Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences
Tome 79, No 11, 2026

GEOLOGY
Hydrogeology

THERMAL AND MINERAL WATERS OF THE REPUBLIC OF SRPSKA: HYDROGEOLOGICAL CLASSIFICATION AND RESOURCE POTENTIAL

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Received on August 9, 2026
Presented by K. Stoykova, Corresponding Member of BAS, on September 29, 2026

Abstract

Thermal and mineral waters are an important hydrogeological resource of the Republic of Srpska, controlled by geological and tectonic setting, aquifer characteristics, and groundwater circulation depth. This study provides a regional synthesis of their hydrogeological and hydrogeochemical features and evaluates their resource potential using available geological, hydrogeological, hydrochemical, and field data. A total of 48 representative occurrences were identified, of which 11 have temperatures above 20 °C and three exceed 40 °C. The waters were grouped into three hydrochemical zones and three principal hydrogeological system types: shallow- to intermediate-depth mineral-water systems, fault-controlled thermal systems in carbonate and ophiolitic settings, and deep artesian geothermal systems in northern Republic of Srpska. The greatest potential for direct geothermal use is associated with the deep artesian systems, particularly in Semberija, whereas other occurrences are mainly relevant for balneological, recreational, bottling, and spa use. The results show that resource potential depends on the combined effects of temperature, discharge, hydrochemical composition, aquifer characteristics, and degree of investigation rather than on temperature or mineralization alone.

Key words: hydrochemical zones, groundwater, geothermal potential, balneological use, resource assessment

The authors would like to thank the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contracts on realization and financing of the scientific research work of the Faculty of Mining and Geology in 2026, 451-03-33/2026-03/200126 and 451-03-34/2026-03/200126).

https://doi.org/10.7546/CRABS.2026.11.07

Introduction. Thermal and mineral waters are products of interacting hydrogeological, geochemical, and geothermal processes. Their temperature, mineralization, ionic and gas composition depend on lithology, circulation depth and residence time, tectonic structure, water–rock interaction, mixing, and gas-water processes [1–3]. Accordingly, similar temperatures or mineralization levels may reflect different formation mechanisms, and these waters should be interpreted within the hydrogeological systems in which they occur.

Definitions of mineral, thermal, and thermal mineral waters vary among countries and studies, particularly with respect to temperature thresholds, mineralization, composition, origin, and use [4]. From a resource perspective, temperature alone is insufficient for evaluating system value. Discharge, aquifer depth and type, hydrochemical composition, regime stability, and abstraction conditions are also important [5]. Hydrochemical characteristics may further indicate circulation conditions and possible uses, while trace elements and radionuclides require consideration where relevant [6].

The significance of these waters extends beyond traditional balneological use. Depending on their natural characteristics and local conditions, they may support recreation, bottling, spa and wellness development, and direct geothermal applications [5, 7]. Balneological potential, however, should be distinguished from clinically demonstrated therapeutic effects [8–11].

The Republic of Srpska is suitable for regional analysis because of its pronounced geological and tectonic heterogeneity and the diversity of known hydrogeological systems [12, 13]. This study therefore provides a regional synthesis of thermal and mineral waters, focusing on the relationships among geological setting, aquifer type, circulation depth, temperature, mineralization, and hydrochemical composition, and assesses how these factors control their resource potential.

Study area. The Republic of Srpska occupies the northern and eastern parts of Bosnia and Herzegovina and extends across several geotectonic units of the Dinarides, parts of the Vardar Zone, and the southern margin of the Pannonian Basin. Its geological structure includes Paleozoic to Quaternary sedimentary, magmatic, and metamorphic rocks. Carbonate complexes are widespread in the central, eastern, and southern parts, whereas ophiolitic rocks and younger Neogene-Quaternary sediments are particularly important in the central and northern areas. The geographical location of the study area is shown in Fig. 1.

Hydrogeological conditions are correspondingly diverse and include intergranular, fractured, karst-fractured, and karst aquifers. Thermal and mineral water occurrences are mainly associated with deep regional faults, fractured carbonate and ophiolitic complexes, and deep artesian basins. These settings enable groundwater circulation ranging from relatively shallow infiltration systems to deep confined systems with long residence times. Circulation depth, aquifer lithology, structural permeability, and degree of confinement are therefore the principal controls on

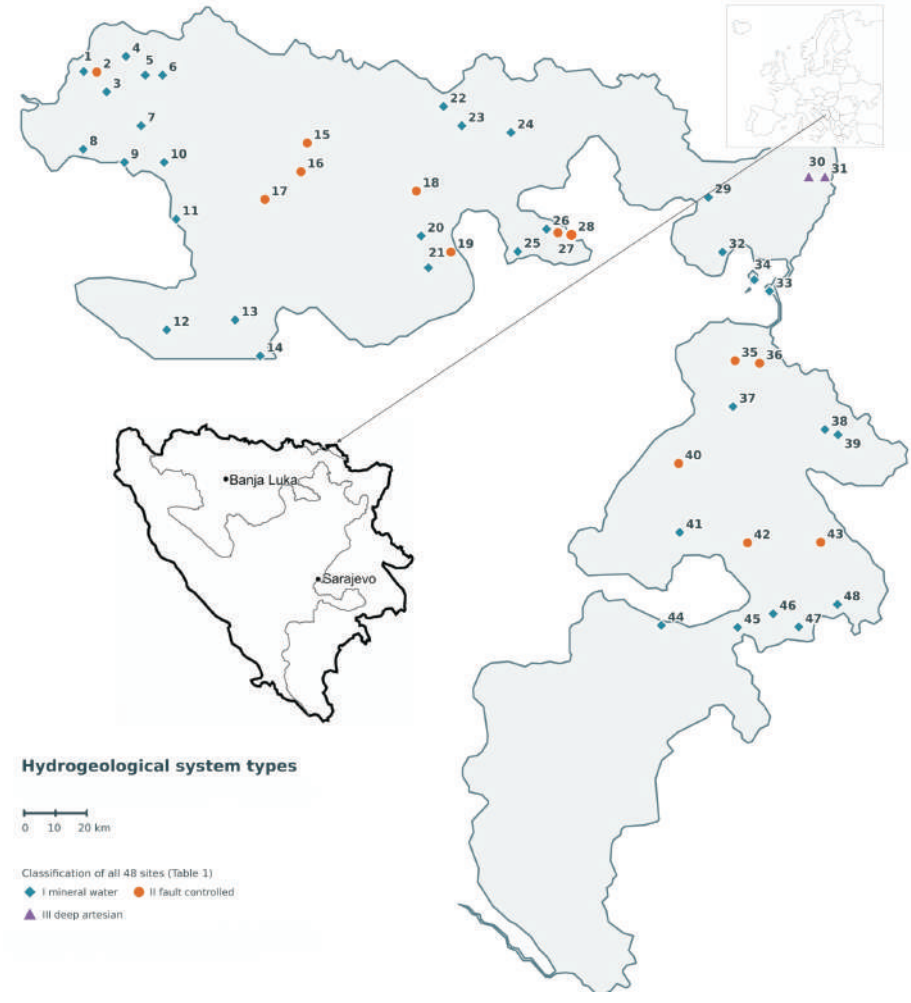

Fig. 1. Hydrogeological classification of the thermal, mineral, and thermal mineral water occurrences in the Republic of Srpska

the formation and distribution of thermal and mineral waters in the Republic of Srpska.

Methodology. The study combined desk-based analysis with hydrogeological field reconnaissance. Existing geological, hydrogeological, and hydrochemical data were reviewed and integrated with field observations from selected thermal and mineral water localities, including the mode of groundwater occurrence, geological and structural relationships, and basic in situ physicochemical measurements [14, 15].

The desk-based analysis included regional maps, explanatory documentation, and available data on temperature, discharge, mineralization, hydrochemical type, gas composition, and water use [12,13]. The regional assessment [16] provides site-

level hydrogeothermal data, which are considered here within the system classification.

A total of 48 representative occurrences were selected for regional comparison. Where several springs or wells belonged to the same hydrogeological system, they were treated as a single locality while retaining relevant differences among individual water points.

Hydrochemical interpretation was based mainly on dominant cations and anions, mineralization, temperature, and gas composition, considered together with aquifer type, lithostratigraphic position, and structural setting [17]. The existing subdivision into three hydrochemical zones was retained for regional comparison. Geothermal potential was assessed using temperature together with discharge, aquifer depth, mineralization, and available information on exploitation conditions [18].

Resource potential was evaluated separately from current use and included balneological and recreational applications, bottling, and direct geothermal use. No heat-output calculations or inferential statistical analyses were performed where sufficiently reliable and comparable data were unavailable. Documented measurements were therefore distinguished from regional interpretations and assumptions.

Results and discussion. Thermal, mineral, and thermal mineral waters in the Republic of Srpska are unevenly distributed and are concentrated mainly along regional faults, lithostratigraphic contacts, karst and karst-fractured aquifers, the ophiolite belt, and deep artesian basins. A total of 48 representative occurrences were identified, while the total number of individual springs and boreholes exceeds 100. Of the mapped occurrences, 11 have temperatures above 20 °C and only three exceed 40 °C, indicating the predominance of mineral and moderately thermal waters over high-temperature systems.

The analysed waters were assigned to three hydrochemical zones reflecting differences in circulation conditions, aquifer type, system confinement, and water-rock interaction. The first zone comprises mainly CO_2 and CO_2-N_2 waters and shows the greatest hydrochemical variability. Waters range from low-mineralized bicarbonate types to more complex compositions controlled by local lithology, mineral dissolution, ion exchange, mixing, and circulation depth. Slatina, where thermal mineral waters reach about 43 °C, illustrates the importance of fault-controlled ascent and mixing between deeper CO_2-rich and infiltrating waters.

The second hydrochemical zone includes predominantly low-mineralized thermal waters of meteoric origin circulating through fractured and karst-fractured rocks. Carbonate aquifers and younger fault systems are particularly important for deeper circulation and upward flow. Laktaši and Gornji Šeher have temperatures of about 30 °C, while Kulaši combines temperatures of approximately 29–30 °C with very low mineralization and high pH, reflecting water-rock interaction in an ultrabasic and ophiolitic setting. In eastern Republic of Srpska,

the Višegrad system represents concentrated thermal discharge within tectonized carbonate rocks. By contrast, the mineral waters of Srebrenica are generally non-thermal and are related mainly to interaction with hydrothermally altered and mineralized rocks.

The third hydrochemical zone is associated mainly with deep artesian systems of Semberija and Posavina. In Semberija, thermal waters occur in Neogene, Cretaceous, and Triassic aquifers and generally show increasing temperature with depth. Temperatures of about 75 °C have been recorded at Dvorovi, approximately 82 °C in borehole DV-1, and about 73 °C in a Triassic aquifer at Slobomir. Borehole Bij-1 recorded more than 110 °C at about 2400 m depth, indicating favourable deep thermal conditions, although exploitable geothermal potential also depends on transmissivity, discharge, water chemistry, and sustainable abstraction. The vertical variability in temperature and hydrochemistry further indicates that Semberija should be considered a multilayered and hydrogeologically segmented geothermal system rather than a single homogeneous aquifer.

Comparison of the occurrences allows three principal hydrogeological system types to be distinguished: shallow- to intermediate-depth mineral-water systems controlled mainly by lithology and water-rock interaction, fault-controlled thermal systems in carbonate and ophiolitic terrains, and deep artesian geothermal systems of Semberija and Posavina. These groups complement the hydrochemical zonation and link formation conditions with resource potential (Table 1). The spatial distribution of the three hydrogeological system types listed in Table 1 is shown in Fig. 1.

Available documentation indicates that thermal and thermal mineral waters have traditionally been used mainly for balneological and recreational purposes. Slatina, Laktaši, Banja Vrućica, Kulaši, Mlječanica, Višegradska Banja, and Dvorovi are among the most important localities in this respect. Bottling potential exists locally, but suitability depends on hydrochemical stability and regulatory requirements. The greatest potential for direct geothermal use is associated with Semberija and other deep sedimentary structures in the northern part of the Republic of Srpska, where higher-temperature waters may support heating, agricultural applications, and cascading heat-use systems.

Of the 48 classified occurrences, 33 belong to type I, 13 to type II, and two to type III. These counts show the distribution of the systems, not the volume of available water. In type I, Cerovica and Svodna have mineralization of 2.59 and 1.70 g/L, respectively, while springs in the same northwestern area generally yield up to 0.1 L/s. Their resource value is therefore linked chiefly to local mineral-water and balneological use, provided that discharge and water quality remain stable.

In type II, the Laktaši thermal spring discharges approximately 16–20 L/s at 30 °C, while Slatina reaches about 43 °C with a reported borehole flow of 25 L/s. Reported abstraction from three wells at Višegradska Banja is 25–28 L/s. The

Table 1

Hydrogeological grouping of thermal and mineral water occurrences and their resource implications in the Republic of Srpska

Hydrogeological system type	**Geological and hydrogeological setting**	**Dominant controls and hydrochemical/thermal expression**	**Classified occurrences**	**Main resource implications**
I Shallow to intermediate mineral-water systems	Paleozoic and Mesozoic clastic and carbonate complexes, mineralized volcanic-hydrothermal terrains and locally mixed lithological settings	Predominantly infiltration-controlled circulation; strong influence of water-rock interaction, lithology, local faults and variable residence time. Generally low to moderate temperatures, highly variable mineralization and ionic composition, with locally CO_2-rich or metal-rich waters.	1 Cerovica; 3 Svodna; 4 Strigova; 5 Jelovac; 6 Mlječanica; 7 Čarakovo; 8 Budimlić Japra; 9 Koprivna; 10 Tomašica; 11 Kozica; 12 Vaganac; 13 Balkana; 14 Stupna; 20 Ukrinica; 21 Vlajići; 22 Kuljenovci; 23 Oklop; 24 Podnovlje; 25 Rječice; 26 Prenja; 29 Koraj; 32 Priboj; 33 Kozluk; 34 Jasenica; 37 Korijen; 38 Crni Guber; 39 Očna voda; 41 Bup; 44 Štuke; 45 Luke; 46 Okosovići; 47 Zaborak; 48 Rudo	Primarily balneological and mineral-water potential; locally favourable for bottling where water quality and long-term stability are demonstrated.
II Fault-controlled thermal systems	Carbonate and ophiolitic terrains intersected by regional and local fault systems	Deep meteoric circulation and structural permeability enable heating, ascending flow and mixing with shallower waters. Elevated temperatures are accompanied by strongly variable mineralization, while hydrochemistry reflects both circulation depth and lithological controls.	2 Lješljani; 15 Laktaši; 16 Slatina; 17 Šeher; 18 Kulaši; 19 Teslić; 27 Sočkovac; 28 Boljanić; 35 Medoš; 36 Perin grad; 40 Knežina; 42 Toplik; 43 Višegradska banja	Balneological and recreational potential; locally favourable for direct low-temperature heat use and cascading applications.
III Deep artesian geothermal systems	Multilayer sedimentary basins of northern Republic of Srpska, particularly Semberija	Deep confined circulation, long residence time, vertical aquifer compartmentalization and geothermal gradient. These systems show the highest recorded temperatures and pronounced vertical variations in mineralization, ionic composition and gas regime between aquifers.	30 Dvorovi; 31 Slobomir	Highest potential for direct geothermal utilization; requires aquifer-specific assessment of transmissivity, sustainable yield and reinjection.

deeper type III systems attain higher temperatures: the Dvorovi S-1 well has a reported flow rate of 7.5 L/s at 75 °C, and the Slobomir GD-2 well reaches 73 °C at a depth of approximately 1800 m. Together, these examples show that the higher-temperature artesian waters warrant further assessment for direct heat use, while the shallower mineral-water systems are primarily relevant for balneological and local commercial applications.

Resource potential therefore depends on the combination of temperature, discharge, hydrochemical composition, aquifer characteristics, and technical feasibility. High-temperature systems favour direct geothermal use, whereas stable mineral composition may support balneological use or bottling. Moderate temperatures combined with sufficient discharge and favourable location may be more suitable for recreational, spa, and wellness development [7].

A major limitation is the uneven degree of investigation. Some localities are supported by deep drilling, testing, and repeated chemical analyses, whereas others are known mainly from reconnaissance or older documentation. The mapped distribution should therefore be interpreted as a regional representation of known occurrences rather than as a map of exploitable reserves, and areas with fewer recorded occurrences do not necessarily have low hydrogeological potential.

Conclusion. The novelty of this study lies in the regional interpretation of the thermal, mineral, and thermal mineral waters of the Republic of Srpska as parts of distinct hydrogeological systems rather than as isolated occurrences. By integrating geological and tectonic setting, aquifer type, circulation depth, temperature, mineralization, hydrochemical composition, and gas content, the study provides a basis for distinguishing waters that may show similar physicochemical characteristics but differ in genesis, circulation conditions, and resource potential.

Three regionally recognizable hydrogeological system types were identified: shallow- to intermediate-depth mineral-water systems predominantly controlled by lithology and water-rock interaction, fault-controlled thermal systems in carbonate and ophiolitic settings, and deep artesian geothermal systems in the northern part of the Republic of Srpska. The hydrochemical zones can therefore be interpreted not only as classification units, but also as expressions of different circulation regimes, aquifer settings, and degrees of confinement. This strengthens their value for regional hydrogeological interpretation and comparison.

The results further show that resource potential cannot be defined by temperature or mineralization alone. Discharge, hydrochemical composition, aquifer depth, regime stability, and degree of investigation must be considered jointly when assessing suitability for balneological, recreational, bottling, or geothermal use. The regional framework developed in this study should therefore be regarded as a basis for prioritizing future investigations rather than as a definitive estimate of exploitable reserves.

Future work should focus on improved hydrochemical and hydrodynamic monitoring, isotope and gas studies, and more detailed investigation of the most

promising geothermal systems, particularly in Semberija. For these systems, sustainable production and reinjection should be evaluated together with reservoir characteristics, whereas balneologically and commercially important waters require long-term monitoring of chemical and microbiological stability.

Acknowledgements. The authors express their gratitude to the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for supporting scientific research, which is essential for the advancement of a knowledge-based society. Also, the authors would like to thank the editor and the reviewers for their suggestions, which have helped improve the quality and clarity of the paper.

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