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Hydrogeochemical properties of thermal springs for natural therapeutic uses in medical geology at the Ciwidey area, West Java, Indonesia

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Abstract
The thermal springs in the Ciwidey region of Indonesia exhibit significant geological heritage and represent significant potential for natural therapeutic applications in medical geology. This study is for assessing hydrogeochemical characteristics of multiple thermal springs in the Ciwidey region and determine their appropriateness for natural therapeutic uses in medical geology. This research examines the hydrogeochemical characteristics of 13 thermal springs in Ciwidey using Atomic Absorption Spectrophotometry (AAS; AA-7000 SHIMADZU), classifying them into three distinct categories based on dominant chemical signatures: Sodium Chloride (Na-Cl), Calcium Sulphate (Ca-SO_4), and Sodium Bicarbonate (Na-HCO_3). Every hydrogeochemical type has unique therapeutic properties linked with their geochemical origin deep geothermal reservoirs, gypsum-rich lithology, or carbonate interactions. The analytical model established from this study identifies specific zones for potential therapeutic use: Na-Cl type waters (e.g. sites P2, P6, P10, P20) promote muscular relaxation and skin relief; Ca–SO_4 type springs (sites P3–P13) improve bone and joint health; and Na-HCO_3 type waters (P9, P14) aid in pH regulation and alleviate digestive and dermatological issues. The present research findings reveal essential insights into the therapeutic potential of Ciwidey's springs and emphasize the significance of site-specific assessments in medical geology.

Keywords:
thermal springs, hydrogeochemical, therapeutic, medical geology, geothermal

1. Introduction

Indonesia is situated along a volcanic pathway known as the Ring of Fire, which spans the islands of Sumatra, Java, the Nusa Tenggara Islands, Sulawesi, and the Maluku Islands. Many of these volcanic paths possess significant potential for geothermal energy (**Waya et al., 2022**). Geothermal sources can arise from three factors: the existence of a heat source, meteoric water, and reservoir rock (**Skopljak et al., 2017; Vlahović & Skopljak, 2019**). Thermal water or light steam ascends to the Earth's surface through faults or joints, which are zones of water passage, manifesting as thermal springs, fumaroles, and solfataras (**Pirajno, 2020**). Thermal springs represent a distinctive geological environment characterized by a high geothermal gradient, ancient volcanism, seismic activity, tectonic conditions, orogeny, and structural features **(Bennett & Walraevens, 2023; Suhail et al., 2024**).

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Thermal springs, in addition to being vital natural resources, also signify important geological heritage sites. Thermal spring water, a naturally occurring solution, demonstrates dynamic chemical and physical properties influenced by certain geological conditions (**Li et al., 2024**). Derived from subterranean mineral water, it preserves elevated microbiological cleanliness and demonstrates potential therapeutic properties (**Kekes et al., 2023**), enhanced by diverse chemical composition and health benefits (**Martínez et al., 2017**). Thermal springs are of considerable importance in scientific and medical research, as well as in geotourism and medical geology (**Erfurt-cooper, 2010**). Hydrotherapy utilizing thermal springs water, a type of balneotherapy, originated as an efficacious treatment method for rehabilitation in Europe in the 1800s (**Li et al., 2024**). Thermal springs water hydrotherapy acquired popularity after several decades because of its chemical-physical features, including chemical composition, temperature, and molecular concentration (**Maria et al., 2024**). Thermal springs can be categorized based on their chemical constituents, such as bicarbonate, sulfate, sulfide, and chloride (**Cacciapuoti et al., 2020**).

Thermal springs have emerged as a prominent tourist destination. Public interest in thermal springs is observed throughout multiple continents: Europe (42.3%), Asia (26.3%), and Africa (21.7%) (**Valeriani et al., 2018**). In 2017, China accounted for 31.2% of worldwide tourism revenue, attributed to visitors to its thermal springs and mineral resources **(Yeung & Johnston, 2020**). The physicochemical form of thermal waters varies considerably between sources, affected by the rock type and the period of their travel through the rock. This includes a summary of global hydrochemical facies studies, such as those by **Farhat et al. (2021)** in Baltistan, **Rafiq et al. (2024)** in Saudi Arabia, and **Suhail et al. (2024)** in Kullu-Manali, India. These studies highlight the variability in thermal water chemistry due to geological settings, rock types, and subsurface travel time, as emphasized by (**Torres-Ceron et al., 2019**). Certain experts contend that therapeutic thermal water originated decades ago in Asia, where Indians, Japanese, and Chinese initially utilised water extracts from tea and natural thermal springs for medical and spiritual detoxification (**Wangchuk et al., 2021**).

Medical hydrology is a contemporary discipline within medicine; in 1986, thermal springs were recognized as an alternative method for achieving optimal physical and mental health (**Martínez et al., 2017**). Medical hydrology has evolved alongside scientific advancements and is dependent on various disciplines, including Geology, Natural Sciences, Chemistry, Physics, Physiology, and Pharmacy (**Ahaneku & Muogbo, 2024; Li et al., 2023; Finkelman et al., 2018; Buck et al., 2016; Centeno et al., 2016**). Medical hydrology, commonly known as medical water treatment or hydrotherapy, employs water as a therapeutic medium under various physicochemical conditions to prevent and address health issues (**Wangchuk et al., 2021**). Physicochemical techniques are utilized to discover thermal spring water during the earliest stages of hydrothermal resource exploration, particularly in thermally permeable reservoirs (**Farhat et al., 2021; Torres-Ceron et al., 2019**).

Indonesia has adopted the modernisation of thermal spring resorts, especially in urban-proximate regions such as the Patuha volcanic area in South Bandung, West Java (**Rahayudin et al., 2020**). These sites have converted natural thermal springs into leisure wellness destinations, providing accommodations, balneotherapy services, and swimming facilities to entice visitors in pursuit of relaxation and health advantages. The growing wellness trend has prompted enhancements in resort facilities, offering contemporary conveniences while maintaining the therapeutic advantages of mineral-rich waters. The Ciwidey region in West Java, Indonesia, is distinguished due to geothermal activity, which is evident in many thermal springs that have historically been employed for their therapeutic properties. These geothermal features hold significant cultural and economic value while also serving as an intriguing topic for scientific inquiry in medical geology (**Ríos Reyes et al., 2020**). The hydrogeochemical characteristics of thermal springs, including temperature, pH, mineral composition, and trace elements, are essential in assessing their medicinal potential (**Maria et al., 2024**). Minerals, including calcium, magnesium, bicarbonates, and sulfates, prevalent in geothermal fluids, are recognized for their therapeutic benefits in treating musculoskeletal illnesses, dermatological maladies, and circulatory problems (**Cacciapuoti et al., 2020**). Comprehending the geochemical characteristics of these thermal springs elucidates the subsurface processes, water-rock interactions, and geological structures that affect their composition (**Utama et al., 2024**). Furthermore, assessing the therapeutic potential of these waters necessitates a multidisciplinary approach incorporates hydrogeochemistry, and public health considerations.

This study aims to describe the hydrogeochemical properties of various thermal springs with an emphasis on their mineral composition and assess their suitability for natural therapeutic applications in the Ciwidey region of West Java, Indonesia. The uniqueness of this research is that it examines the therapeutic potential of Ciwidey's thermal springs through an analysis of their hydrogeochemical features within the framework of medical geology. This investigation uncovers distinctive water chemistry, geological factors, and public health consequences particular to the Indonesian geothermal region. The study examines the role of several minerals in thermal springs in promoting health advantages, including enhanced circulation, less inflammation, and alleviation of skin disorders. Understanding the geochemical mineralization to comprehend the therapeutic potential of these thermal springs could encourage the advancement of therapeutic and medicinal treatments that leverage natural geothermal resources.

2. Study Area

2.1. Geological Setting

The Indonesian archipelago is located in a very active tectonic zone, where the Eurasian, Indian–Australian, and Pacific plates converge, resulting in frequent earthquakes and volcanic eruptions (**Hamilton, 1973; Katili, 1974**). This severe geological environment created a volcanic belt around Java, encompassing the Ciwidey area in West Java. Ciwidey is situated inside a young volcanic complex, encircled by more ancient volcanoes like Mount Patuha, Puncaklawang, Urug, and Tikukur (**Ashat et al., 2019; Rahayudin et al., 2020; Sriwana et al., 1998, 2000**).

The geological conditions of the Patuha–Ciwidey region are characterized through a range of volcanic and sedimentary rocks that significantly influence the hydrothermal system. The area consists of lava and lahar deposits from Mount Patuha (Qv) and Mount Kendeng

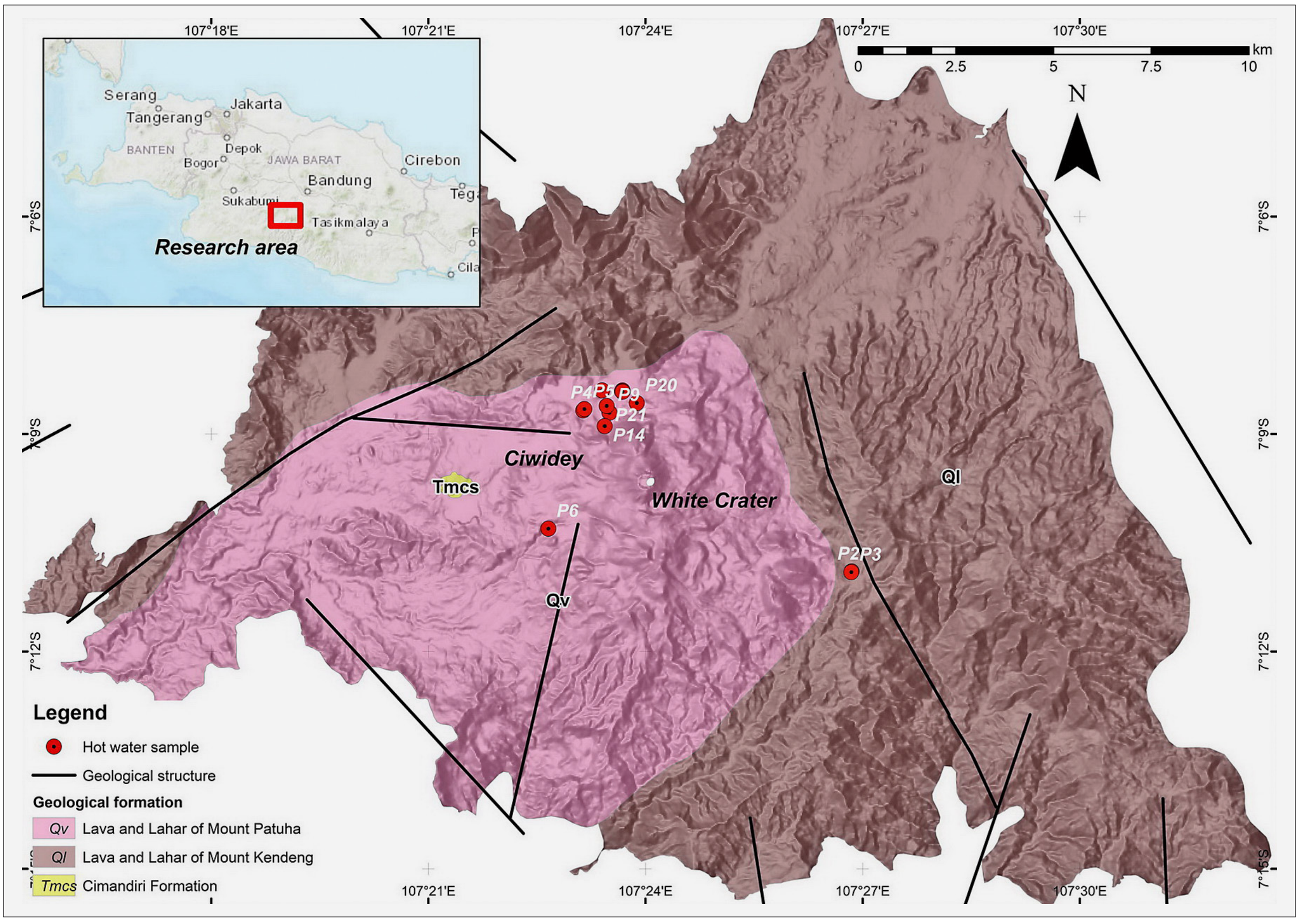

Figure 1. Map of the study area of the Ciwidey region, West Java Province, Indonesia (**Alzwar et al., 1992**)

(Ql), which are Quaternary volcanic materials that improve permeability and promote water–rock interactions. The Cimandiri Formation (Tcms), a Tertiary sedimentary formation consisting of sandstones, shales, and conglomerates, is underlain by significant fault zones (**Alzwar et al., 1992**) (see **Figure 1**). The vertical movement of boiling reservoir steam is responsible for the formation of fumaroles and hot springs in the Ciwidey region. Its ascent to the surface is governed by the Ciwidey normal fault. Ciwidey's sulfuric acid hot water is created when reservoir steam condenses near the surface (steam heating) (**Rahayudin et al., 2020**). The interconnected reservoirs in the Patuha region, located laterally between the White Crater, Cibuni, and Ciwidey. These reservoirs are divided by the Cimanggu Normal Fault, which separates the Cibuni Crater reservoir from the White Crater reservoir, while the Cileulur Normal Fault delineates the White Crater reservoir from the Ciwidey Crater reservoir (**Khasmadin & Harmoko, 2021**). These faults serve as pathways for geothermal fluid movement and define separate reservoirs, enhancing the mineralization and hydrogeochemical variety of the thermal springs. The geothermal system in the Patuha region, especially near White Crater, Kawah Cibuni, and Kawah Ciwidey, indicates surface characteristics like fumaroles and crater lakes that signify an upflow zone, with steam emissions penetrating the surface via permeable geological formations (**Ashat et al., 2019**). This geological context is crucial for comprehending the spatial distribution, recharge processes, and therapeutic potential of Ciwidey's thermal waters.

2.2. Hydrogeological Condition

The heterogeneous geological structure, consisting of lava and lahar deposits from Mount Patuha and Mount Kendeng, along with the Cimandiri Formation, significantly influences the hydrogeochemical properties of the thermal springs in Ciwidey (**Rahayudin et al., 2020**). Volcanic deposits promote vigorous water–rock interaction, leading to increased concentrations of minerals like salt, calcium, and sulphate (**Ashat et al., 2019; Chandra et al., 2022**). The geological features, volcanic structure, fault-controlled permeability, and lithological diversity are essential in determining the hydrogeochemical signatures present in the thermal springs (**Rahayudin et al., 2020; Sumotarto et al., 2021**). Furthermore, the Cimandiri Formation, characterised by its sedimentary strata and fault structures, facilitates groundwater flow and permeability, allowing for deeper circulation of geothermal fluids and stimulating the interaction between magmatic gases and meteoric waters

(**Rahayudin et al., 2020**). Fumaroles, hot springs, and mud pools are examples of geothermal phenomena that are produced by the region's volcanic vents, faults, and precipitous inclines. These geothermal phenomena are particularly prevalent in areas such as Kawah Putih and Kawah Cibuni (**Lazzerini & da Silva, 2020; Rahayudin et al., 2020; Sriwana et al., 2000**).

The thermal springs are direct representations of this dynamic geological environment, significantly influenced by the youthful volcanic complex of Mount Patuha and adjacent peaks, including Mount Urug, Puncaklawang, and Tikukur (**Sriwana et al., 2000; Rahayudin et al., 2020**). The hot springs with moderate temperatures are located on the northern side of the Patuha volcanic area, have a chloride bicarbonate dissolving water type, a neutral pH, and are dominated by Na-Ca-SO_4, indicating a combination of reservoir and meteoric water (**Bujung et al., 2010**). Several of the thermal springs selected here are utilised for bathing and therapeutic purposes (**Maria et al., 2024**). These locations are also situated near prominent trekking paths and tourist destinations. The majority of the chosen locations are situated adjacent to the residential zone. The geological framework not only affects the hydrogeochemistry but also enhances the geothermal potential and therapeutic variety found in the region's thermal waters.

3. Materials and methods

3.1. Sampling and water quality analysis

A total number of 13 thermal springs waters were collected in polyethene screw capped bottles in May 2025. The bottles were washed with tap water followed by rinsing with distilled water before collecting the samples. All precautions were taken during sampling, transportation and storage. The geographical coordinates of each site, including latitude, longitude, and elevation, were documented utilizing the Global Positioning System (Garmin GPS Map 66s). The water temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), oxidation-reduction potential (ORP), and salinity of the thermal springs were assessed in situ using Yieryi New TDS pH/TDS/EC/Temperature meter digital water quality monitor tester meter during sampling. Bicarbonate and chloride concentrations were determined through acidimetric and argentometric titration techniques. In compliance with APHA standard procedures; APHA 2320 B for bicarbonate (alkalinity) using acid titration. APHA 4500-Cl B for chloride measurement applying argentometric titration with silver nitrate (**APHA., 2017**). The sulphate analysis was conducted through a Shimadzu UV VIS 1700 double-beam spectrophotometry. The results were expressed in milligrams per Liter (mg/L), with the exception of pH (measured in units) and electrical conductivity (EC; measured in µS/cm).

3.2. Measurements and Data Analysis

The analysis of sodium, magnesium, calcium, and potassium cations was conducted using an Atomic Absorption Spectrophotometry (AAS) equipment through AA-7000 SHIMADZU, incorporating background correction with Deuterium lamps (D2-lamps) and hollow cathode lamps. Reagent blanks, duplicate samples, and reference standard samples have been created to validate the precision of the analytical methods (**Bisergaeva & Sirieva, 2020**). The analysis of sulphate, chloride, and bicarbonate anions was conducted using UV-Vis spectrophotometry, argentometry (Mohr method), and acidimetry, respectively. The geochemical data were analyzed using Liquid Chemistry Plotting Spreadsheet Version 3, that are was created by Powell Geoscience Ltd (**Powell & Cumming, 2010**). The fluid type was classified using a triangular ternary diagram based on the amounts of chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-). This graphic facilitates in identifying the origins of geothermal fluids through illustrating the relative concentrations of three major anions, that signify various hydrochemical environments, including volcanic, sedimentary, or meteoric sources.

4. Results

The water physicochemical characteristics are related to its subsurface pathways, the temperature at depth, the mineral composition of the surrounding rocks, and the movement time (**Kieu & Nguyen, 2024; Pham & Nguyen, 2024**). Thermal spring waters have diverse chemical compositions, according to the lithological characteristics (**Mohamedi & Chenakers, 2022**). The Ciwidey region contains abundant groundwater that produces several thermal springs. The current study proposes to identify the physicochemical properties that provide health benefits for natural therapeutic applications in medical geology within the Ciwidey area. A summary of physicochemical characteristics of Ciwidey thermal Springs during the month of April 2025 are shown in **Table 1**. The temperature of thermal springs ranges from 32.6 to 92.6°C. Regarding the context of temperature, mineral waters can be classified as cold (< 20°C at source), hypothermal (20-30°C at source), mesothermal (30-40°C at source), and hyperthermal (> 40°C at source). The thermal spring in Ciwidey is classified as mesothermal – hyperthermal waters. The pH of Ciwidey thermal springs ranges from 1.71 to 7.08. Thermal water is categorised into six types based on pH levels: strong acid ($pH < 2$), acid ($2 \leq pH < 4$), weak acid ($4 \leq pH < 6$), neutral ($6 \leq pH < 7.5$), weak alkaline ($7.5 \leq pH < 9$), and alkaline ($pH \geq 9$) (**Farhat et al., 2021**). The total dissolved solids (TDS) of thermal waters range from 61 to 1170 mg/L. Increased TDS levels may signify extended groundwater residence time and greater flow distance (**Lee et al., 2021**). The hydrogeochemical analysis indi-

Table 1. Physico-chemical parameters of some thermal waters around the Ciwidey region.

Site	Temp	pH	EC	TDS	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}
P2	87.9	2.3	1676	837	0.87	2.09	0.01	0.05	90.85	0.01	596.70
P3	74.8	2.54	108	61	1.54	1.95	0.33	1.86	71.68	0.01	548.78
P4	42.5	6.48	1245	623	89.76	23.22	55.90	60.58	158.11	360.51	186.42
P5	40.2	6.07	1219	624	91.78	24.63	47.38	49.98	116.70	329.40	126.07
P6	92.6	1.71	1176	645	7.36	2.55	0.06	3.54	124.19	0.01	319.11
P9	36.8	6.18	836	409	181.88	22.77	23.30	17.03	48.84	377.59	55.85
P10	52.3	5.66	2370	1170	199.74	83.31	50.35	79.95	345.98	338.55	300.97
P11	57.4	5.86	2300	1120	169.76	76.22	53.48	78.52	344.06	377.59	316.44
P12	47.4	7.08	1664	832	266.82	70.86	47.33	70.91	303.80	330.62	248.24
P13	32.6	6.2	776	387	0.01	17.64	5.82	27.10	89.10	213.50	108.00
P14	70.3	6.13	935	464	429.99	28.93	4.96	20.55	66.10	413.58	56.00
P20	60.8	5.89	2060	1010	293.32	66.79	30.92	61.57	240.54	368.44	285.02
P21	46.3	5.93	1475	706	281.41	54.21	176.73	53.68	250.13	417.85	63.31
min	32.6	1.71	108	61	0.0052	1.94	0.01	0.049	48.84	0.01	55.845
max	92.6	7.08	2370	1170	429.99	83.31	176.73	79.95	345.98	417.85	596.7
average	57.07	5.233	1372	683.69	154.94	36.55	38.198	40.41	173.08	271.36	246.99

Temp: Temperature (°C); EC (μS/cm); All Units mg/L except pH

Table 2. Physico-chemical parameters comparison between Ciwidey thermal springs and other parts of the world.

Parameter	Ciwidey (This study)	Baltistan, Pakistan (Farhat et al., 2021)	Saudi Arabia, (Rafiq et al., 2024)	Manali, India, (Suhail et al., 2024)	Toyam, Japan, (Sasaki et al., 2021)	Fengshun, South China, (Luo et al., 2022)	Gandaki, Nepal, (Chalise et al., 2023)
T	32.6 - 92.6	41	56	49	59.9	80.1	64.3
pH	1.7 - 7.1	7.5	7.9	8.0	7.54	8.0	8.8
EC	108 - 2370	510	3161	-	195	357	16270
TDS	61 - 1170	305	2055	709.9	-	-	6637
Na^+	0.005- 429.9	15	463	231	310	97.7	370
K^+	1.95 - 83.3	3.95	93	45	40	3.9	137
Ca^{2+}	0.01 - 176.7	81	295	37	8.6	3.9	364
Mg^{2+}	0.05 - 79.9	20	2.04	15	0.3	0.1	121
Cl^-	48.8-345.9	10.8	538.52	341	490	12.2	39.64
SO_4^{2-}	55.8 - 596.7	82.5	433.39	70	57	7.7	24.9
HCO_3^-	0.01 - 417.8	271	71.06	296	82	241	490

Units mg/L except pH, EC (μS/cm), Tem. (◦C).

cates that the thermal springs in the Ciwidey region include Na^+ (0.0052–429.99 mg/L), K^+ (1.94–83.31 mg/L), Ca^{2+} (0.01–176.7 mg/L), and Mg^{2+} (0.04–79.9 mg/L). SO_4^{2-} (55.8 - 596.7 mg/L), Cl^- (48.84 - 345.98 mg/L), and HCO_3^- (0.01 - 417.85 mg/L).

The origin of the major ions has been explained as follows (**Hem, 1985**): Na^+ (Sodium): Generally sourced from the weathering of sodium-rich plagioclase feldspars found in andesitic and basaltic volcanic rocks. K^+ (Potassium): released from the transformation of potassium-rich minerals like orthoclase and biotite, usually found in volcanic rocks. Ca^{2+} (Calcium): derives from the dissolution of calcic plagioclase and secondary carbonate minerals such as calcite, which may develop during hydrothermal processes. Mg^{2+} (Magnesium): originates from the decomposition of mafic minerals including pyroxene and olivine, which are prevalent in basaltic lava flows and lahar deposits. SO_4^{2-} (Sulfate): Generated from the oxidation of sulfide minerals, and the absorption of volcanic gases, which interact with groundwater to yield sulfuric acid. Chloride (Cl^-): Usually injected through magmatic degassing and the leaching of chloride-containing minerals or evaporites within the geothermal reservoir. Bicarbonate (HCO_3^-): Produced by the dissolution of carbonate minerals and the reaction of CO_2 (from magmatic or biogenic origins) with meteoric water. The volcanic deposits of Mount Patuha and Mount Kendeng represent the major lithological sources for these ions, while the faulted sedimentary layers of the Cimandiri Formation enhance fluid circulation and enhance deeper water–rock contact (**Rahayudin et al., 2020**). This comprehensive geological framework elucidates the observed ion concentrations and validates the local geothermal activity and therapeutic water characteristics.

The thermal spring's diverse ion concentrations, including sodium, potassium, calcium, magnesium, sulphate, chloride, and bicarbonate, indicate a complex hydrogeochemical system created from various lithologies and mixed water sources (**Martínez et al., 2017; Kieu & Nguyen, 2024; Pham & Nguyen, 2024**). Elevated sodium chloride, chloride, and sulphate concentrations indicate extended interactions with volcanic rocks and evaporite minerals, potentially involving magmatic contributions, whereas increased calcium and magnesium levels suggest dissolution from carbonates and anhydrites (**Lee et al., 2021**). Bicarbonate enrichment could indicate meteoric water infiltration and CO_2 absorption alongside moving through carbonate deposits (**Kieu & Nguyen, 2024; Pham & Nguyen, 2024**). Collectively, these patterns signify a dynamic system influenced by both profound geothermal processes and surface factors (**Gómez Diaz, 2021**).

The physicochemical form of thermal waters varies considerably between sources, affected by the rock type and the period of their travel through the rock. Thus, the thermal water's ascent to the surface is of crucial significance as it might modify its chemical composition (**Torres-Ceron et al., 2019**). Several studies have also been published on the analysis of hydrochemical facies of hot springs from various regions worldwide (see **Table 2**). The high concentrations of Na^+ and SO_4^{2-} in Ciwidey springs are consistent with the volcanic origin and magmatic gas interactions described in **Torres-Ceron et al. (2019)**. **Farhat et al. (2021)** observed elevated Cl^- and HCO_3^- levels in Baltistan springs, which are comparable to our findings, though the geological sources differ. **Rafiq et al. (2024)** identified Na-HCO_3 facies in the Ain Al-Harrah geothermal system, similar to some Ciwidey samples, suggesting analogous water–rock interaction processes. **Suhail et al. (2024)** emphasized the role of lithology and residence time in shaping water chemistry, which aligns with our interpretation of the Ciwidey system's volcanic-sedimentary framework.

5. Discussion

5.1. Hydrogeochemistry Classification of Ciwidey Thermal Spring Waters

The Ciwidey geothermal zone, located within a young volcanic complex and surrounded by older formations, displays numerous geological features that collectively affect the hydrogeochemical qualities of its thermal springs (**Alzwar et al., 1992; Ashat et al., 2019; Rahayudin et al., 2020; Sriwana et al., 1998, 2000**). The interaction between volcanic rocks and geothermal fluids enhances mineral enrichment particularly sodium, calcium, and sulphate while fault-controlled permeability and lithological diversity facilitate deep groundwater circulation and mixing of meteoric water with magmatic gases (**Rahayudin et al., 2020; Sumotarto et al., 2021**). These values holistically support Ciwidey's thermal waters as a promising resource for medicinal and wellness purposes. These strata experience considerable hydrothermal alteration and water–rock contact, leading to the mobilization of various ions into the geothermal fluids (**Hem, 1985; Mahala, 2019**). The water temperature typically fluctuates between 38°C and 45°C, thus being great for improving blood circulation and muscular relaxation (**Mahala, 2019; Yashod, 2025**). The pH values range from 6.8 to 7.5, signifying neutral to slightly alkaline conditions that are friendly on the skin and effective in treating inflammatory diseases (**Mahala, 2019)**. EC levels range from 1,200 to 2,500 µS/cm, indicating a high (**Pham & Nguyen, 2024**) concentration of dissolved ions that boost therapeutic efficacy. Meanwhile, TDS concentrations range from 800 to 1,800 mg/L, providing the water mineral-rich and ideal for balneotherapy, particularly skin and joint treatments (**Mahala, 2019; Yashod, 2025**).

The most significant step in natural hydrogeochemical analysis is to classify the water types for all samples. This study identified water type and source interpretation applying a Piper diagram (**Piper, 1953; Appelo & Postma, 1993**). The Piper diagram is extensively employed to categorize water types based on main cation and anion concentrations, enhancing the analysis of hydrogeochemical processes resulting from the interaction between water and aquifer materials (**Iskandar et al., 2013; Piper, 1953**). The classification of thermal waters can be conducted based on various parameters, including water mineralisation and their physicochemical composition (**Lee et al., 2021; Luo et al., 2022; Malkemus et al., 2021**). The physicochemical composition of thermal waters significantly differs among sources, depending on the duration of transition through rock and the type of rock encountered (**Fikri-Benbrahim et al., 2021**). The hydrogeochemical composition of water samples in the Ciwidey area is summarized in **Table 1**. Major cations and anions were analyzed using the Piper diagram. All water data showed distinction in chemical characteristics (see **Figure 2a**). The Piper diagram illustrates the chemical composition of the water samples, utilising reaction values derived from the concentrations of their principal constituents (cations and anions). An analysis of the Piper diagram (see **Figure 2a**) reveals that the heat waters distinctly occupy specific regions. The chemical composition of the examined groundwater transitions from fresh to alkaline along the extensive flow course, influenced through by the geological environment characterised between alternating volcanic and carbonate rock formations inside the aquifers.

The thermal water data were classified into Na–Cl, Ca–SO_4, and Na–HCO_3 water types. The relative abundance of specific ions, including Na^+, Cl^-, Ca^{2+}, SO_4^{2-}, and HCO_3^-, in thermal springs is a multifaceted process shaped by diverse geological and hydrological processes s (**Mahala, 2019**). Thermal water dissolve ions from surrounding rocks and transports them to the surface, potentially contributing to the prevalence of the Na-Cl water type identified in the current research. Whenever water traverses the earth's crust, it gets minerals and salts from the rocks it encounters, therefore influencing its chemical composition (**Chalise et al., 2023**). Significantly, Na and Cl are among the most prevalent elements in thermal springs, and their occurrence can be attributed to the dissolution of sodium chloride-bearing rocks, such as halite or rock salt. The thermal water solubilizes these minerals and transports them to the surface. our may be the primary reason for the enrichment of the Na–Cl water type in our study. The Na-HCO_3 characteristics mainly belong to groundwater and water of meteoric origin which are found in locations P9, and P14. The Na-Cl indicates an outflow characteristic of the system, has experienced an intensive dilution process with shallow groundwater in locations P2, P20, and P21.

The concentrations of Ca^{2+} and SO_4^{2-} at sampling points P3, P4, P5, P6, P10, P11, P12, and P13 indicate strong mineralization, consistent with the presence of a Ca–SO_4 water type. The circulation in this case occurs through Patuha mountain with a way through evaporite rocks represented mainly by gypsum, favoring high sulfates content (**Iskandar et al., 2018**). The Ca-SO_4, and Na-HCO_3 types exhibit relatively high concentrations of Ca and Na, along with near-neutral to alkaline conditions, primarily resulting in calcite precipitation (**Rahayudin et al., 2020**), as evidenced by the travertine formations.

The anions elements are also important in signifying a fundamental process of fluids during lateral flow towards the surface (see **Figure 2b**). According to the thermal springs anion Cl–SO_4–HCO_3 ternary diagrams, there are four distinct water anion types in the Ciwidey region, as detailed below:

1. Sulfate–Chloride Waters

The waters-type in volcanic geothermal systems, identified through their position around the SO_4 peak in

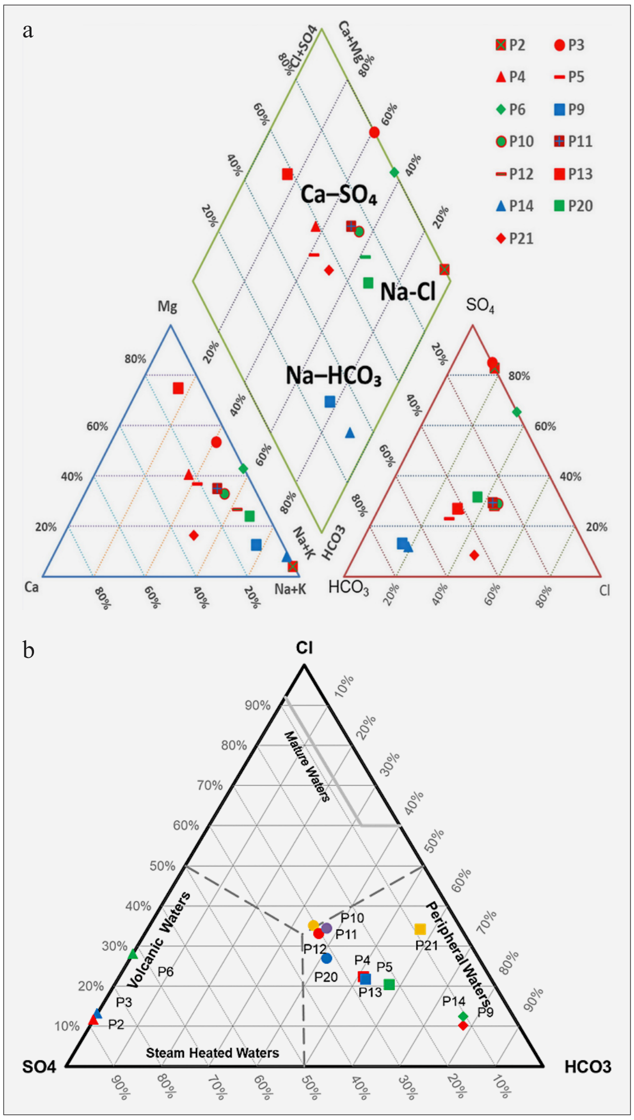

Figure 2. **(a)** Data plot of thermal springs in a Piper diagram **(b)** Data plot of thermal springs anion Cl–SO_4–HCO_3 ternary diagrams in the Ciwidey region.

Cl–SO_4–HCO_3 ternary diagrams, generally originate from the oxidation of volcanic gases like hydrogen sulfide (H_2S) above the surface or from the oxidation of pyrite (FeS_2) in shallow areas (**Rahayudin et al., 2020**). These processes generate highly acidic fluids composed of sulfate and lacking in chloride and bicarbonate, commonly found around fumaroles, crater lakes, and steam-heated springs (**Sriwana et al., 2000**). In areas like the Patuha Geothermal Field, samples P2, P3, and P6 from the crater lake exhibit this signature, showing interactions between surface gases and acid rock processes that imply magmatic influence and near-surface geothermal activity. The decreased concentrations of calcium and magnesium indicate limited contact with carbonate or silicate formations. Medical Geology for high sulfate levels could trigger gastrointestinal discomfort upon consumption, whereas increased chloride can increase hypertension in susceptible individuals (**Crespo et al.,**

2021). Trace metals such as Fe^{2+} and Mn^{2+} are present in moderate concentrations; although required in minimal quantities, they can become hazardous at higher levels (**Duvert et al., 2019**). These streams could have an acidic pH, enhancing the solubility of toxic metals such as arsenic or lead when these elements exist in the surrounding geology.

2. Bicarbonate-rich waters

Bicarbonate-rich waters have elevated concentrations of bicarbonate and calcium-magnesium, signifying interaction with carbonate rocks like limestone or dolomite (**Quattrini et al., 2016**). The presence of moderate sulfur and chloride indicates potential mixing with deeper geothermal fluids (**Çevikoğlu & Başaran, 2023**). The thermal springs at P9, and P14 presumably derive from shallow meteoric recharge areas that have infiltrated sedimentary formations. Bicarbonate-rich waters are often alkaline, helpful in the neutralization of stomach acid and commonly utilized in therapeutic bathing (**Farhat et al., 2021**). However, increased levels of calcium and magnesium may facilitate the development of kidney stones in people who are at risk (**Sorensen, 2014**). The very low concentrations of trace metals keep these waters suitable for ingestion; nevertheless, monitoring has been necessary (**Moldovan et al., 2022**).

3. Chloride-Bicarbonate Waters

Chloride-Bicarbonate Dilution as Peripheral Water: The majority of thermal springs in Ciwidey are situated between the chloride and bicarbonate elements P4, P5, P13, and P21. The thermal springs exemplify deep geothermal reservoirs that exhibit prolonged residence durations and significant water–rock interaction (**Zhang et al., 2023**). These waters are significantly mineralized and could present hazards when consumed consistently. Increased sodium and chloride levels might impact cardiovascular health, whilst elevated sulfate could cause laxative symptoms (**Fikri-Benbrahim et al., 2021**). The elevated quantities of mineral in this group raise concerns regarding metal toxicity, particularly for susceptible groups such as children and pregnant women. Prolonged exposure might culminate in neurological or renal complications (**Gwenzi et al., 2018**).

4. Mixed Composition Waters

The thermal springs at P9, P10, P11, P12, P20, and P21 situated mixed composition Chloride - Bicarbonate waters. This thermal springs water is generated from the dilution or amalgamation of chloride during lateral flow, facilitated by either groundwater or bicarbonate water (**Joshi et al., 2018**). This water type indicates the boundary of significant upflow and outflow zone structures in elevated terrain systems (**Iskandar et al., 2013**). Elevated chloride concentrations at P10, P11, P12, P20, and P21 signify proximity to the upflow zone. It likely represents a transitional zone where shallow and deep waters mix, possibly influenced by fault zones or fractures that allow vertical fluid movement (**Wang et al., 2018**). Mixed waters can be unpredictable in their health effects. While they may be suitable for balneotherapy, the high trace metal content could pose long-term health risks if used for drinking (**Hamidizadeh et al., 2017**).

5.2. Therapeutic Properties of Ciwidey's Thermal Springs

The therapeutic effects of thermal water are closely linked to its geochemical composition, specifically the concentrations of ions such HCO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+}, and Cl^-, these directly affect physiological processes (**Hem, 1985; Mahala, 2019; Pham & Nguyen, 2024; Yashod, 2025**). Calcium and magnesium promote bone strength, muscular function, and nerve signaling, whereas sodium and potassium maintain fluid balance and muscle relaxation. Sulfate and bicarbonate have anti-inflammatory and detoxifying properties, assisting in the treatment of rheumatic and skin disorders. Chloride promotes mineral absorption and hydration. These ions, whose are absorbed through the skin during balneotherapy, have been demonstrated to relieve musculoskeletal pain, enhance circulation, and promote general health, therefore their presence in thermal waters is an important consideration in therapeutic classification (**Hem, 1985; Mahala, 2019; Pham & Nguyen, 2024; Yashod, 2025**).

The mineral composition and temperature fluctuations in Ciwidey's thermal springs indicate unique therapeutic properties: Acidic waters (pH < 4) can facilitate dermatological therapies by promoting exfoliation and microbial regulation (**Cavanah, 2018**). Neutral and bicarbonate-rich springs enhance skin hydration and pH equilibrium, advantageous in spa treatments (**Cavanah, 2018; Fikri-Benbrahim et al., 2021**). The presence of calcium and sulfate suggests a possible benefit for bone and joint health, consistent with treatment methods for rheumatic and musculoskeletal illnesses. Soaking in thermal springs high in calcium and magnesium is essential for stimulating growth and sustaining strong bones. It also aids in alleviating illnesses such as vascular problems, neuritis, arthritis, bronchial infections, and dysmenorrhea. Furthermore, it promotes dermal health and facilitates the conversion of blood glucose into energy (**Torres-Ceron et al., 2019; Cacciapuoti et al., 2020**). Hyperthermal waters with increased ion concentration may improve blood circulation, promote relaxation, and stimulate metabolism (**Cacciapuoti et al., 2020**). Major minerals present in thermal waters can be integrated into society for their nutritional benefits to the human body (**Shoedarto et al., 2016**). Numerous ailments can be addressed via the utilization of various hot springs that include advantageous major minerals often found in thermal water (**Al Dulaymie et al., 2013**).

The hydrogeochemical composition of thermal springs has its own unique advantages for human health. The water derived from these springs has a capacity to boost digestion, enhance blood circulation, alleviate dermatological illnesses, soothe muscles, speed up the healing process, and detoxify the lymphatic system of the body (**Erfurt, 2011; Martínez et al., 2017; Cavanah, 2018; Lazzerini & da Silva, 2020; Cacciapuoti et al., 2020; Vaidya & Nakarmi, 2020; Zhang et al., 2022**).

5.3. Hydrogeochemistry properties of thermal springs for natural therapeutic uses

The significance to use thermal waters for therapeutic purposes is naturally determined by their thermal and chemical contents. The thermal spring of Ciwidey contains a lot of minerals that affect the human body in different external and internal mechanisms for physical rehabilitation and hydrotherapy. Thermal springs in the Ciwidey region have been divided into three hydrogeochemical types: Sodium Chloride (Na-Cl), Calcium Sulfate (Ca-SO_4), and Sodium Bicarbonate (Na-HCO_3), each offering unique therapeutic advantages (see **Figure 3**). The therapeutic effects correspond with the chemical profiles of each spring type, indicating that their hydrogeochemical compositions are crucial in defining their natural medical applications.

1. Sodium chloride (Na-Cl) thermal springs.

Sodium chloride thermal springs are a significant type of geothermal water, especially found in areas with deep geothermal reservoirs (**Chalise et al., 2023**) . The elevated chloride concentration in these springs signifies that the water derives from deeper subsurface sources and experiences limited interaction with surface water. Na-Cl thermal springs, typically marked by high temperatures, are frequently utilized as markers of advanced geothermal systems (**Çevikoğlu & Başaran, 2023**). Sodium chloride springs, often neutral to slightly alkaline, enhance circulation and skin health owing to their elevated mineral content. In Ciwidey, designate the thermal spring areas as P2, P6, P10, and P20. These springs, rich in salt and chloride ions, may improve skin hydration and aid in maintaining the body's electrolyte balance. Their thermal and chemical properties are considered beneficial for muscle relaxation therapy and for augmenting metabolic activity (**Cacciapuoti et al., 2020**). Consequently, Na-Cl thermal springs are frequently utilized in spa treatments aimed at relieving tension and fatigue (**Martínez et al., 2017**). The Sodium-Chloride thermal water is utilized to address numerous ailments of the musculoskeletal system, encompassing osteoarthritis, rheumatic disorders, arthritis, central nervous system problems, and post-traumatic stress. Sodium chloride is also advised for migraine sufferers (**Mohamedi & Chenaker, 2022**).

2. Calcium sulfate (Ca-SO_4) thermal springs.

Calcium sulfate thermal springs generally arise from the interaction of geothermal water with gypsum or anhydrite-bearing rocks. These springs exhibit high sulfate concentrations, potentially rendering the water slightly acidic. These springs are typically located in hydrothermal areas linked to calcium-rich sedimentary formations (**Zhao et al., 2024**). The $CaSO_4$ thermal springs located at P3, P4, P5, P6, P10, P11, P12, and P13. The presence of calcium and sulfate ions is thought to enhance bone and joint health, rendering these waters advantageous for musculoskeletal therapy. They are commonly utilized in the management of rheumatic diseases and associated disorders (**Vaidya & Nakarmi, 2020**). Moreover, the sulfate concentration in the water may promote skin detoxification and improve peripheral blood circulation (**Cacciapuoti et al., 2020**).

3. Sodium bicarbonate (Na-HCO_3) thermal springs.

Sodium bicarbonate thermal springs generally originate from the interaction of geothermal water with carbonate rocks or from mixing with meteoric water. These springs display high amounts of bicarbonate ions, which enhance their alkalinity. These characteristics are typically linked to shallow geothermal systems or regions where geothermal fluids combine with surface water (**Maria et al., 2024**). The Na-HCO_3 thermal springs are located at P9 and P14. The alkaline properties of Na-HCO_3 rich thermal springs may assist in balancing the pH of the skin and body, potentially benefiting dermatological health (**Vaidya & Nakarmi, 2020**). They are utilized therapeutically to relieve skin irritation, enhance skin elasticity, and are frequently incorporated into treatments for digestive health by alleviating gastrointestinal pain and reducing physiological acidity (**Cacciapuoti et al., 2020**). Clinical studies underscore their advantages for digestive health, such as neutralizing gastric acid, elevating gastric pH, accelerating gastric emptying, and stimulating digestive hormones. (**Capurso et al., 1999**).

The Ciwidey region demonstrates both the complicated geothermal dynamics of the area and its considerable potential for integrative health applications. The unique mineral compositions in each spring type offer a customized basis for therapeutic applications, including dermatology, muscle relaxation, and treatments for joints and metabolism. This association emphasizes the significance of geochemical characterization in optimizing natural resources for wellness interventions, establishing Ciwidey as an appropriate location for sustainable geomedical tourism and therapeutic hydrotherapy development. The therapeutic effectiveness of these springs is intricately linked to their chemical compositions, highlighting the essential importance of hydrogeochemical profiles in determining their natural health uses. The therapeutic application of thermal waters is fundamentally associated with their temperature and mineral composition, that affect diverse physiological reactions. Ciwidey's thermal springs, abundant in important minerals, influence both exterior and internal biological systems, facilitating physical rehabilitation,

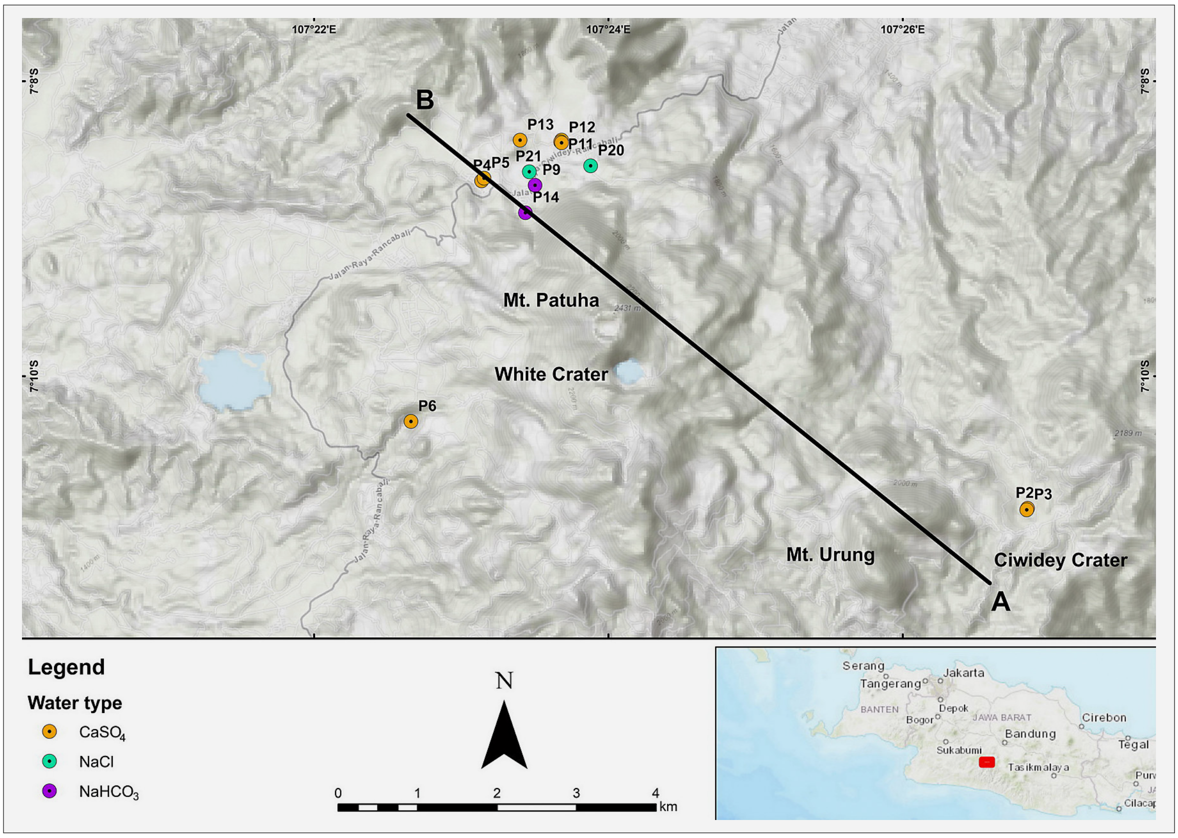

Figure 3. Hydrogeochemical water types in the Ciwidey region

muscular relaxation, cleansing, and enhanced circulation via hydrotherapeutic processes. Their heterogeneous composed renders them great assets for integrative wellness approaches and natural health strategies.

5.4. *Conceptual Model of Hydrogeochemistry in Thermal Springs*

Thermal springs are natural discharges of groundwater heated by geothermal activity, enriched with various minerals through complex interactions with geological structures (**Shoedarto et al., 2020**). Water traversing the Earth's crust dissolves minerals including halite, gypsum, and carbonates, producing unique hydrochemical fingerprints characterized as sodium chloride (Na-Cl), calcium sulfate (Ca-SO_4), and sodium bicarbonate (Na-HCO_3). These variations are affected by local geology, including evaporite-rich formations near volcanic systems such as Patuha Mountain, and hydrological parameters such as flow naturally, residence time, and dilution through shallow groundwater (**Rahayudin et al., 2020**).

The medical advantages of thermal springs are closely linked to their hydrogeochemical appearance, particularly determines their natural therapeutic properties. The conceptual model of hydrogeochemistry in the Ciwidey thermal springs assists to determine specific therapeutic areas (see **Figure 4**). Thermal springs containing sodium chloride (Na-Cl), commonly found in deep geothermal systems, are distinguished by their high temperatures and increased mineral concentration. Located in Ciwidey at sites including P2, P6, P10, and P20, these springs facilitate skin hydration, improve circulation, encourage muscular relaxation, and assist in alleviating migraines and musculoskeletal ailments. Calcium sulphate (Ca-SO_4) thermal springs arise from the interaction with gypsum-rich rocks and exhibit moderate acidity due to elevated sulphate concentrations. Located at sites P3 to P13, they enhance bone and joint health, facilitate skin cleansing, and promote enhanced peripheral blood circulation. Thermal springs of sodium bicarbonate (Na-HCO_3) at P9 and P14 arise from the interaction of geothermal water with carbonate rocks, yielding alkaline waters recognised for its ability to equilibrate body pH and alleviate digestive and dermatological conditions. This conceptual model illustrates how chemical signatures designate the specific therapeutic potential of each spring type.

Each water variety signifies distinct geochemical origins and therapeutic potentials (**Farhat et al., 2021**). Na-Cl rich springs, located in outflow zones, exhibit reduced mineral content due to interaction with surface aquifers (**Chalise et al., 2023**), whereas Na-HCO_3 dominated springs originate from meteoric and deep groundwater sources, frequently associated with alkaline conditions and calcite precipitation (**Iskandar et al., 2013**). Calcium sulfate waters demonstrate significant mineralization from gypsum-rich formations, promoting sulfate accumulation and observable travertine deposits in areas such

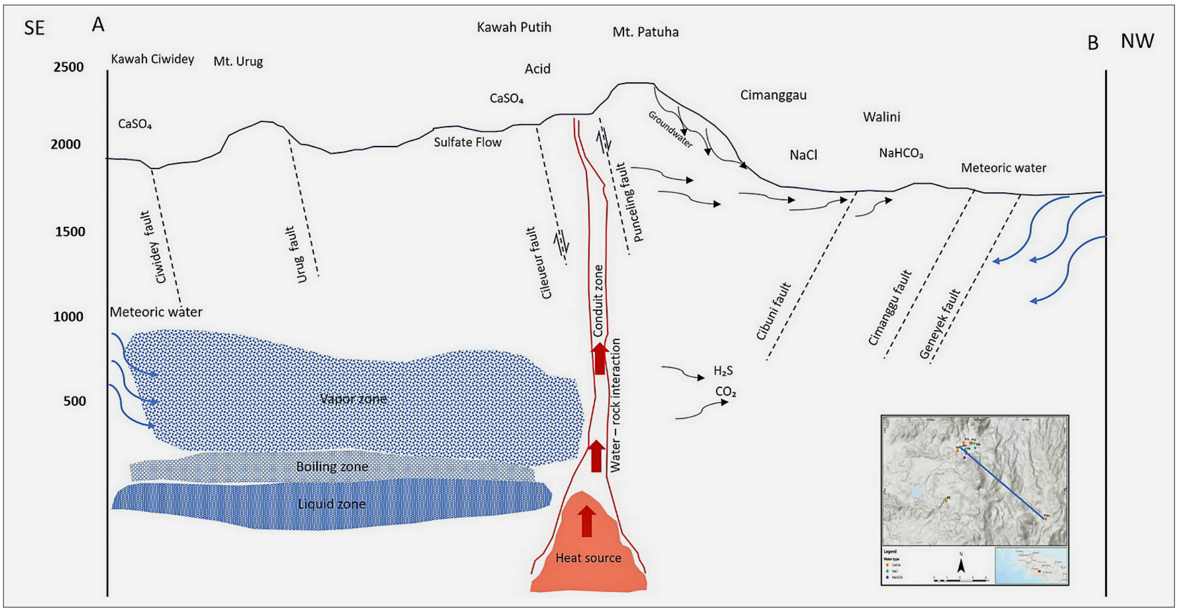

Figure 4. The conceptual model of hydrogeochemistry in the Ciwidey thermal springs, modified after (**Rahayudin et al., 2020**)

as Ciwidey (**Rahayudin et al., 2020**). The physicochemical parameters, including high levels of calcium, salt, chloride, sulfate, and bicarbonate, as well as neutral to alkaline pH, establish optimal environments for balneological uses (**Al Dulaymie et al., 2013**). These mineral waters facilitate treatments for dermatological ailments, musculoskeletal disorders, metabolic regulation, cardiovascular issues, and respiratory health via bathing, ingestion, or inhalation. The hydrogeochemistry of thermal springs provides insight into subsurface geological processes and acts as a resource for natural healing, based on mineral balance and environmental peacefulness.

6. Conclusions

The thermal springs in Ciwidey, Indonesia, represent a unique combination of rock formation and therapeutic properties. This work presents an innovative conceptual zoning approach that associates hydrogeochemical categories with targeted health-related applications. The springs were classified into three primary chemical types: Sodium Chloride (Na-Cl), Calcium Sulphate (Ca-SO_4), and Sodium Bicarbonate (Na-HCO_3), each originating from specific geological settings including deep geothermal fault systems, gypsum-rich formations, and carbonate-influenced lithologies. The algorithm identifies particular spring locations corresponding to specific medical benefits: Na-Cl type springs located at points P2, P6, P10, and P20 facilitate muscular relaxation and support dermatological ailments; Ca-SO_4 type springs situated between sites P3 and P13 are advantageous for skeletal and joint health; and Na-HCO_3 type springs at P9 and P14 contribute to pH balance, enhance digestive functions, and improve skin quality. This integrative methodology, combining geochemistry with medical geology, represents a notable progression in the strategic growth of geomedical hydrotherapy. Incorporating geographic specificity into therapeutic mapping establishes the framework for the sustainable management and maintenance of Ciwidey's geothermal resources, guaranteeing their enduring viability in comprehensive health and wellness applications. Further investigation and frequent monitoring of potential toxic metal elements in thermal spring water are required to assure public health safety. Controlled use is especially important when harmful quantities surpass acceptable limits.

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SAŽETAK

Hidrogeokemijske značajke termalnih izvora za prirodnu terapijsku upotrebu u medicinskoj geologiji na području Ciwidey, Zapadna Java, Indonezija

Termalni izvori u regiji Ciwidey u Indoneziji odražavaju bogato geološko nasljeđe i pružaju velike mogućnosti za prirodne terapijske primjene u medicinskoj geologiji. Cilj je ovoga istraživanja procijeniti hidrogeokemijske značajke nekoliko termalnih izvora u regiji Ciwidey i odrediti prikladnost za prirodnu terapijsku primjenu u medicinskoj geologiji. U okviru ove studije istražene su hidrogeokemijske značajke 13 termalnih izvora u regiji Ciwidey korištenjem atomske apsorpcijske spektrometrije (AAS; AA-7000 SHIMADZU), klasificirajući ih u tri različita tipa termalnih izvora na temelju dominantnih kemijskih značajki: natrijsko-kloridni (Na-Cl), kalcijsko-sulfatni (Ca-SO_4) i natrijsko-bikarbonatni (Na-HCO_3). Svaki hidrogeokemijski tip ima jedinstvena terapijska svojstva povezana s geokemijskim podrijetlom, dubokim geotermalnim vodonosnicima, litologijom bogatom gipsom ili interakcijama karbonatnih stijena. Analitički model uspostavljen u okviru ove studije identificirao je specifične zone za potencijalnu terapijsku primjenu: vode tipa Na-Cl (npr. lokacije P2, P6, P10, P20) potiču opuštanje mišića i regeneraciju kože; vode tipa Ca-SO_4 (lokacije P3 – P13) poboljšavaju zdravlje kostiju i zglobova; a vode tipa Na-HCO_3 (P9, P14) pomažu u regulaciji pH vrijednosti i ublažavanju probavnih te dermatoloških problema. Rezultati ovoga istraživanja otkrivaju bitne uvide u terapeutski potencijal termalnih izvora u regiji Ciwidey i naglašavaju važnost procjene lokalnih specifičnih značajki u medicinskoj geologiji.

Ključne riječi:
termalni izvori, hidrogeokemija, terapeutski, medicinska geologija, geotermalni

Author's contribution

Rizka Maria (Dr, senior researcher, hydrogeology) performed the field work, provided the geology and hydrogeochemical data, thermal water, and medical geology analysis. **Heri Nurohman** (M.Sc., junior researcher, geological engineering) presented all images and assisted with modelling analysis. **Hilda Lestiana** (M.T., junior researcher, geomatic engineering) provided the geographic modelling analysis. **Riostantieka Mayandari Shoedarto** (PhD., junior researcher, geomatic engineering) provided geological analysis. **Eki Naidania Dida** (M.Il, junior researcher, chemical engineering) provided the chemical data. **Jakah** (MT. junior researcher, geology engineering) provided the XRF data. **Ernowo** (Dr, senior researcher, geology), provided the geology data. **Yudi Rahayudin** (PhD, senior researcher, gological engineering) provided the geological conditions of the research area.
All authors have read and agreed to the published version of the manuscript.