic contact with older deposits. Badenian deposits (M1) cover large areas of the southern hills of the investigated area. The base part of the deposits is built from breccias and conglomerates of basement rocks on which Badenian transgression took place, after which sedimentation of the most common organogenic, lithothamnium limestone began. The dominant facies is a massive, yellow-coloured, biogenic limestone with algae, foraminifera and molluscs. Sandstones often alternate with this kind of limestone. In the upper part of the Badenian sequence, marls and sandstones are dominant. Sarmatian deposits (M3) continuously and concordantly follow on the Badenian sediments. They occur along the southern edge, in the central and eastern part of the study area. They are mostly made of the thin laminated and layered limestone, sandy limestone, and calcareous and bituminous marls. Pannonian deposits (M6) are located in the southeastern part of the study area. They are continuously deposited on Sarmatian sediments. Šimunić (1992) divided them into two groups based on the lithological composition and fossil content. The Lower part belongs to white marly limestone and limy clay known as Croatica deposits, while grey-yellow thick-layered marls known as Banatica deposits represent the uppermost brackish sediments. Pontian (M7) deposits occupy a small area in the far southeastern part of the study area. During the Pontian, sedimentation continued in a caspi-brackish environment. These are predominantly marls, divided by fossil content into Lower Pontian Abichi deposits and Upper Pontian Rhomboidea deposits (Šimunić, Pikija, Hečimović, & Šimunić, 1981).

2.3. Hydrogeological settings

From a hydrogeological perspective, the Middle and Upper Triassic (T2,3) deposits are permeable. During history they were subject to a series of intense tectonic activities which caused the creation of secondary, fracture porosity. Rocks with this type of porosity allow the fast infiltration of surface water into deeper parts of the carbonate massif and consequently the formation of aquifers with significant water supply potential, something also characteristic of the Upper Triassic (T3) deposits. Although, fractured, Jurassic (J) deposits belong to a permeable type of rocks, however they are not significant aquifers because of their extremely local character and shallow thickness. Jurassic-Cretaceous (J, K) deposits are also permeable, but only appear in the western part of the study area. Cretaceous volcanogenic–sedimentary deposits (K1,2) are impermeable and they present a hydrogeological barrier for groundwater flow. Cretaceous basic eruptive rocks (ββ) and Oligocene–Miocene (OI, M) sediments are impermeable. In hydrogeological terms, Badenian deposits (M1) can have low and high permeability. In their coarse clastic and carbonate development, they form a permeable environment that enables the infiltration of surface water and the formation of aquifers in contrast to the Badenian marls, which have low permeability. Sarmatian (M3), Pannonian (M6) and Pontian (M7) deposits are classified as low permeability deposits. Table 1 presents the spatial distribution of hydrogeological units at the surface of the research area.

2.4. Hydrological settings

The main characteristic of the southern slopes is lack of permanent surface flows over an altitude of 400 m asl, the occurrence of periodical springs at an altitude between 400 and 500 m asl and the occurrence of permanent springs (and permanent surface flows) at lower altitudes. There are three meteorological stations
located near the study area (Bednja, Krapina and Novi Marof). Figure 1 presents average monthly air temperature while average annual temperature in the 2004–2013 period was 10.9°C. The mean annual rainfall in the 2004–2013 period varied from 592 to 1264 mm with an average of about 920 mm (Figure 2). The first step in determining the quantity of potential available water is to estimate annual evapotranspiration, expressed in mm. The annual evapotranspiration is calculated using the Turc (1954) formula and is 532 mm. The difference between precipitation and evapotranspiration is the sum of the surface runoff and effective infiltration. Given the characteristic of rocks at the south hills of Ivanščica Mountain, and consequently the lack of surface runoff (except during extremely heavy rainfall), the difference can be equated to the effective infiltration with an average precipitation of 920 mm, evapotranspiration of 532 mm and effective infiltration of 388 mm over an area of 8,977,514 m² (surface area of Triassic and Badenian aquifers), the volume of infiltrated water is about 3,483,275 m³ (Main map). We can therefore expect the total exploitation amount of groundwater to be about 110 l/s (Bačani, 2014).

### 2.5. Hydrogeochemical settings

From July to September 2013, 41 springs were recorded. Individual capacities of recorded springs were mainly lower than 1 l/s, except for I-38 which was about 5 l/s (Bačani et al., 2013). In situ measurements of water temperature, pH, oxygen content, electrical conductivity, turbidity and total dissolved solids were taken at 10 springs. In the spring water samples, concentrations of hydrogen-carbonates, nitrates, fluorides, sulphates, calcium, potassium, sodium, magnesium, lead, zinc, iron and manganese were measured. The results of the physical and chemical analysis are shown in Table 2.

According to the results of basic chemical composition of water plotted on the Piper diagram (Main map), springs I-14, I-23, I-26, I-34a, I-34e and I-36 belong to Ca-HCO₃ (calcium-hydrogen carbonate) type of water, I-8 and I-10 to CaMg-HCO₃ (calcium magnesium-hydrogen carbonate) type of water, and I-2 and I-38 to MgCa-HCO₃ (magnesium calcium-hydrogen carbonate) type of water (Bačani, 2014). This type of water and hydrogeochemical facies is the result of dissolution of carbonates. Dissolution of dolomite and limestone is represented in water from springs I-2, I-8, I-10 and I-38 (Figure 3).

Dissolution of dolomite dominates in springs I-2 and I-38. Spring I-2 is located at the contact of very permeable Triassic and Cretaceous impermeable layers which indicates that water originates from the Triassic aquifer. The dominance of magnesium in spring I-38 does not match the chemical composition of the presumed aquifer in its hinterland (Badenian limestone). The temperature (18.1°C) of this spring suggests that the water is a mixture of the deeper Triassic and Badenian aquifer.

### 3. Discussion and conclusions

Based on the hydrogeological characteristics and hydrogeological features, three categories of rocks were identified (Main map):
high permeability rocks of Middle and Upper Triassic (T2+3), Upper Triassic (T3), Jurassic (J), Jurassic-Cretaceous (J, K) and Badenian (M2);

• low permeability rocks of Badenian (M4), Sarmatian (M5), Pannonian (M6) and Pontian (M7);

• impermeable rocks of the Cretaceous volcano-sedimentary complex (K1,2), basic eruptive rocks (ββ) and OligoMiocene (Ol, M).

Due to the surface appearance and spatial distribution, two main aquifers can be identified: a Triassic dolomitic-limestone aquifer which occupies 33.8% of the total study area and a Badenian carbonates aquifer, which occupies 7.3% of the total study area. Beneath the Triassic carbonate aquifer there is the Lower Triassic clastic deposit complex which, in hydrogeological terms, is impermeable or with low permeability. Transgressive Cretaceous volcaniclastic or Neogene sediments overlie the Triassic aquifer in the research area. In places where Badenian carbonates overlie the Triassic carbonates, they form a unique aquifer. The Badenian carbonate aquifer overlies transgressively and is discordant on older stratigraphic members. In hydrogeological sense this is extremely convenient for groundwater accumulation, especially in places where they overlie on the Triassic aquifer. Above this aquifer, there are mostly fine-grained marls and sandstones of Badenian age or marl–clay–sand thinly layered sediments of Sarmatian age which have low permeability. The water balance and hydrogeochemical investigations resulted in the definition of the total exploitation amount of groundwater (110 l/s) and double groundwater origin, that is, the hydraulic connection of the Triassic and Badenian aquifer.

Software

The hydrogeological map was originally constructed using ESRI ArcGIS 10. The final map was compiled in ArcMap 10.1.

Disclosure statement

No potential conflict of interest was reported by the authors.

Table 2. The physical and chemical parameters of spring water.

| Parameter          | Unit | I-2 | I-8 | I-10 | I-14 | I-23 | I-26 | I-34a | I-34e | I-36 | I-38 |
|--------------------|------|-----|-----|------|------|------|------|------|------|------|------|
| Temperature        | °C   | 10.4| 12.7| 12.9 | 13.3 | 10.8 | 10.9 | 10.5 | 10.3 | 10.5 | 18.1 |
| pH                 |      | 7.43| 7.03| 7.11 | 7.32 | 7.93 | 7.44 | 7.59 | 7.46 | 7.21 | 7.42 |
| Dissolved oxygen   | mg/l | 6.84| 3.55| 4.41 | 6.28 | 7.93 | 7.41 | 6.92 | 7.61 | 7.19 | 5.34 |
| Electrical conductivity | µS/cm | 516 | 605 | 531 | 637 | 416 | 567 | 539 | 421 | 448 | 442 |
| Turbidity          |      | 0.11| 0.84| 0.75 | 1.44 | 1.76 | 0.41 | 4.35 | 2.36 | 3.5 | 3.4 |
| TDS – total dissolved solids | ppm | 235 | 310 | 118 | 315 | 200 | 275 | 211 | 204 | 217 | 222 |
| Hydrogencarbonate  | mg/l | 445.3| 433.1| 481.9 | 475.8 | 347.7 | 445.3 | 433.1 | 323.3 | 341.6 | 359.9 |
| Nitrates           | mg/l | 2.2 | 0.9 | 0.9 | 1.6 | 1 | 0.9 | 0.1 | 3.2 | 3.5 | 1.9 |
| Chlorides          | mg/l | 1.1 | 1.6 | 1.4 | 4.1 | 1.5 | 1.6 | 1.3 | 1.3 | 1.5 | 1.8 |
| Fluorides          | µg/l | <40 | 114 | 157 | 151 | 68 | 69 | 74 | 51 | 56 | 75 |
| Sulphates          | mg/l | 4.9 | 20.8 | 26.5 | 29.1 | 14.8 | 9.3 | 3.5 | 10.6 | 14.7 | 9.5 |
| Calcium            | mg/l | 64 | 89.2 | 102.4 | 118.3 | 83.1 | 114.9 | 84 | 86.8 | 63.1 |
| Potassium          | mg/l | 0.2 | 0.5 | 0.4 | 3.1 | 0.5 | 0.2 | 0.2 | 0.3 | 0.6 |
| Sodium             | mg/l | 0.4 | 2.6 | 3.6 | 4.8 | 0.8 | 0.9 | 1.1 | 0.8 | 1.2 | 1.8 |
| Magnesium          | mg/l | 32.1 | 16.5 | 19.4 | 8.6 | 2.4 | 1.9 | 1.4 | 1.1 | 2.9 | 21.4 |
| Lead               | µg/l | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Zinc               | µg/l | 34 | 24.2 | 23.3 | 25.4 | 18.8 | 23.2 | 30.1 | 15.9 | 13.2 | 21.1 |
| Iron               | µg/l | 5.4 | 28.4 | 50.3 | 5.5 | 43.6 | 31.9 | 28 | 63 | 54 | 54 |
| Manganese          | µg/l | 13.8 | 9.5 | 12.1 | 17 | 5.3 | 23.5 | 19.8 | 17.6 | 16.8 | 5.5 |

Figure 3. The ratio of calcium, magnesium and hydrogencarbonate in the sampled water.
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