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Hydrogeologic structures in two Serbian spa towns – Sijarinska banja and Selters banja

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Abstract. The objective of the paper is to identify the boundaries of hydrogeologic structures in which natural mineral waters occur, using two examples: old mineral water (Sijarinska Banja) and young mineral water (Selters Banja). The research addresses the distance from recharge zones, depth of occurrence, and points of discharge. Apart from the three spatial dimensions, the study also includes the time dimension – water age. The following parameters are examined: geologichydrogeologic conditions in the places of occurrence of mineral water, connection between mineral water and permeable fault zones, distance of surface water divides, previously-defined maximum possible depths of occurrence, possible flow rates, and the determined age. If the flow followed a straight line, the maximum distance of the recharge zone would be up to 7 m for the young and up to 11 km for the old mineral water. However, it is obvious that this is never the case in fractured systems, given that water travels much longer distances from the point of entry to the point of drainage from aquifers. Assessment of geologic-hydrogeologic and hydrodynamic conditions, relative to the determined age of the mineral water, leads to the conclusion that the distance between the recharge and drainage zones can be less than 5 km. The paper shows that insight into the depth of infiltration into permeable fault zones can also be gained by studying the depth of circulation relative to known hydrodynamic zones. The inference is that the largest amount of groundwater is restored in the hydrodynamic zone of slow groundwater renewal, which is below a depth of 1.5 km at Sijarinska Banja and below 1.3 km at Selters Banja.

Key words: spread, fault zone, distance of recharge zone, depth, hydrodynamic zoning, mineral water.

Апстракт. Циљ овог рада био је да се на примеру једне од старијих (Сијеринска б.) и једне од млађих („Селтерс“ б.) угљокиселих минералних вода Србије дефинишу границе пространства хидрогеолошких структура у којима се оне формирају. Истраживане су у свом пространству постојања, између области прихрањивања, дубине залегања и зона истицања угљокиселих вода. Осим трију просторних у разматрање је укључена и димензија време – старост вода. За ова истраживања су узети у обзир: геолошко – хидрогеолошки услови области формирања угљокиселих вода, неоспорна веза угљокиселих вода и водопропусних разломних зона, удаљеност површинских вододелница, раније дефинисана теоретска максимална могућа дубина залегања ових структура, могућа брзина кретања вода у датим хидродинамичким условима и утврђена њихова старост. Показало се, да би у случају праволинијског кретања вода, максимална удаљеност области прихрањивања износила, за млађе воде до 7 km, а за старије до 11 km. Међутим, било је јасно да у пукотинским системима то никада није случај, будући да воде прелазе далеко дуже путање у односу на праволинијско растојање од места уласка до места истицања из датих водоносних средина. Из анализе геолошко – хидрогеолошких и хидродинамичких услова, а за утврђене старости вода, закључено је да удаљености између области прихрањивања и зона дренирања могу да буду и мање од 5 km. У раду је показано да се дубина досезања инфилтрационих вода у водопропусним разломним зонама може сагледати и анализом дубина њихове циркулације у односу на познате хидродинамичке зоне. Закључено је да се главна количинска измена одвија у домену хидродинамичке зоне успорених процеса водозамене, која код Сијаринске бање досеже испод 1,5 km, а испод 1,3 km дубине код „Селтерс“ бање.

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Кључне речи: пространство, разломна зона, удаљеност области прихрањивања, дубина залегања, хидродинамичка зоналност, минерална вода.

Introduction

In Serbia, there are more than 65 naturally-carbonated thermal mineral water sites. Many authors have provided brief geological and hydrogeological descriptions of the immediate spread of the hydrogeologic structures in which such water occurs, and presented results of physicochemical, radioactivity and isotope testing (ČEKIĆ 2013; MILANOVIĆ *et al*. 2012; PROTIĆ 1995; MILOJEVIĆ 1964, 1954). Given the large number of occurrences in Serbia, this research addresses only two: the spa towns of Sijarinska Banja (old mineral water) and Selters Banja (young mineral water).

It is without doubt that the origin of the mineral waters is associated with permeable tectonic structures (LONBARDI & VOLTATTORNI 2010; WEIMLICH 2005, WEIMLICH *et al*. 2003, 1998; CERON *et al*. 2000; GREBER 1994). On the one hand, they allow carbon dioxide from the depth of origin to migrate toward the ground surface and, on the other hand, meteoric water to be infiltrated into deep formations.

The main hydrogeologic structures of Sijarinska Banja and Selters Banja are active and disjunctive fault zones. In the case of the former, it is a large interbloch structure in a low mountainous area, and in the latter an inter-bloch structure in a zone of horsts and trenches, covered by thick Tertiary strata (MARINKOVIĆ, 2014). At Sijarinska Banja, the mineral water has always been free-flowing, whereas at Selters Banja it was detected inadvertently, given that there were no manifestations on the ground surface.

The hydrogeologic structures were studied in terms of their spread between recharge zones, depth, and points of discharge of mineral water, along with the post-infiltration residence time. The research was based on the indisputable relationships between the mineral water and the regional permeable fault zones, the identified maximum possible depth of the hydrogeologic structures (MARINKOVIĆ *et al.* 2013), the potential (theoretical) average mineral water flow velocity in the given setting, and the determined age of the mineral water. The distances from surface water divides, along the permeable regional faults in which the mineral water occurs, were also taken into account. These distances were additionally used to estimate the average velocity of groundwater flow. In view of the above, as well as the fact that in fractured aquifers groundwater travels a much longer distance than it would along a straight line from the point of infiltration to the point of drainage (descending and ascending pathways, meandering in 3D space), it was concluded that the consideration of the hydrogeological structure, this distance may be less than 5 km.

The depths of the hydrogeologic structures at Selters Banja and Sijarinska Banja were considered relative to known hydrodynamic zones (high, low and very low rates of groundwater renewal). The results show that the largest amount of water is restored in the hydrodynamic zone of slow groundwater renewal.

It follows from the results of this research that the identified linear directions (tectonic zones) and approximated ultimate boundaries of the hydrogeologic structures are quite reliable and that this knowledge will facilitate exploration aimed at increasing the capacity of water sources, detecting thermal groundwater or addressing other specific tasks.

Method

For consideration of the issue of this work were used available to us the results of previous research. They relate primarily to the age of mineral water, rate of groundwater flow in the analog lithological environments and hydrodynamic conditions and the results achieved hydrogeological research in narrow fields of mineral water.

Given that exploration has shown that the fractured hard rocks (schists, igneous rocks, limestones, marls) comprise the main setting of the fault zones in which the mineral water occurs, the average velocity through the hydrogeologic structures was assumed based on the theoretical velocity of groundwater flow in fractured schists (from $n \times 10^{-8}$ to $n \times 10^{-4}$ m/s), and the theoretical velocity in the hydrodynamic zone of slow groundwater renewal, which is greater than 0.2 m/year or 6.3×10^{-9} m/s (DRAGIŠIĆ 1997). Recognizing these theoretical velocities, it was assumed that the relation between the travel distance and velocity must be such that the recharge zones are in the catchment area in which the mineral water occurs. The average flow velocity was first estimated for Selters Banja, where the geologichydrogeologic conditions are such that it is obvious that the recharge zone is within the catchment of the Alinac River (MILOJEVIĆ 1964). Given that the determined age of the mineral water at Selters Banja is 19,300 years, the average flow velocity must be about $1.15 \cdot 10^{-8}$ m/s (within limits of the theoretical range). As such, if a higher than average flow velocity was assumed, the distance would have been unrealistically large or the meandering of the flow in 3D space so extensive as to increase the travel distance multiple times relative to the linear distance. For this reason, and taking into account the threshold values of groundwater flow velocities in schists, the lower (slower) limit was assumed for the average flow velocity – $1.1 \cdot 10^{-8}$ m/s. This average flow velocity is also consistent with the theoretical velocities within the hydrodynamic zone of slow groundwater renewal.

The depth of the mineral water in the hydrogeologic structures was defined relative to the depths of known hydrodynamic zones: rapid, slow and very slow groundwater renewal.

Results and discussion

Geologic-hydrogeologic setting

The mineral water at Selters Banja in the City of Mladenovac occurs near the confluence of the Lug River and its right-bank tributary the Alinac (Fig. 1). It is withdrawn from wells near the right banks of the two rivers. This mineral water was discovered inadvertently in 1898, while Atanasijević brothers were drilling a 239 m deep well on their farm (Protić 1995). The rate of free flow was 1.3 l/s and the water temperature 31.5 °C. It was believed that this well tapped an aquifer in Sarmatian sediments and that recharge occurred in the upper part of the Alinac River catchment, where hard bedrock is exposed (Milojević 1964). Two wells at Selters Banja that tap Lower Cretaceous carbonate rocks have been drilled up to a depth of 816.4 m (Milojević & Tomić 1978) and 1150 m (Polić 1983), respectively. The rocks are slightly karstified and deemed to form the main aquifers at depths below 800 m. This depth was reached by drilling through Neogene sediments, whose thickness at Selters Banja is estimated at 238–275 m. Upper Cretaceous sediments (flysch) were detected between these strata and a main aquifer, which are widely exposed in the west, in the upper catchment of the Alinac River. They are generally represented by marls and sandstones. An 816.4 m deep well partly tapped mineral water from this flysch sequence, in the depth interval 613–816 m. The groundwater temperature was 48–50 °C and its composition similar to that of the previously extracted groundwater. The groundwater was saline (TDS 7.3 g/l) and the pH level was 6.9. The concentration of carbon dioxide was 0.34 g/l and that of radium 0.52 Bq/l.

Recent exploration has corroborated reserves of 6 l/s of mineral water of the $ClHCO_3$ – Na type, with a TDS level of 6.76 g/l and CO_2 concentrations from 443 to 567 mg/l (Čekić 2013). The conclusion was that recharge occurs through infiltration of meteoric water along the edges of the basin, where Lower Cretaceous sediments are exposed on the ground surface, in a zone of broken-up rocks with open fractures and fissures and along faults, and also partly from subsurface inflow from deeper water-bearing layers.

There is a regional neotectonically-active formation along the valley of the Lug River, known as the Lužnica-Topčider Fault (Pavlović 1980). Near Mladenovac it intersects with the Varovnica Fault, which is also neotectonically active, and a fault structure followed by the valley of the Alinac River. In hydrogeological terms, the Neogene sediments at Selters Banja form a complex of permeable and impermeable strata; Mesozoic flysch strata are largely impermeable, whereas the Lower Cretaceous sediments constitute a permeable lithologic setting of fractured-karst porosity. The highest porosity is found in fault zones, in hard carbonate rocks and Neogene sediments. The spread of these lithologic settings is deemed to be such that they likely constitute the main region of groundwater circulation.

The mineral water at Sijarinska Banja emerges along a 800 m long linear zone (Fig. 2). The zone features numerous springs at the bottom of a very steep valley of the Banjska River. The water source area, arbitrarily divided into two parts (upper spa and lower spa), originally comprised several shallow wells and one deep well (Protić 1995; Stanković & Zlokolica, 1993; Ilić 1988).

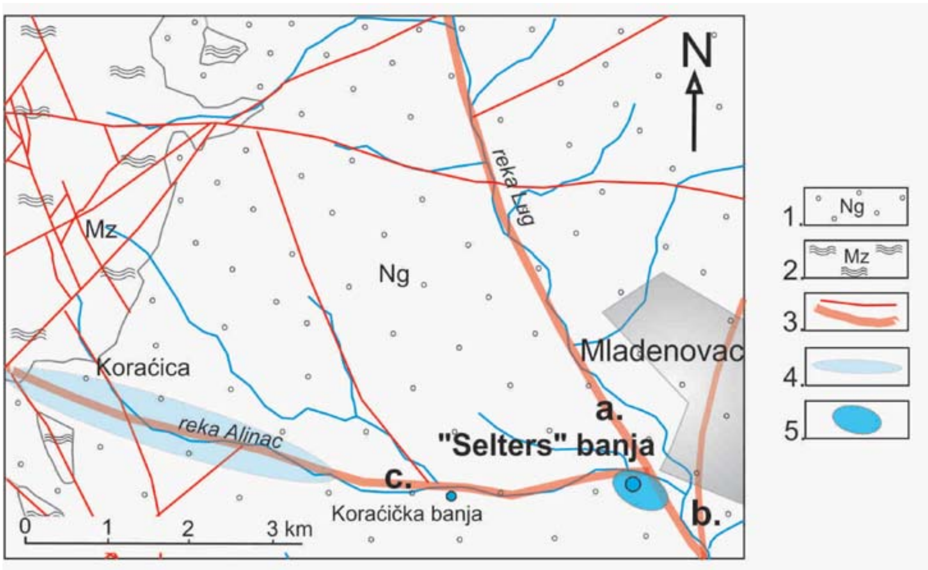

Fig. 1. Geological-hydrogeological map of the area of occurrence of mineral water at Selters Banja: **1.** complex of Neogene sediments; **2.** Mesozoic bedrock (carbonate rocks, flysch and serpentinites separated by faults); **3.** fault structure (a. Lužnica–Topčider fault; b. Varovnica fault; c. Alinac River Fault); **4.** recharge zone; and **5.** drainage zone.

The drilling history of the shallow wells began with drinking water supply wells in the alluvions of the Banjska River, which were about 4 m deep. Over time, ordinary and mineral water became mixed. Then, several wells, 9 to 12 m, were drilled through igneous rocks, up to the point of contact with the schists, where the flow was generally artesian. During the course of drilling on the left bank of the Banjska River, an 8 m high geyser erupted. Its water temperature was 71°C. There was another eruption, about 1 m high, from a depth of 12 m, while drilling was taking place near the Main Spring. An 80 m deep well was drilled in crystalline schists with calc tufa interbeds, near the Gejzir Hotel. There was a sudden occurrence of mineral water at 60 m. The rate of pulsating free flow was from 0.06 to 0.18 l/s. A 102 m deep well was drilled in igneous rocks. The water temperature was initially 65 °C, but later dropped to 58 °C. Temperature logging revealed an inversion, from 65 °C in the 15–37 m interval to 56 °C at a depth of 100 m. In the “upper spa”, the mineral water is drained via several low-capacity springs (Jablanica, Zdravlje, etc.) and withdrawn from a number of wells whose depths range from 4 to 40 m. After these shallow wells, a deep well was drilled in the “upper spa” through schists, up to a depth of 1232 m. Here the most significant flow rates of mineral water come from tectonic zones at 360 m and 840 m. The shallower tectonic zone delivered 60 l/s of artesian groundwater whose temperature was 77.8 °C, and the deeper zone 33 l/s of artesian groundwater at 72 °C.

The oldest and most widespread rocks in Sijarinska Banja are crystalline schists. They are interspersed with Tertiary igneous rocks. Mineral waters occur within the zone of the Tupale Fault, along the fringes of an igneous mass. This deep fault divides two geotectonic units – Serbian-Macedonian Massif (east) and Vardar Zone (west) (VUKANOVIĆ *et al.* 1973). Judging by data collected on the ground surface, the dip is rather steep to the east and the movement reversed, with a very pronounced displacement component along the trending direction. Movements along the fault have been intermittent. In the Paleogene, they opened pathways for volcanics. The same movements have continued to the present day. At Sijarinska Banja, on about 600 m^2, there is a rather large mass of marbleized onyx adjacent to andesites and crystalline schists. The onyx is believed to have originated from one of the hot springs, which often changed its location due to rapid sedimentation of large masses of aragonite.

According to exploration drilling and mapping along the Banjska River, mineral water emerges from permeable zones at the points of contact between igneous rocks and highly-silicified schists, permeable tectonic zones in the igneous rocks, and open fractures and tectonized zones in the highlysilicified schists.

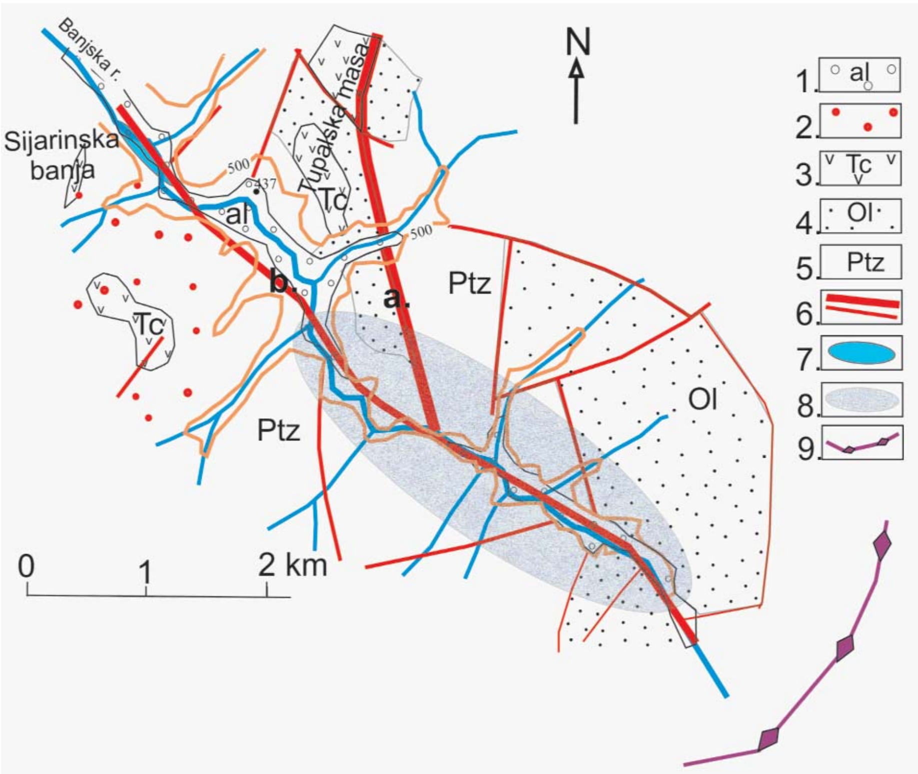

Fig. 2. Geological-hydrogeological map of the area of occurrence of mineral water at Sijarinska Banja: **1.** alluvial sediments; **2.** hydrothermally altered rock; **3.** Tertiary igneous rocks; **4**. Oligocene sediments; **5.** crystalline schists; **6.** fault structures (a. Tupale fault zone; b. Banjska River fault zone); **7.** drainage zone; **8.** recharge zone; and **9.** surface water divide.

Hydrogeologic structures

The linear distribution of the occurrences of mineral water in Serbia is a clear indication of their genetic association with tectonic structures, and their (high) permeability is a result of disjunctive neotectonic movements of bordering blocks (MARINKOVIĆ *et al.* 2012). Exploration has shown that a fault zone is the main hydrogeologic structure of a mineral water occurrence (MARINKOVIĆ 2014). It can be deep and very wide, up to 10 km, and can extend for more than 100 km (STEPANOV 1989). Permeable layers of Quaternary and/or Tertiary unconsolidated sediments also constitute hydrogeologic structures of mineral waters in Serbia, where they „screen“ fault zones in the solid bedrock.

The main hydrogeologic structure at Sijarinska Banja is the regional fault zone followed by the Banja River Valley. It runs entirely through the solid bedrock (Proterozoic crystalline schists with Tertiary igneous intrusions). Neotectonic activity has maintained and continues to maintain high permeability. There have been intermittent movements during and after ore solution circulation stages (VUKANOVIĆ *et al*. 1973). In the drainage zone, the fault zone is “screened” by alluvial sediments and marbleized onyx deposits. The spread of these delayed carbonate rocks is an indicator of paleo flows. Drilling of the previously-mentioned shallow wells was accompanied by sudden groundwater discharges after the near-surface lithologic medium, where rapid sedimentation of aragonite had sealed fractures and fissures. The closure of permeable fracture systems, along with the accumulation of a considerable mass of marbleized onyx on the ground surface, caused the points of discharge to move. On this observation scale, the tamping and displacement processes are associated with the ground surface and a small depth below the surface (30–50 m), where carbon dioxide is expected to be released at a given temperature and pressure. The wells at Sijarinska Banja are located along the edge of the hydrothermally-altered zone, which indicates a connection between earlier circulation of hot solutions and contemporary thermal water flows – as a post-volcanic occurrence. It also seems clear that the paleo and contemporary flows of thermal water have the same heat source.

The southern extension of the fault structure marked by mineral water springs is connected with the main direction of the Tupale Fault (Fig. 2). It is apparent that the trending of the faults reflects a deep fault zone of a certain width, in which the permeable hydrogeologic structure likely spreads along the western side (where there is evidence of paleo circulation of thermal solutions). The drilled permeable tectonized zones, which are distinct at depths of 360 m and 840 m (Figs. 3 and 5), are associated with the deep fault zone and suggest a rather large depth. In the regional fault domain, mineral water circulation at depth is associated solely with these permeable tectonized zones. There is every indication that they comprise a network of highly regular linear zones, which in broad terms belong to the systems that feature a certain spatial orientation. Beyond these bounded permeable tectonized zones the rocks are compact – impermeable.

Mineral water at Selters Banja is formed near the City of Mladenovac, in an area where three neotectonically active tectonic structures cross. The closest is the structure that follows the Alinac River Valley and the other two are regional fault structures known as

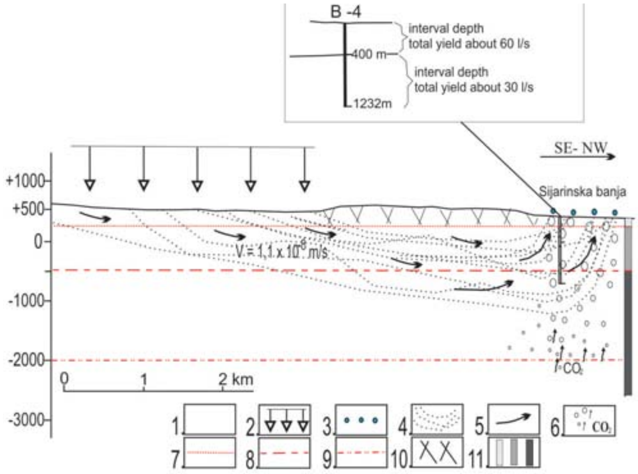

Fig. 3. Schematic geological-hydrogeological section through the hydrogeologic structure at Sijarinska Banja: **1.** crystalline schist (silicified) with igneous intrusions; **2.** recharge zone; **3.** drainage zone; **4.** zone of dominant subsurface flow; **5.** general direction of subsurface flow; **6.** direction of carbon dioxide migration; **7.** regional drainage base; **8.** theoretical depth of the hydrodynamic zone of slow groundwater renewal; **9.** theoretical maximum depth of mineral water; **10.** compact rock; and **11.** hydrodynamic zones: rapid (light gray), slow (gray) and very slow (dark gray) renewal.

the Lužnica–Tupižnica Fault, along the Lug River, and the Varovnica Fault. Wells IB-1 (816.4 m deep) and IB-2 (1150 m) tap mineral water in marly limestones and limestones, from the depth interval of 600 to 1150 m (ČEKIĆ 2013). There are Neogene sediments with permeable and impermeable strata up to a depth of 300 m, largely impermeable Upper Cretaceous flysch from 300 m to 750 m, and further below permeable Mesozoic, slightly-karstified carbonate rocks (Fig. 4).

The first well, after a depth of 239 m, captures mineral water from Sarmatian sediments in the lowest part of the Neogene, and partly also from underlying marly limestones of the Upper Cretaceous (MILOJEVIĆ 1964). The two deep wells tap mineral water in carbonate rocks below the Upper Cretaceous flysch, which are Lower Cretaceous and it appears also partly Jurassic. A relatively small amount is also captured from (overlying) marly limestones and marls of the Upper Cretaceous (flysch). Drilling of the wells did not reveal any tectonized zones. However, it is a fact that this area is situated near the zone where the three previously-mentioned neotectonic structures intersect and that the aquifer is hydraulically linked with the (main) fault zone. Its proximity is indicated by carbon dioxide, which it allows to migrate upward from the depth of origin.

It follows that the fractured-karst aquifer in Mesozoic carbonate rocks is situated on the fringe of the deep fault zone. Thethe fault zone appears to run

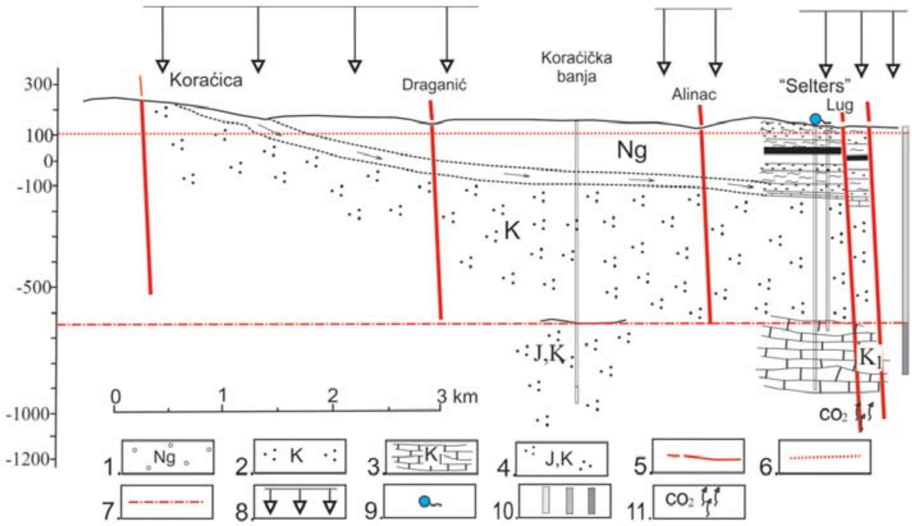

Fig. 4. Schematic geological-hydrogeological section through the hydrogeologic structure at Selters Banja (ČEKIĆ 2013; MILOJEVIĆ, 1964, supplemented): **1.** Neogene sediments; **2.** Lower Neogene flysch; **3.** Lower Cretaceous slightly-karstified sediments; **4.** Jurassic and Cretaceous flysch; **5.** fault; **6.** regional drainage base; **7.** theoretical depth of hydrodynamic zone of slow groundwater renewal; **8.** recharge zone; **9.** point of emergence of mineral water; **10.** hydrodynamic zones: rapid (light gray), slow (grey) and very slow (dark gray) groundwater renewal; and **11.** direction of carbon dioxide migration.

along the Alinac River Valley or (less likely) the Lug River Valley. Based on drilling logs and general geological exploration, the largest amount of mineral water renewed at Selters Banja is associated with slightly-karstified carbonate rocks that underlie the Cretaceous flysch, within the zone of the nearby (as expected), regional, active fault zone.

Distance of recharge zones

The spread of the hydrogeologic structures is also determined by the distance between the recharge zone and the discharge zone (point of emergence). In the geological-hydrogeological circumstances such as exist at Sijarinska Banja and Selters Banja, these distances were assessed in terms of the spread of the permeable fault zones and the linear distance from the wells to the boundaries of the catchments of surface streams near these two spa towns (Banjska River, Alinac River and Lug River ?). Additionally, the fact that the distance between the recharge zone and the place of discharge needs to be consistent with the determined water age and average flow velocity (per the theoretical velocity for the pertinent permeable lithologic setting) was taken into account.

The mineral waters in the subject hydrogeologic structures are of meteoric origin (PERIĆ & MILIVOJEVIĆ 1990). Atmospheric precipitation is infiltrated directly or indirectly from surface streams and peripheral water-bearing media. Adjusted to linear structures, the recharge zones acquire the contours of an elongated oval shape. The water age reflects the travel distance from infiltration to discharge and the average flow velocity. In hard rocks, the pathway is determined by the regional, active neotectonic structure. At Sijarinska Banja, the pathway appears to be mapped out by the regional fault of the Banjska River and possibly other faults of a smaller scale (spread, etc.) in the zone of the deep Tupale Fault. At Selters Banja, it is determined by neotectonic faults that cross in this area (fault along the Alinac River Valley, fault along the Lug River Valley – the Lužnica-Topčider Fault and the Varovine Fault).

Given the linear extent of the hydrogeologic structures and the assumed average groundwater flow velocity (1.1×10^{-8} m/s), the (upstream) distance between the recharge zone and the wells is not greater than 11 km at Sijarinska Banja and 7 km at Selters Banja. However, in view of the fact that in fractured systems groundwater flow does not follow a straight line, these waters travel a much longer distance from the point of entry into to the point of exit from a given water-bearing medium. Looking at only downward and upward travel, it follows that the distance of the recharge zones could also be less than 5 km.

Maximum depth of mineral water occurrences

Theoretically, in Serbia's lithosphere mineral water can be found at a maximum depth of 2.5 km, which is determined by the depth of the lithostratigraphic substrates of carbon dioxide (MARINKOVIĆ *et al*. 2013). It is related to the geotectonic unit of the Vardar Zone, where 90% of the registered occurrences of mineral water are located. Recognizing these constraints, the maximum depths of mineral waters at Sijarinska Banja and Selters Banja were determined by examining zones of similar rates of renewal – according to the known hydrodynamic zones of rapid, slow and very slow groundwater renewal.

It is clear that in the case of ascending systems and water age measured in thousands of years, it is not practical to distinguish zones of **rapid groundwater renewal** in the given sense. However, ascending flows of mineral water in the strata closer to the surface can be exposed to lateral infiltration of groundwater from this hydrodynamic zone. Such groundwater causes seasonal variations in water temperatures and discharges of springs and wells. The depth of the occurrences is determined by the regional drainage base. At Sijarinska Banja, the regional drainage base is the Jablanica River (390 m above sea level) and at Selters Banja the Kubršnica River (110 m.a.s.l.). Relative to the recharge zones, which in the case of the considered hydrogeologic structures are located above 500 m.a.s.l. at Sijarinska Banja and above 200 m.a.s.l. at Selters Banja, it follows that the hydrodynamic zones can reach depths greater than 100 m.

Theoretically, the zone of **slow groundwater renewal** lies below the zone of rapid groundwater renewal. Full replacement takes between 100 years and 100 million year (DRAGIŠIĆ 1997). Groundwater movement in this zone is rather slow compared to the zone of rapid renewal. In relatively small artesian basins (Selters Banja), the average depth can be up to 1000 m and in mountainous areas (Sijarinska Banja) up to 2000 m. The natural velocity of groundwater flow is greater than 0.2 m/day or 6.3×10^{-9} m/s.

Deep boreholes (over 1.1 km) clearly indicate that in the considered permeable fault zones the rate of groundwater renewal decreases with depth. At Sijarinska Banja, this was demonstrated while a deep well was being drilled (Fig. 5). From the tectonic zone a yield of about 60 l/s was measured at 360 m, roughly 30 l/s at 840 m, and no flows (water-bearing tectonized zones) were registered down to the ultimate depth of 1150 m.

The highest rate of groundwater renewal at Sijarinska Banja, which corresponds to the zone of slow renewal, occurs at depths between 300 and 1000 m. Thereafter, it gradually declines to below a depth of 1500 m. In this regard, it is fully consistent with the theoretical depth (1000 to 2000 m) in the given mountainous setting. It is obvious that below 1500 m there is a hydrodynamic zone of very slow groundwater renewal.

The mineral water at Selters Banja is captured from the depth interval of 350 to 1150 m (between 200 m and –1000 m above sea level). This interval is entirely in the hydrodynamic zone of slow groundwater renewal (Fig. 6). The thickness of the interval is therefore about 800 m and the highest rate of groundwater renewal traces to the main water-bearing medium – Lower Cretaceous slightly-karstified carbonate rocks. An active fault zone in the vicinity allows the mineral water to move upward from the Lower Cretaceous limestones to the permeable Sarmatian layer (bottom of the Neogene complex of sediments). The water-bearing medium tapped by the deep wells is also recharged from the fault zone. The mineral water has not emerged on the ground surface because this was prevented by impermeable Neogene strata. Obviously, active tectonic movements cannot create a (linear) permeable zone through these strata. It follows that the main aquifer of mineral water in the Lower Cretaceous carbonate rocks is recharged and drained along the linear zones of active neotectonic movements, that the depth of the zone of slow groundwater renewal depends on the depth of these carbonate rocks and the permeable fault zone, and that the recharge zone must be on or beyond the Neogene fringe.

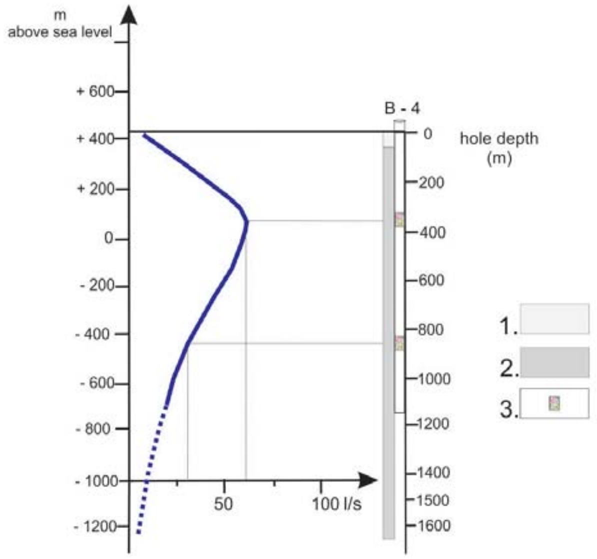

Fig. 5. Schematic representation of hydrodynamic zoning (groundwater renewal) at Sijarinska Banja: **1.** hydrodynamic zone of rapid groundwater renewal; **2.** zone of slow groundwater renewal; and **3.** water-bearing tectonized zone.

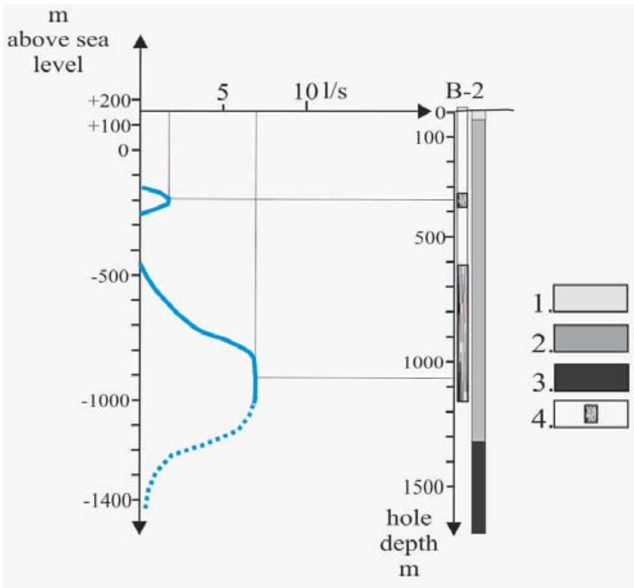

Fig. 6. Schematic representation of hydrodynamic zoning (groundwater renewal) at Selters Banja: **1.** zone of rapid groundwater renewal; **2.** zone of slow groundwater renewal; **3.** zone of very slow groundwater renewal; **4.** aquifer.

The zone of **very slow groundwater renewal** is at depths greater than 1000m/2000m. The natural rate of groundwater flow is very low (less than 0.05–0.1 m/year). Consequently, the end of the zone of slow and the beginning of the zone of very slow groundwater renewal at Sijarinska Banja is to be expected in the depth interval of 1.5 to 2.0 km, and in the case of Selters Banja below 1.3 km.

It follows that the largest amount of groundwater in the considered hydrogeologic structures is restored in the hydrodynamic zone of slow groundwater renewal.

Conclusion

The spread of the considered hydrogeologic structures could only be assessed in general, to an extent that in regional terms provides a sufficiently clear picture of the expanse, distance of recharge zones and depths of the studied occurrences of mineral waters.

The lowest average rates of groundwater flow ($1.1 \cdot 10^{-8}$ m/s) were determined on the basis of the distance of the surface water divides, water age, and theoretical velocities in analogous fractured settings. Considering all the above and the fact that in fractured aquifers groundwater travels much longer than the linear distance from the point of infiltration to the point of discharge (descending and ascending pathways, meandering flow in 3D space), the conclusion is that this distance at Selters Banja can be from less than 5 km to not more than 7 km, and at Sijarinska Banja from less than 5 km to a maximum of 11 km.

The highest rate of groundwater renewal in the studied hydrogeologic structures occurs within the known hydrodynamic zone of slow groundwater renewal, and the generation and migration of carbon dioxide in the zone of very slow groundwater renewal. At Sijarinska Banja, this happens at depths up to 1.5 km and there is a gradual decrease with depth. Below this depth and down to 2 km, there is a boundary between the zone of slow and the zone of very slow groundwater renewal. At Selters Banja, mineral water is captured from the depth interval of 360 to 1150 m, and the highest rate of groundwater renewal occurs below a depth of 800 m, associated with slightly-karstified carbonate rocks. The depth of the mineral water in this spa town is determined by the depth and permeability of the rocks and neotectonically active faults. Drilling has not revealed a tectonized zone but the proximity of active regional fault structures and the presence of carbon dioxide gas clearly indicate that it is close and that there is a hydraulic link with the encountered water-bearing media in marly and slightly-karstified carbonate rocks (in the depth interval of 360 to 1150 m). In the hydrogeologic structure at Selters Banja, the boundary between the hydrodynamic zones of slow and very slow groundwater renewal is below a depth of 1.3 km.

The identification of regional fault zones where mineral waters are formed and renewed, the distance of the recharge and drainage zones, and the depth of the mineral water facilitate efficient hydrogeologic exploration for the purposes of increasing water source capacity, locating thermal groundwater, and addressing other specific tasks.

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Резиме

Хидрогеолошке структуре Сијаринске Бање и Младеновачке „Селтерс“ бање

Циљ овог рада био је да се на примеру једне од старијих (Сијаринска б.) и једне од млађих („Селтерс“ б.) угљокиселих минералних вода Србије дефинишу границе пространства хидрогеолошких структура у којима се оне формирају. Истраживања су показала да се основном хидрогеолошком структуром ових вода може сматрати разломна зона (Маринковић 2014). Познато је да оне буду велике ширине, и до 10 km, пружања и преко 100 km и дубоког залегања (Степанов 1989). Хидрогеолошке структуре угљокиселих минералних вода Србије су и водопропусни слојеви квартарних и /или/ терцијарних невезаних седимената, тамо где они „екранирају“ разломне зоне угљокиселих вода у чврстим стенама геолошке основе. У Сијаринској бањи угљокиселе воде су истицале природним путем, док су у „Селтерс“ бањи оне откривене случајно, будући да се нису испољавале на површину терена.

Старост вода је у сагласности са дужином путање коју вода пролази од момента инфилтрације до момента истицања и просечном брзином тока. У чврстим стенама њихова путања је на тој дужини „трасирана“ регионалном активном неотектонском структуром. За Сијаринску бању, ова путања је предиспонирана регионалним разломом Бањске реке и евентуално другим разломима мањих размера (пружања и др.) у домену дубоког тупалског разлома. За термоминералне воде Младеновачке „Селтерс“ бање то се односи на неотектонске раседне структуре које се на овом подручју укрштају (расед долином реке Алинац, долином реке Луг Лужничко-топчидерски расед и Варовнички расед).

Угљокиселе воде су атмосферског (инфилтрационог) порекла (Перић & Миливојевић 1990). Атмосферске падавине се инфилтрирају директно или индиректно преко површинских токова и граничних водоносних средина. Прилагођене линијским структурама, области прихрањивања задобијају контуре издуженог овалног облика. Узимајући у обзир линијско пружање хидрогеолошких структура и усвојену просечну брзину подземних вода у њима, од $1{,}1 \cdot 10^{-8}$ m/s, добија се да је област прихрањивања за хидрогеолошку структуру Сијаринске бање од изворишта удаљена (узводно) највише 11 km, а за „Селтерс“ бању 7 km. Међутим, будући да у пукотинским системима подземни ток не може да има праволинијску путању, јасно је да воде прелазе далеко дужи пут у односу на праволинијско растојање од места уласка до места истицања из датих водоносних средина. Ако се рачуна само дужина силазне и узлазне путање, произилази да разматране удаљености области прихрањивања могу да буду и мање од 5 km.

У раду је показано да се дубина досезања инфилрационих вода у водопропусним разломним зонама може сагледати и анализом дубина њихове циркулације у односу на познате хидродинамичке зоне (интензивних, успорених и веома успорених процеса водозамене). Теоретски, у литосфери Србије угљокиселе воде могу да досежу максимално до 2,5 km дубине, односно до дубине коју одређује

дубина залегања литостратиграфских супстрата угљендиоксида (Маринковић *и др*., 2013).

За област Сијаринске бање регионални дренирајући базис представља река Јабланица (390 m надморске висине), а за област „Селтерс“ бање река Кубршница (110 m надморске висине). У односу на области прихрањивања, које се код разматраних хидрогеолошких структура налазе на надморској висини изнад 500 m за Сијаринску бању, односно изнад 200 m за „Селтерс“ бању, произилази да у њима хидродинамичка зона интензивних процеса водозамене може да досеже до дубине веће од 100 m.

У раду је закључено да се главна количинска измена у разматраним хидрогеолошким структурама одвија у домену познате хидродинамичке зоне успорених процеса водозамене, а генерисање и миграција угљендиоксида у домену зоне веома успорених процеса водозамене. Постигнути резултати дубоким бушотинама, преко 1,1 km дубине, јасно указују да се у предметним водопропусним разломним зонама са дубином смањује количинска измена подземних вода (интензивност водозамене). У Сијаринској бањи она се јасно испољила при бушењу дубоке бушотине. Из тектонске зоне на 360 m измерена је издашност око 60 l/s, на 840 m око 30 l/s, а од 840 m до крајње дубине 1150 m, приливи нису регистровани (водоносне тектонски изломљене зоне). За Сијаринску бању највећа количинска измена одвија се до 1,5 km дубине, са тенденцијом поступног смањивања са дубином. Испод ове, а до највише 2 km дубине, налази се граница између хидродинамичке зоне успорених и веома успорених процеса водозамене. Код „Селтерс“ бање угљокиселе термоминералне воде су захваћене у интервалу од 360 до 1150 m дубине, а главна количинска измена ових вода одвија се испод 800 m дубине и везана је за слабо карстификоване карбонатне стене. Дубина досезања вода ове бање условљена је дубином залегања и водопропусношћу ових стена и неотектонски активних разлома. Тектонизирана зона није набушена, али близина активних регионалних раседних структура и постојање гаса угљендиоксида, јасно указују на њихову близину и хидрауличку везу између њих и набушених водоносних средина у лапоровитим и слабо карстификованим карбонатним стенама (у интервалу 360–1150 m дубине). За хидрогеолошку структуру „Селтерс“ бање граница између хидродинамичке зоне успорених и веома успорених процеса водозамене налази се испод 1,3 km дубине.

Дефинисањем пространства регионалних разломних зона у којима се угљокиселе воде формирају и обнављају, удаљености области прихрањивања од изворишта и дубине досезања угљокиселих вода, омогућавају се рационалнија и ефикаснија хидрогеолошка истраживања – за потребе повећања издашности изворишта, изналажења вода виших температура и решавања других конкретних задатака.