Riset Geologi dan Pertambangan
Earth science journal · Open access · BRIN Earth Sciences & Maritime · BRIN Publishing
BRIN
ISSN 0125-9849 e-ISSN 2354 6638

RESEARCH ARTICLE
OPEN ACCESS

Riset Geologi dan Pertambangan (2026) Vol. 36, No. 1, 151–165
DOI: 10.55981/risetgeotam.2026.1536

Keywords:
Cirasea River
Groundwater
Hydrogeochemical
Volcanic Deposits
Land-use

Corresponding author:
Anna Fadliah Rusydi
anna.fadliah.rusydi@brin.go.id
Rizka Maria
rizka.maria@brin.go.id

Article history:
Received: 25 November 2025
Revised: 02 December 2025
Accepted: 29 December 2025

Author Contributions:
Conceptualization: AFR, RM
Data curation: AP, RM
Formal analysis: NS, DM, YR, RM, AFR
Funding acquisition: RM
Investigation: EH, NS, DM, YR, RM, AFR
Methodology: RM, AFR, AP, WN
Supervision: EH, DM, IJ, RM, AFR
Visualization: AP, AYA, AFR
Writing – original draft: EH, AP, NS, DM, AYA, WN, IJ, RM, AFR
Writing – review & editing: AFR, RM

Citation:
Hartati, E., Purwoarminta, A., Syakira, N., Marganingrum, D., Rahayudin, Y., Afandi, A. Y., Naily, W., Juwana, I., Maria, R., Rusydi, A. F., 2026. Hydrogeochemical characteristics of the Cirasea River in Indonesia: impact of groundwater interaction, geological features, and land use on water quality. J. Ris. Geol. Pertam, 36(1), 151–165, doi: 10.55981/risetgeotam.2026.1536

Hydrogeochemical characteristics of the Cirasea River in Indonesia: Impact of groundwater interaction, geological features, and land use on water quality

Etih Hartati[1,6], Ananta Purwoarminta[2], Nissa Syakira[1], Dyah Marganingrum[3,6], Yudi Rahayudin[4], Ahmad Yusuf Afandi[5], Wilda Naily[3,6], Iwan Juwana[1,6], Rizka Maria[2,6], Anna Fadliah Rusydi[5,6]

[1]Environmental Engineering Department, National Institute of Technology (Itenas), Bandung, Indonesia.
[2]Research Center for Geological Resources, National Research and Innovation Agency (BRIN), Indonesia.
[3]Research Center for Environment and Clean Technology, National Research and Innovation Agency (BRIN), Indonesia.
[4]Polytechnic of Energy and Mining, Ministry of Energy and Mineral Resources (ESDM), Indonesia.
[5]Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Indonesia.
[6]Centre for Research Collaboration Sustainable Environmental Carrying Capacity, Itenas Bandung – BRIN.

Abstract

This study was conducted to investigate the hydrogeochemical features and sources of pollution in Cirasea River located in the highly polluted Citarum Watershed, Indonesia. Field sampling was performed during the dry season to provide insight into the water quality during its most critical period. The water quality of river water and groundwater samples was evaluated and the natural geological controls and anthropogenic impact were compared using integrated hydrogeochemical methods (Gibbs, Stiff, and Piper diagrams) and statistical analyses (Pearson's correlation). Gibbs analysis showed that the main factor controlling the composition of water was water-rock interaction. Stiff diagrams revealed an evolutional trend of water chemistry from upstream to downstream, controlled by lithology (upstream) and land use (downstream). Piper diagrams showed that the dominant hydrochemical facies for both river and groundwater was Ca^{2+}–Mg^{2+}–HCO_3^- which is typical for volcanic rock weathering. Statistical analysis confirmed that the lithological types (Qgpk and Qmt) significantly affected the hydrogeochemical parameters (TDS, EC, Na^+, K^+, HCO_3^-). The study also showed the impact of land use, especially dryland agriculture (TDS, EC, K^+, SO_4^{2-}) and residential areas (Na^+, Cl^-, Mg^{2+}, HCO_3^-) on groundwater chemistry. The results provide a scientific basis for targeted monitoring and sustainable management strategies for reduction of water quality degradation in the Cirasea River sub-watershed considering both geological and anthropogenic pressures.

1. Introduction

River pollution represents a significant global environmental challenge, driven by rapid urbanization, industrial effluents, agricultural runoff, and environmental changes in watershed dynamics (Das et al., 2025; Pham & Nguyen, 2024). In addition to surface water degradation, groundwater systems, particularly in volcanic regions, face similarly complex challenges. Volcanic aquifers contain complex geochemical interactions between groundwater and the adjacent lithology (Razi et al., 2024). The Citarum River Basin in Indonesia is among the most severely contaminated watersheds, with significant degradation of both surface and subsurface water quality due to high population density, textile businesses, and unregulated waste disposal (Ginkel et al., 2015; Iskandar et al., 2017; Times, 2018; Astuti et al., 2024). Domestic activities account for approximately 40% of the total waste entering the Citarum River, whereas the remaining 60% originates from industrial discharges, agricultural runoff, and livestock wastewater (Febrita & Roosmini, 2022). Within this highly stressed system, the Cirasea River, as one of the major upstream tributaries, exhibits alarming ecological degradation, as evidenced by a Heavy Metal Pollution Index (HPI) of 131, which categorizes it as "heavily polluted" and indicates severe contamination by multiple trace metals (Maria et al., 2024). Rapid population growth, expanding industrial activities, and intensive agricultural practices within the Cirasea Sub-watershed further exacerbate pressure on water bodies, with pollutants such as pesticides, excess nutrients, and industrial waste contributing to significant declines in water quality (Fitria & Sarminingsih 2025). As an upstream catchment supporting the agricultural zones of Ciparay, Ibun, Kertasari, Majalaya, Pacet, and Paseh Districts (Husodo et al., 2021), the degradation of the Cirasea River poses not only substantial risks to regional agricultural productivity but also threatens the domestic and farming needs of residents who rely on it. This deterioration has accelerated the loss of sensitive aquatic species and weakened the ecological resilience of the upper Citarum.

The Cirasea River, a tributary of the upper Citarum River basin, is essential for replenishing volcanic aquifers that sustain household and agricultural needs (Iskandar et al., 2013; Marganingrum et al., 2013; Djuwita et al., 2021; Nursyifa et al., 2019; Husodo et al., 2021; Maria et al., 2024). However, land-use changes, unsustainable sewage infrastructure, and seasonal hydrological fluctuations have contributed to increased pollution concentrations in this sub-catchment, affecting groundwater sustainability (Aouati et al., 2023; Sabino et al., 2023). The Cirasea River is one of the tributaries of the Citarum Hulu River Basin. The Cirasea River flows through semi-urban and rural areas, making it vulnerable to intricate pollutant influxes and hydrochemical changes (Syamsiyah et al., 2025). Water availability and quality, as a dynamic and renewable natural resource, are significantly affected by hydrological processes and groundwater conditions, rendering groundwater sustainability a crucial element in hydrogeochemical evolution (Mareta et al., 2023). Groundwater flow analysis is crucial for comprehending groundwater-surface water interactions, pollutant transport, and the impact of geology and land-use factors on hydrogeochemical properties and water quality dynamics (Nugraha et al., 2024). These interactions play an important role in controlling the spatial variation of major ions, trace elements, and overall water quality within the Cirasea River system.

Due to its strategic hydrological importance, the Cirasea sub-watershed is poorly represented in hydrogeochemical studies. Previous studies in volcanic areas have dealt with large aquifer systems or water quality downstream, often neglecting the complex interactions between surface contamination and shallow groundwater in recharge zones (Razi et al., 2024; Gountié Dedzo et al., 2023; Maria et al., 2024; Astuti et al., 2024). However, most of the existing studies have focused on the main Citarum River, leaving a significant gap in information on the hydrogeochemical characteristics and pollutant dynamics of its tributaries, including Cirasea. This study combines complex hydrogeochemical and statistical methods to characterize water quality as well to distinguish between natural geological and anthropogenic sources. The results also offer a scientific basis for the development of targeted monitoring and sustainable management strategies to mitigate water quality degradation in the Cirasea River sub-watershed, especially in areas facing combined geological and anthropogenic pressures.

2. Study Area

2.1 Geological Setting

The Cirasea Sub-Watershed is situated within Bandung Regency, encompassed by the Citarum Hulu Watershed. Geographically, its coordinates extend from 107º 37’ 49.1747” E to 107º 48’ 30.8923” E and from 6º 59’ 32.9636” S to 7º 14’ 35.2305” S. The area encompasses several designated protected zones, including the Gunung Malabar Nature Reserve, Papandayan Nature Reserve, Kawah Kemojang Nature Tourism Park, and Gunung Mesigit. Administratively, it comprises the districts of Kertasari, Majalaya, Ciparay, Pacet, Paseh, and Ibun. Geologically, the region is characterized by hilly terrain located in the transition zone between the foothills of Mt. Malabar and the highlands of Bandung.

The Cirasea River flows through the Quaternary volcanic complex. Based on the geological map (**Figure 1**), samples S1-S2 and C1 are situated within a transitional zone between the Qopu unit, comprising the Mandalawangi–Mandalagiri Volcanics, and the Qwb unit, characterized by young andesite. This zone is predominantly defined by volcanic breccia and andesite lava resulting from both ancient and recent volcanic activity. Samples S3 and C5 are located within a transitional region between the Qopu and Qgpk (Guntur–Papandayan–Kendang volcanic rocks). Samples S4 through S6 and C8-C10 are positioned at the boundary between the Qmt (Malabar-Tilu volcanic materials) and Qgpk units, where deposits of breccia, lava, and pyroclastic deposits indicative of intermediate volcanic activity are predominant. Sample S7 is also within this zone and exhibits similar lithological characteristics. Additionally, samples S8-S9 and C11 are located within the Ql unit and represent lake deposits composed of clay, silt, and fine to coarse sand. In the Bandung Basin hydrogeological system, the low-permeability Kosambi Formation serves as an aquitard, whereas the permeable Cibeureum Formation operates as a confined aquifer, demonstrating that groundwater-surface water interactions and geological controls significantly affect the hydrogeochemical properties of the Cirasea River (Maryudhaningrum et al., 2025).

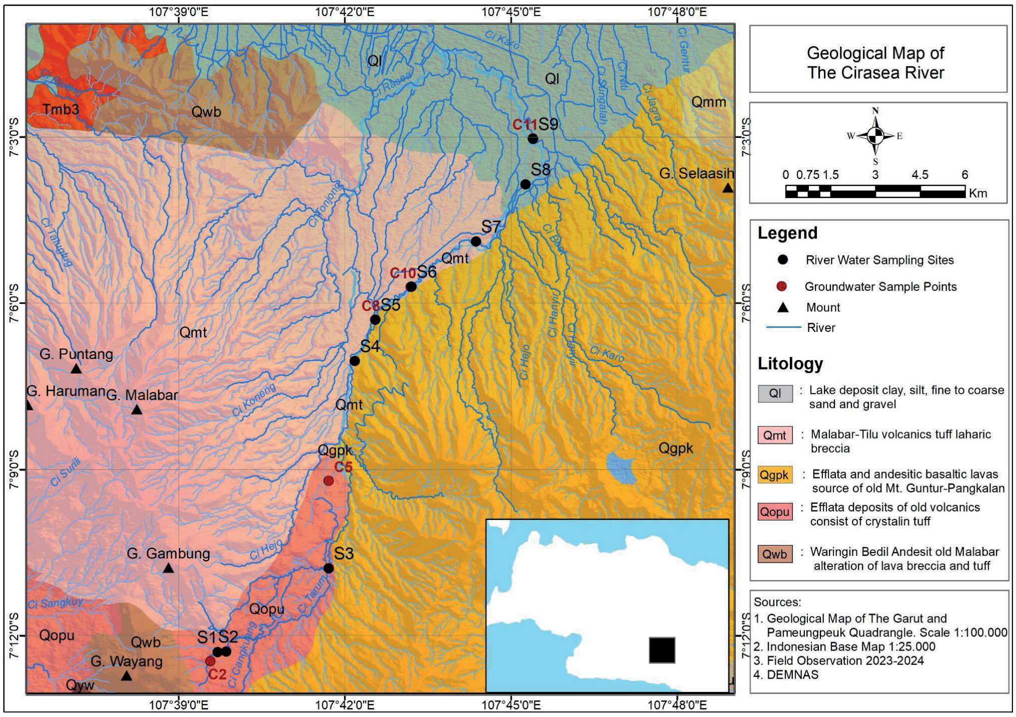

Figure 1. Geological map and sampling point

2.2 Land-uses

The land use in the Cirasea watershed area is diverse, including agricultural fields, residential zones, and industrial areas (**Figure 2**). In the upstream-to-midstream regions, the primary land uses are agriculture, plantations, and rice fields, whereas further downstream, industrial zones start to emerge. Residential areas are spread throughout various locations and become more concentrated in the downstream areas. Overall, samples were collected from sites where agriculture and residential areas intersect.

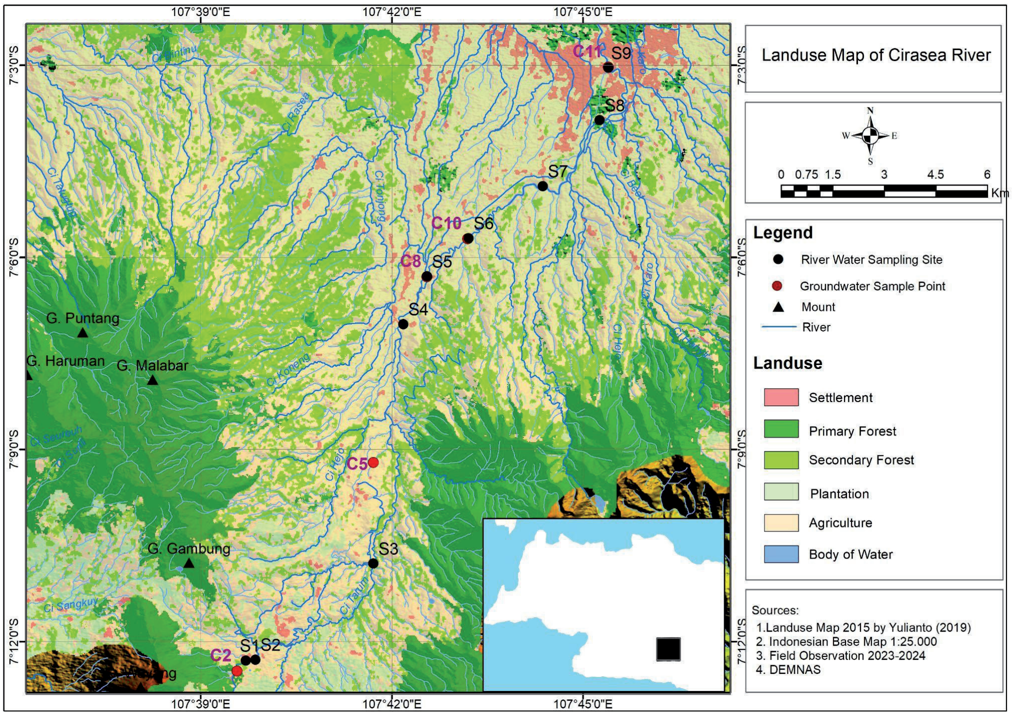

Figure 2. Land use map and sampling points

3. Methods

The field campaign was conducted in July 2024 (dry season) across nine river water samples (Figures 1 and 2). In addition, five groundwater samples from unconfined aquifers were collected to understand better the hydrogeochemical processes in the river system (Figures 1 and 2). The data collected during the dry season are expected to serve as a basis for characterizing the river's condition during its most critical period, as increased precipitation during the rainy season may reduce dissolved ion concentrations. Nonetheless, precipitation can also enhance soil leaching, and in some instances, anthropogenic waste may further contribute to this process, making rainy-season sampling important in the future.

Site selection was based on lithological characteristics of the research area and land-use criteria, which were considered representative of the predominant geological condition and land-use types in the study region (Figure 2), as well as accessibility considerations in accordance with SNI 6989.57:2008, Surface Water Sampling Methods. The specific criteria were devised to ensure that the sampling sites accurately represent the hydrogeological and environmental parameters of the study area. These criteria consider geological heterogeneity, land use patterns, and hydrological conditions, which are essential for reflecting geographical diversity in water quality. Table 1 summarizes the comprehensive subjects.

Table 1. Selection criteria for representative river and groundwater samples

Criteria	Specific Considerations	Rationale for the Representativeness
Geological Conditions	Lithology (volcanic, sedimentary).	Controls mineral dissolution and natural background chemistry.
	Structural features (faults, fractures).	Faults/fractures enhance groundwater flow and contaminant transport.
	Aquifer type (unconfined).	It affects recharge, vulnerability, and water quality.
Land Use Patterns	Agricultural zones	Agricultural chemical fertilizer residues.
	Urban	Domestic waste.

Criteria	Specific Considerations	Rationale for the Representativeness
Hydrological Setting	River order (mainstream, tributary).	Tributaries may capture localized pollution.
	Proximity to recharge and discharge zones.	Recharge zones reflect direct land use impacts.
	Seasonal flow variations	Seasonal variation affects dilution and concentration
Accessibility and Safety	Ease of sampling (depth, flow velocity)	Ensures practical and repeatable monitoring
	Safety for the field team	Reduces bias from inaccessible sites

At each site, in situ measurements of pH, water temperature (WT), total dissolved solids (TDS), and electrical conductivity (EC) were performed using a calibrated Horiba U-52G 10 instrument. For laboratory analysis, water samples were obtained via the grab sampling technique, which involves collecting a sample at a single observation point, and stored in sterilized polyethylene. Polyethylene bottles were sterilized with 10% HCl and rinsed thrice with the sample water. The analyzed parameters encompassed sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-), and sulfate (SO_4^{2-}). All parameters, except bicarbonate, were quantified by ion chromatography with conductivity detection using an ICS-6000 system (Thermo Fisher Scientific Inc., MA, USA). Sample preparation involved field filtration through a 0.45 μm hydrophilic filter, followed by preservation under frozen conditions until analysis. Bicarbonate concentration was determined through titration employing phenolphthalein as an indicator.

To ensure the accuracy of laboratory analytical results, the charge balance error (CBE) is calculated to assess them. An acceptable CBE value ranges from −5% to +5%, indicating that the ion analysis results show satisfactory analytical consistency and reliability (Appelo & Postma, 2005; Prapanchan et al., 2023). Additionally, the total concentrations of cations and anions (measured in meq/L) should also be close to the EC (in μS/cm) value divided by 100 (Appelo & Postma, 2005).

Hydrogeochemical analysis is conducted to thoroughly assess water quality and understand the characteristics of hydrogeochemical facies. This evaluation uses the Gibbs diagram to determine the relationship between water composition and aquifer properties (Ahmed, 2022), as well as the Stiff and Piper Diagrams to illustrate the major ions, characteristics, and water quality (Mairizki, 2021; Rao et al., 2024). A statistical analysis is then performed to examine the relationships among geology, land use, and the hydrogeochemical properties of water samples, identifying the key factors affecting the chemical characteristics of Cirasea River water, whether of natural (geological) origin or due to human activities. This methodological approach aligns with those successfully used in previous studies (Fahmi et al., 2023; Dede et al., 2024). Statistical analysis was performed using IBM SPSS Statistics version 26, employing Pearson's correlation coefficient to evaluate the relationships among hydrogeochemical parameters, geological characteristics, and land-use types.

4. Results and Discussion

4.1 Psychochemical characteristics

Cirasea River water quality across nine sampling sites (S1⍰S9) shows spatial variability in parameters, reflecting diverse environmental conditions along the river (Table 2). The observed water temperature fluctuates from 23.11°C to 26.95°C, with a mean value of approximately 24.80°C. Meanwhile, groundwater has a slightly lower temperature, averaging 24.86°C. The pH of both river water and groundwater is neutral, with averages of 7.82 and 7.07, respectively. TDS concentrations in river water range from 107 to 144 mg/L, with an average of 118.9 mg/L. In contrast, groundwater has a lower average TDS of 93.6 mg/L. EC values for river water vary from 159 to 222 μS/cm, averaging 179.8 μS/cm, indicating low to moderate ionization and no significant salinity or contamination. The EC values for groundwater are nearly identical to those of the river water sample, averaging 183.4 μS/cm.

Table 2. Physical and chemical properties of the Cirasea River and surrounding groundwater

Parameter	WT	pH	TDS	EC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
Unit	°C	-	mg/L	µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
					River						
S1	23.11	7.65	114	176	9.89	2.21	10.04	6.40	2.7	21.28	72.48
S2	23.31	7.54	117	175	9.43	3.25	9.05	6.07	2.64	15.03	86.18
S3	21.15	7.6	114	173	9.56	4.19	11.93	6.06	3.31	15.23	71.31
S4	24.13	7.53	117	175	8.61	3.91	8.57	5.04	3.65	9.67	95.2
S5	26.64	7.21	144	222	8.77	3.7	4.89	5.92	4.06	8.83	94.03
S6	26.18	8.35	113	169	12.36	3.68	2.83	7.20	6.77	12.81	116.74
S7	26.76	8.29	115	171	8.96	3.5	11.9	6.30	3.44	8.68	108.9
S8	26.95	7.95	129	198	8.93	3.43	44.29	7.07	4.51	12.39	107.73
S9	24.95	8.30	107	159	8.49	3.07	7.84	5.80	3.98	10.44	98.71
Average	24.80	7.82	118.9	179.8	9.44	3.44	12.37	6.21	3.90	12.71	94.59
					Groundwater						
C2	24.7	7.07	107	208	8.60	5.28	9.12	7.68	15.46	8.74	64.01
C5	23.5	7.07	109	209	12.46	4.42	15.39	2.14	11.34	9.46	70.78
C8	25.1	7.82	86	174	10.51	5.87	10.82	5.17	13.4	8.93	75.91
C10	25.6	7.91	83	167	9.83	4.5	11.08	5.6	13.4	8.12	82.25
C11	25.4	7.69	83	159	14.16	2.27	11.46	7.8	13.4	11.43	82.13
Average	24.7	7.07	93.6	183.4	11.12	4.47	11.57	5.68	13.40	9.34	75.02

Still in Table 2, the major cation concentrations in the groundwater samples are as follows: Na^+ ranged from 8.49 to 12.36 mg/L, with a mean of 9.44 mg/L; K^+ varied between 2.21 and 4.19 mg/L, averaging 3.44 mg/L; Ca^{2+} levels ranged from 2.83 to 44.29 mg/L, with a mean of 12.37 mg/L; and Mg^{2+} concentrations spanned from 5.04 to 7.20 mg/L, with an average of 6.21 mg/L. Overall, the cation composition of the groundwater samples is similar to that of the river water samples, with the concentrations ordered as Ca^{2+}> Na^+ > Mg^{2+}> K^+, and means of 11.57, 11.12, 5.68, and 4.47 mg/L, respectively. The elevated Na^+ concentration observed in sample S6 suggests significant water-rock interaction with sodium-rich minerals. Conversely, the notably high Ca^{2+} concentration in sample S8 indicates the influence of volcanic lithology, including basalt and andesite. The weathering of Ca^{2+}mineral-bearing contributes to the release of Ca^{2+} ions into the water. These ionic compositions reflect the weathering of volcanic rock deposits within the watershed.

Furthermore, the major anion, Cl^-, ranged from 2.64 to 6.77 mg/L with a mean of 3.90 mg/L. SO_4^{2-} exhibited concentrations between 8.68 and 15.23 mg/L, with an average of 12.71 mg/L. HCO_3^- levels are relatively high, spanning 71.31 to 116.74 mg/L and averaging 94.59 mg/L. In general, the anion concentrations of river water samples from highest to lowest comprise HCO_3^-, SO_4^{2-}, and Cl^-. Similar river water samples, groundwater samples mainly contain HCO_3^- as the dominant anion. Nevertheless, the second most prevalent anion is Cl^-, f, followed by SO_4^{2-}. The mean concentrations analyzed are 75.02, 13.40, and 9.34 mg/L for HCO_3^-, SO_4^{2-}, and Cl^-. Comparing anions in these water sources indicates that river water quality is heavily influenced by human activities in addition to interactions with rocks.

4.2 Hydrogeochemistry in understanding the geogenic impact

4.2.1 Gibbs Diagram

The Gibbs diagram is used to elucidate the primary processes that influence the chemical composition of Cirasea River water. This diagram plots the ratios of major ions against TDS, specifically utilizing the ratios of $Na^+/(Na^+ + Ca^{2+})$ for cations and $Cl^-/(Cl^- + HCO_3^-)$ for anions (Gibbs, 1970). By examining the data distribution in the diagram, it is possible to determine whether the water's chemical characteristics are predominantly influenced by precipitation, mineral weathering, or evaporation. The Gibbs ratio values for anions range from 0.218 mg/L to 0.847 mg/L, with a mean of 0.570 mg/L. Conversely, the cation values range from 0.028 mg/l to 0.111 mg/l, with an average of 0.064 mg/l. The diagram indicates that the Cirasea River water resides within the rock-dominance zone, suggesting that geological formations and mineral weathering exert significant influence on its chemistry. This means an interaction between the water and geological materials, including contributions from the weathering of volcanic and sedimentary rocks in the basin.

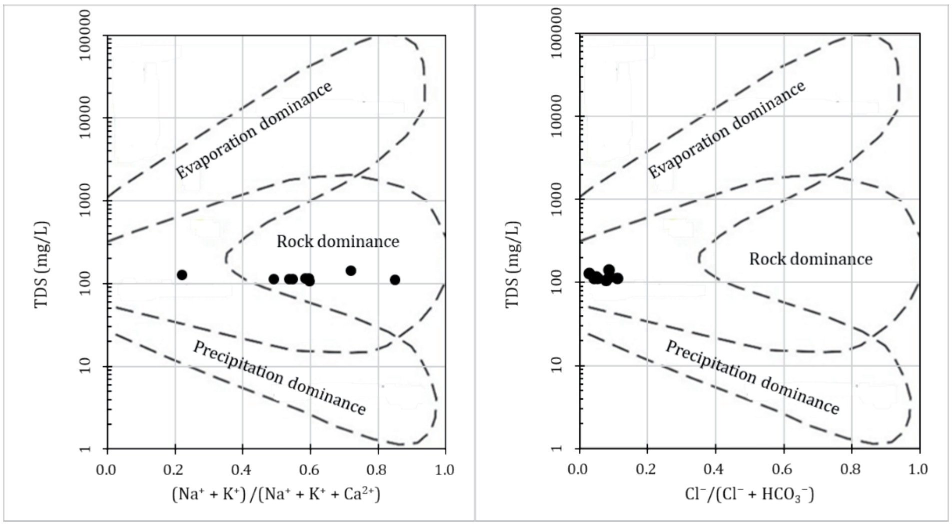

Figure 3. Gibbs Diagram showing the primary process controlling the chemical composition of the Cirasea River.

The Gibbs analysis indicates that water composition and chemical variation in the Cirasea River is mainly controlled by water-rock interaction rather than by the effects of precipitation and evaporation (Figure 3). The chemical dominance of rock weathering indicates the river is either a groundwater-fed system or an effluent system. This is similar to the research by Arifin et al. (2021), which discovered that the unconfined aquifer around the upper Citarum River has hydraulic conductivity between 8.34×10^{-7} and 2.19×10^{-5} m/s and is a gaining stream system. This shows that the rocks in the study area are permeable, which is in agreement with the Gibbs Diagram analysis. This also corresponds with the findings of Nabil et al. (2023) in Baleendah–Soreang in which most of the groundwater samples also show the dominance of rock weathering processes in the medial-distal zone characterized by volcanic rock and lake sediment lithology. In the same vein, Nugraha et al. (2019) found that the groundwater on the southern slopes of Merapi Volcano is dominated by the Ca^{2+}–Na^{+}–HCO_3^{-} facies, which indicates significant weathering of young volcanic rocks.

4.2.2 Stiff Diagram

The Stiff diagram is a graphical tool used to categorize water samples into hydrochemical groups based on their primary ions (Kagabu et al., 2011). The shape of the diagram indicates the relative proportions of various ions, while its size corresponds to the total ionic concentration, thereby identifying the dominant ion within the sample (Singh and Gewali, 2010).

The spatial variations of the ion composition along the river segment at the sampling points (S1–S9) are presented in Figure 4. Pattern diagrams for sites S1–S3 are consistent in depicting a narrow and elongated morphology, suggestive of relatively low dissolved ion concentrations with HCO_3^{-} as the dominant anion. This morphological similarity is explained by similar geological conditions, since all three sites are located within an ancient volcanic rock formation (Qopu), which represents effusive deposits of past volcanic activity. On the other hand, the groundwater sample C1, also belonging to this geological unit, is characterized by Ca^{2+} as the major cation and HCO_3^{-} as the major anion. Sample C5, however, is characterized by a prevalence of Ca^{2+} and Mg^{2+} cations, while HCO_3^{-} is still the dominant anion. These chemical characteristics show that the groundwater in this segment is still influenced by the mineral weathering of plagioclase in the volcanic sedimentary rocks.

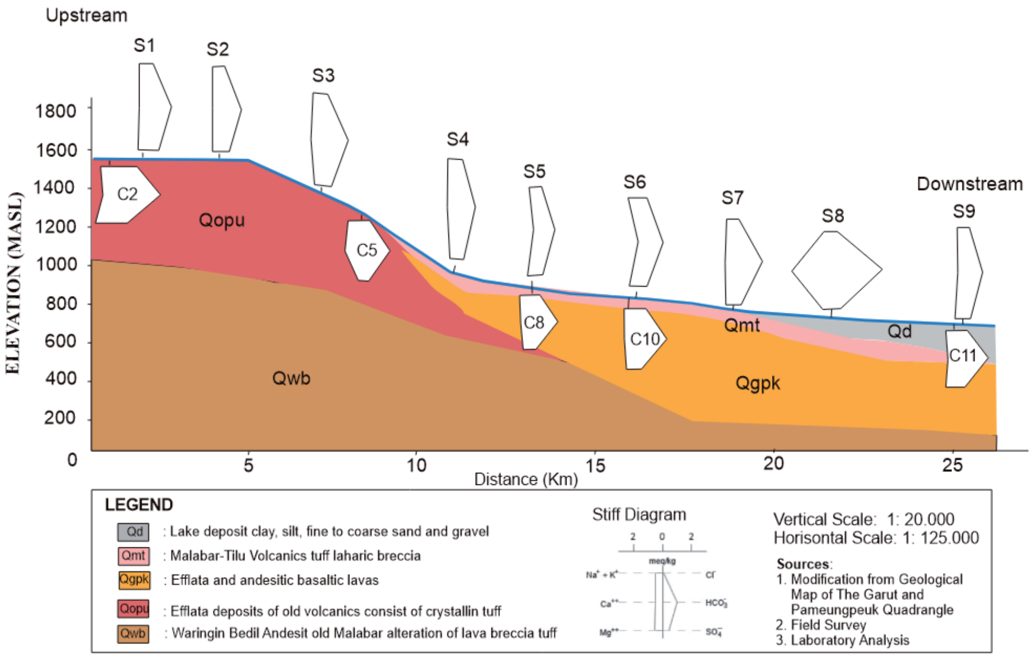

Figure 4. Stiff Diagram showing chemical composition and changes along the Cirasea River

Figure 4 still shows similar pattern for samples S4–S6, which have a narrow diagrammatic shape and dominated by Ca^{2+} and HCO_3^- ions. These samples are located in the volcanic rocks of Mount Malabar-Tilu (Qmt). This segment shows a similar pattern but with higher concentrations of Na^+, suggesting chemical evolution due to further interactions between water and volcanic rocks (Maria et al., 2024). Furthermore, Nabil et al. (2023) found that in this zone, the groundwater is predominantly of $CaHCO_3$ and $CaMgHCO_3$ types, which evolve to $CaNaHCO_3$ through cation exchange processes. The dominant cation in groundwater samples of C8 and C10 sites is Ca^{2+} and HCO_3^- ions respectively. The concentration of Na^+ is significantly greater than in the earlier sections of the study. These results suggest that the water types of river water and groundwater in this segment are similar, but the hydrochemical types of groundwater are more diverse. Therefore, it can be concluded that both water sources are affected by the interaction with volcanic rocks in this area.

Samples S7-S9 in the downstream section are dominated by lake sediment rock types (Ql). The expansion of the polygon in the diagram especially for S7 and S8 indicates an increase in total ion content and a more balanced distribution between cations and anions. This section has the highest concentrations of anions in groundwater samples, indicating the longest interaction with surrounding rock formations. This is consistent with the type of sediment in the lake, which is clay and known to have low permeability. The high concentration of Na^++K^+ and Cl^- in these points may be due to the mixing of highly mineralized groundwater and cation exchange reactions where Ca^{2+} in the water was exchanged with Na^+ from clay minerals (Putra et al., 2020).

The Stiff diagram demonstrates an evolution of water chemistry from the upstream (S1–S4) to the downstream (S5–S9). Volcanic sedimentary rocks have a greater influence on the upstream area. In contrast, the downstream segment (S7–S9) shows hydrogeochemical alterations due to changes in lithology, land-use practices and anthropogenic influences. This analysis is in agreement with the land-use conditions (Figure 2). The upstream area has less settlements than the downstream area of the study site.

4.2.3 Piper Diagram

Hydrochemical facies of river water samples (S1-S9) and groundwater samples (C2, C4, C8, C10, C11) are presented in a Piper diagram (Figure 5). The analysis shows that the two types of water are mostly dominated by the cations Ca^{2+} and Mg^{2+}. The dominant anion is bicarbonate HCO3-. All the samples have Ca^{2+} – Mg^{2+} – HCO_3^- water facies. The dominance of Ca^{2+} over other cations indicates that the hydrogeochemical features of the study area are mainly influenced by the weathering of calcium-rich plagioclase minerals in volcanic rocks (Jude et al., 2024; Maria et al., 2021). The similarity of water facies between river and groundwater samples indicates a common hydrogeological influence of volcanic sedimentary rocks. It is noteworthy that the river water samples S8 and S9 and the groundwater sample C11 belong to the sedimentary lake rock facies and exhibit the same $Ca^{2+} – HCO_3^-$ facies. However, the sample at S8 is different from the other samples. The facies found are consistent with Nugraha et al. (2019) in the Merapi volcano area and Nabil et al. (2023) in the Baleendah-Soreang volcano region, where the groundwater in volcanic areas is dominated by the $CaHCO_3$ facies. Furthermore, the hydrochemical characteristics may show anthropogenic influences as evidenced by the Stiff diagram (Figure 4). The South Bandung area is primarily characterized by volcanic and lacustrine deposits, exhibiting moderate to high groundwater potential (Ghiffari & Widodo, 2022). Productive aquifers and groundwater flow systems significantly influence groundwater-surface water interactions, solute transport, and the spatial development of water quality in the Cirasea River, especially under the combined effects of geological conditions and land-use practices.

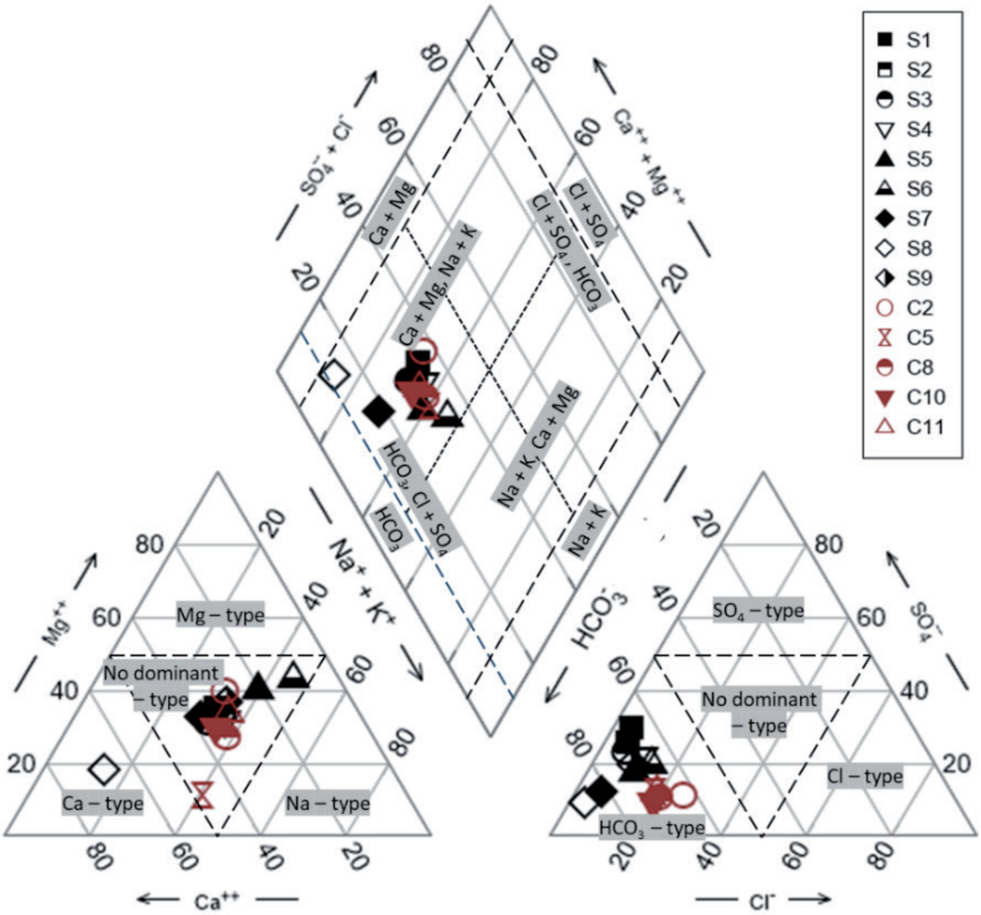

Figure 5. Piper Diagram showing the hydrochemical facies of water samples

4.3 Geostatistical analysis to evaluate the impact of geological and land-uses on water characteristics

Statistical analysis indicates that lithological types significantly influence hydrogeochemical parameters, underscoring the critical role of geological formations in determining groundwater chemistry within volcanic aquifer systems. The high regression coefficients, coupled with notably low p-values ($p < 0.01$) across nearly all parameters, confirm the direct impact of geological variability on groundwater quality (Table 3). Specifically, the rock units Qgpk and Qmt predominantly influence hydrogeochemical parameters: TDS, EC, Na^+, K^+, and HCO_3^-. This suggests that these lithologies exhibit strong mineral-weathering capacity, releasing primary ions into the aquifer. Elevated concentrations of Na^+ and HCO_3^- in Qmt imply the dissolution of feldspar minerals and carbonation reactions characteristic of intermediate to felsic volcanic rocks (Hem, 1985; Koesoemadinata & Hartono, 1981).

Table 3. Statistical analysis of the correlation between hydrogeological parameters, geological conditions, and land use.

	Coef.	Std. Err.	t	P>t	95%Conf	Interval
TDS						
Geology						
Qd	118	7.84	15.05	0	98	138
Qgpk	131	7.84	16.65	0	110	151
Qmt	114	7.84	14.54	0	94	134
Qopu	115	6.40	17.97	0	99	131
Land uses						
Dry land agriculture	124	4.56	27.08	0	113	134
Settlement	113	5.10	22.14	0	101	125
EC						
Geology						
Qd	179	13.68	13.05	0	143	214
Qgpk	199	13.68	14.51	0	163	234
Qmt	170	13.68	12.43	0	135	205
Qopu	175	11.17	15.64	0	146	203
Land uses						
Dry land agriculture	189	7.43	25.43	0	171	206
Settlement	169	8.30	20.3	0	149	188
Na^+						
Geology						
Qd	8.71	0.775	11.24	0	6.72	10.70
Qgpk	8.69	0.775	11.22	0	6.70	10.68
Qmt	10.66	0.775	13.76	0	8.67	12.65
Qopu	9.627	0.633	15.22	0	8.00	11.25
Land uses						
Dry land agriculture	9.152	0.543	16.86	0	7.87	10.44
Settlement	9.81	0.607	16.17	0	8.38	11.25
K^+						
Geology						
Qd	3.25	0.454	7.15	0.001	2.08	4.42
Qgpk	3.81	0.454	8.37	0	2.64	4.97
Qmt	3.59	0.454	7.9	0.001	2.42	4.76
Qopu	3.22	0.371	8.67	0	2.26	4.17
Land uses						
Dry land agriculture	9.15	0.543	16.86	0	7.87	10.44
Settlement	9.81	0.607	16.17	0	8.38	11.25
Ca^{2+}						
Geology						
Qd	26.07	8.47	3.08	0.027	4.31	47.82
Qgpk	6.73	8.47	0.8	0.463	-15.03	28.49
Qmt	7.37	8.47	0.87	0.424	-14.39	29.12
Qopu	10.34	6.91	1.5	0.195	-7.43	28.11
Land uses						
Dry land agriculture	15.94	5.54	2.88	0.024	2.85	29.04
Settlement	7.91	6.19	1.28	0.243	-6.74	22.55
Mg^{2+}						
Geology						
Qd	6.44	0.409	15.73	0	5.38	7.49
Qgpk	5.48	0.409	13.4	0	4.43	6.53
Qmt	6.75	0.409	16.5	0	5.70	7.80

	Coef.	Std. Err.	t	P>t	95%Conf	Interval
Qopu	6.18	0.334	18.49	0	5.32	7.04
Land uses						
Dry land agriculture	6.10	0.307	19.88	0	5.37	6.82
Settlement	6.34	0.343	18.49	0	5.53	7.15
Cl^-						
Geology						
Qd	4.25	0.777	5.46	0.003	2.25	6.24
Qgpk	3.86	0.777	4.96	0.004	1.86	5.85
Qmt	5.11	0.777	6.57	0.001	3.11	7.10
Qopu	2.88	0.635	4.54	0.006	1.25	4.52
Land uses						
Dry land agriculture	3.65	0.575	6.34	0	2.29	5.01
Settlement	4.21	0.643	6.54	0	2.69	5.73
SO_4^{2-}						
Geology						
Qd	11.42	1.90	6.01	0.002	6.54	16.29
Qgpk	9.25	1.90	4.87	0.005	4.37	14.13
Qmt	10.75	1.90	5.66	0.002	5.87	15.62
Qopu	17.18	1.55	11.09	0	13.20	21.16
Land uses						
Dry land agriculture	13.48	1.88	7.15	0	9.03	17.94
Settlement	11.74	2.11	5.57	0.001	6.76	16.72
HCO_3^-						
Geology						
Qd	103.22	4.57	22.59	0	91	115
Qgpk	94.615	4.57	20.7	0	83	106
Qmt	112.82	4.57	24.69	0	101	125
Qopu	76.66	3.73	20.55	0	67	86
Land uses						
Dry land agriculture	88.15	6.59	13.37	0	73	104
Settlement	102.63	7.37	13.92	0	85	120

Bold text highlights significant relationships that contribute most positively,

The coefficient (Coef.) quantifies the extent to which explanatory variables (geology and land use) influence output parameters (concentrations of parameters). The standard error (Std. Err) reflects the variability present among the sample values. The t and P>t values evaluate the significance of this relationship. The [95% Confidence Interval] helps determine whether to reject or accept the correlation. If the P-value ≤ 0.05 and the values between 95% confidence interval are not included 0, it indicates a significant correlation. If the P-value > 0.05 and the values within the 95% confidence interval include 0, it suggests that none of them are significant or related. Then the results of the land-use correlation analysis of hydrogeochemical parameters show that land use has a significant effect. In particular, dryland farming and residential land use have different effects on the chemical composition of groundwater and this reflects differences in human activities at regional scales. Correlation analysis indicates that land use has a significant effect on the hydrogeochemistry of groundwater in volcanic aquifers. The greatest TDS (124) and EC (189) coefficients are observed in the dryland agricultural zone, indicating the significant importance of this land cover for these parameters. This is because of intensive use of fertilizers and pesticides, and faster weathering of soil minerals due to agricultural activities (Sridharan & Senthil Nathan, 2017; Virnodkar et al., 2024). The increased levels of K^+ and SO_4^{2-} in the agricultural regions point towards elevated concentrations of ions in the agricultural inputs (Gugulothu et al., 2022; Sridharan & Senthil Nathan, 2017; Virnodkar et al., 2024).

Residential zones contributed more Na^+, Cl^-, Mg^{2+} and HCO_3^- ions. The high Na^+ and Cl^- levels are likely to be related to the outputs of domestic waste (Mester & Szabó, 2025). The higher concentration of HCO_3^- (102.6 mg/L) suggests carbonate dissolution due to anthropogenic activities entering the local drainage systems (Talabi, 2022). Dryland agriculture has a significant effect on calcium ion p = 0.024 while residential areas are not statistically significant p = 0.243. This indicates that calcium ions are more influenced by natural geogenic processes and dryland farming than by human or domestic sources in residential areas (Jibitha & Joseph, 2023; Samal et al., 2023).

5. Conclusions

The hydrogeochemical assessment of the Cirasea River and its groundwater in the upper Citarum River Basin shows the complex interaction of natural geologic processes and human activities affecting the water quality. The chemical composition of river water and groundwater samples is Ca^{2+}-Mg^{2+}-$HCO3^{-}$ facies which indicates geochemical interactions with regional rocks, especially the weathering of calcium-rich rocks in volcanic formations. The hydrochemical changes are presented in Stiff diagrams, which show the changes along the river course from upstream to downstream. The upstream part is still relatively clean but the downstream parts are affected by human activities, which change the water chemistry with increased concentrations of ions like Na^{+}, Cl^{-}, K^{+} and SO_4^{2-}. Moreover, statistical analysis of hydrogeochemical data and land-use information suggests that these factors significantly influence the concentrations of major cations and anions. The types of rocks in the basin have a high capacity to weather minerals and release primary ions into the aquifer system. In addition, agricultural and domestic waste contributes to the dissolved ion content of the river water. The distinct hydrochemical patterns observed in various sections of the river underscore the significance of accounting for both natural and anthropogenic influences when assessing the sustainability of water resources within volcanic aquifer systems.

The above mentioned hydrogeochemical characteristics and impacts are mainly for dry season conditions, which are expected to be the most vulnerable condition for water quality. However, temporal variability needs to be studied in future work, including the wet season, for a more comprehensive understanding of hydrogeochemical dynamics in the Cirasea sub-watershed. The results further emphasize the importance of targeted management and monitoring strategies, particularly for sub-watersheds (e.g., Cirasea) that are important for recharge processes but that are often neglected in research. Further, this study raises a number of new research questions for future studies, such as analysis of long term trends of specific pollutants under different seasonal and land use conditions, modeling of contaminant transport pathways from agricultural, domestic and industrial activities, assessment of effectiveness of potential mitigation techniques such as riparian buffers and natural adsorbents, and study of temporal variability between dry and wet seasons for better understanding of recharge dynamics.

Acknowledgments

The authors wish to express their gratitude to the Research Programme Number 1/III.4/HK/2025 on Hydrometeorological and Climatological Disaster Mitigation, Earth and Maritime Research Organisation BRIN, for funding and supporting this research. Authors also thank the Indonesian Groundwater Experts Association (PAAI) for helping facilitate the dissemination of this research during the international meeting held on 4–7 August 2025.

References

Ahmed, S., Mulhim, M., Qureshi, F., Akhtar, N., Lagudu, S., 2022. Reckoning groundwater quality and hydrogeochemical processes for drinking and irrigation purposes under the influence of anthropogenic activities, North India. Pollutants 2(4), 486-509. https://doi.org/10.3390/pollutants2040032

Aouati, H., Demdoum, A., Kada, H., Kouadra, R., 2023. The impact of climate change on groundwater quantity and quality in a semi-arid environment: a case study of Ain Azel plain (Northeast Algeria). Acta Geochim. 42(6), 1065–1078. https://doi.org/10.1007/s11631-023-00633-7

Appelo, C.A.J., Postma, D., 2005. Geochemistry, Groundwater and Pollution, 2nd ed. Balkema, Rotterdam. https://dx.doi.org/10.1201/9781439833544

Arifin, Ramdhan, A.M., Suwarman, R., Irawan, D.E., Hutasoit, L.M., Puradimaja, D.J., 2021. Estimation of 3D hydraulic conductivity distribution of unconfined aquifer using the geostatistical method and its relation to water quality and flooding in Upper Citarum River. IOP Conf. Ser.: Mater. Sci. Eng. 1098, 052013. https://doi.org/10.1088/1757-899X/1098/5/052013

Astuti, R.D.P., Maria, R., Nurohman, H., Shoedarto, R.M., Rusydi, A.F., Marganingrum, D., Damayanti, R., Mulyono, A., Rahayudin, Y., Dida, E.N., Yuliyanti, A., 2024. Potentially toxic elements contamination in the water resources: an integrated risk assessment approach in the upper Citarum watershed area. Environ. Geochem. Health. 46(3), 1–29. https://doi.org/10.1007/s10653-023-01818-y

Das, K., Ray, P., Rout, S., Patra, A., 2025. River pollution and biodiversity loss: a global perspective. J. Biodivers. Conservation. 9(2), 234–243. https://doi.org/10.5281/zenodo.15860188

Dede, M., Sunardi, S., Withaningsih, S., Lame, K.C., Hendarmawan, H., Husodo, T., et al., 2024. Landscape dynamics and its related factors in the Citarum River basin: a comparison of three algorithms with multivariate analysis. Geocarto Int. 39(1). https://doi.org/10.1080/10106049.2024.2329665

Djuwita, M.R., Hartono, D.M., Mursidik, S.S., Soesilo, T.E.B., 2021. Pollution load allocation on water pollution control in the Citarum River. J. Eng. Technol. Sci. 53(1), 1–15. https://doi.org/10.5614/j.eng.technol.sci.2021.53.1.12

Fahmi, M.A., Rohman, A., Ahsan, S.A., Firmansyah, F., Perdananugraha, G.M., Rusydi, A.F., 2023. Evaluation of ammonium issues in Indonesian groundwater: potential sources and removal methods. IOP Conf. Ser.: Earth Environ. Sci. 1201, 012108. https://doi.org/10.1088/1755-1315/1201/1/012108

Febrita, J., Roosmini, D., 2022. Analisis beban pencemar logam berat industri terhadap kualitas Sungai Citarum Hulu. JSIL. 7(1), 77–88. https://doi.org/10.29244/jsil.7.1.77-88

Fitria, D., Sarminingsih, A., 2025. Water resources assessment of Cirasea Watershed, Kabupaten Bandung. JPPIPA 11(8), 20–32. https://doi.org/10.29303/jppipa.v11i8.11801

Ghiffari, M. R. Al, & Widodo, L. E. (2022). Site selection for artificial recharge in Cisangkuy sub-watershed, West Java, using combined fuzzy logic and genetic algorithm. Ris. Geol. Pertamb. 32(2), 101–117. https://doi.org/10.14203/risetgeotam2022.v32.1213

Gibbs, R.J., 1970. Mechanisms controlling world water chemistry. Science 170, 1088–1090. https://doi.org/10.1126/science.170.3962.1088

Ginkel, C.H. van, Özerol, G., Lufiandi, 2015. Water quality monitoring in the upper Citarum River Basin: rethinking the role of stakeholders. In Proceedings of the 5th Environmental Technology and Management Conference; 5th ETM-conference, ITB, Bandung, 1-15.

Gountié Dedzo, M., Tsozué, D., Kpoumié, A., Nzeugang Nzeukou, A., 2023. Identification of major sources controlling groundwater geochemistry in Mount Makabaï, Cameroon. Acta Geochim. 42(2), 266–289. https://doi.org/10.1007/s11631-022-00577-4

Gugulothu, S., Rao, N.S., Das, R., Dhakate, R., 2022. Geochemical evaluation of groundwater and suitability for irrigation in South India. Appl. Water Sci. 12(6), 142. https://doi.org/10.1007/s13201-022-01583-w

Hem, J.D., 1985. Study and interpretation of the chemical characteristics of natural water. USGS Water-Supply Pap. 2254. https://doi.org/10.3133/wsp2254

Husodo, T., Wulandari, I., Abdoellah, O.S., Cahyandito, M.F., Shanida, S.S., 2021. Impact of agricultural land changes on farmers' income in Cirasea Watershed. IJEMS. 5(3). https://doi.org/10.26554/ijems.2021.5.3.95-104

Iskandar, I., Notosiswoyo, S., Purnadi, C., Pasaribu, T., 2013. Type and origin of springs and hotsprings at Bandung Basin. Procedia Earth Planet. Sci. 6, 262–268. https://doi.org/10.1016/j.proeps.2013.01.035

Iskandar, I., Farazi, H., Fadhilah, R., Purnandi, C., Notosiswoyo, S., 2017. Groundwater and solute transport modeling at hyporheic zone of Upper Citarum River. IOP Conf. Ser.: Earth Environ. Sci. 71, 012011. https://doi.org/10.1088/1755-1315/71/1/012011

Jibitha, J.B., Joseph, S., 2023. Sources of groundwater contamination: a review. Int. J. Res. Rev. 10(10), 121–126. https://doi.org/10.52403/ijrr.20231016

Jude, N.N., Regina, W.E., Agyingi, C., Valery, T.A., 2025. Geochemical and isotopic insights into groundwater dynamics in Mount Cameroon. Asian J. Geol. Res. 8(2), 234–262. https://doi.org/10.9734/ajoger/2025/v8i2197

Kagabu, M., Shimada, J., Delinom, R., Tsujimura, M., Taniguchi, M., 2011. Groundwater flow system under a rapidly urbanizing coastal city. J. Asian Earth Sci. 40(1), 226–239. https://doi.org/10.1016/j.jseaes.2010.07.012

Koesoemadinata, R.P., Hartono, D., 1981. Stratigraphy and sedimentation in the Bandung region. Proceedings of Indonesian Assoc. Of Geologist Ann. Conf. X., 318–336.

Mairizki, F., Putra, A.Y., Putri, W.A., 2021. Hydrogeochemical characteristics of groundwater in Rokan Hilir, Riau. J. Geosci. Eng. Environ. Technol. 6(4), 243–247. https://doi.org/10.25299/jgeet.2021.6.4.8136

Mareta, N., Maria, R., Lubis, R. F., Alam, B. Y. C. S. S. S., & Hadian, M. S. D. (2023). Assessing the water criticality index of the Welaran Watershed in Kebumen Geopark , Central Java : Towards good water resource management. Ris. Geol. Pertamb. 34(1), 1–12. https://doi.org/10.55981/risetgeotam.2024.1253

Marganingrum, D., Roosmini, Pradono, A., Sabar, 2013. Diferensiasi sumber pencemar sungai menggunakan metode indeks pencemar. Ris. Geol. Pertamb. 23(1), 37–48. http://dx.doi.org/10.14203/risetgeotam2013.v23.68

Maria, R., Satrio, Iskandarsyah, T.Y.W.M., Suganda, B.R., Delinom, R.M., Marganingrum, D., Purwoko, W., Sukmayadi, D., Hendarmawan, H., 2021. Groundwater recharge area based on hydrochemical and environmental isotopes analysis in the South Bandung volcanic area. Indones. J. Chem. 21(3), 609–625. https://doi.org/10.22146/ijc.58633

Maria, R., Astuti, R.D.P., Rusydi, A.F., Marganingrum, D., Mulyono, A., Nurohman, H., Dida, E.N., Damayanti, R., Shoedarto, R.M., Rahayudin, Y., Taufiqurrahman, A., Ferdiano, M.R., Nugraha, D.M., 2024. Heavy metal identification in water resources and the surrounding environment of the Cirasea riparian zone, Indonesia. Indones. J. Chem. 24(5), 1331–1348. https://doi.org/10.22146/ijc.93326

Maria, R., Rusydi, A.F., Marganingrum, D., Damayanti, R., Nurohman, H., Lestiana, H., Shoedarto, R.M., Mulyono, A., Rahayudin, Y., Setiawan, T., Iskandarsyah, T.Y.W.M., Suganda, B.R., Hendarmawan, H., 2024. Use of groundwater quality index, multivariate statistics and hydrogeochemistry for groundwater assessment in the Malabar volcanic area, Indonesia. Rud.-Geol.-Naft. Zb. 39(5), 41–62. https://doi.org/10.17794/rgn.2024.5.3

Maryudhaningrum, S. T., Cakrabuana, W., & Marthakusuma, L. (2025). Land Subsidence due to Groundwater Extraction and Natural Consolidation in the Bandung Basin , West Java , Indonesia. Ris. Geol. Pertamb. 35(1), 25–36. https://doi.org/10.55981/risetgeotam.2025.1363

Mester, T., Szabó, G., Kiss, E., Balla, D., 2025. Towards environmental sustainability: wastewater management and sewer networks for protecting groundwater in rural settlements. Urban Sci. 9(3), 80. https://doi.org/10.3390/urbansci9030080

Nabil, H., Rahmatulloh, S., Sapari, M., Hadian, D., Rachmat, B., 2023. Hydrogeochemical characteristics of groundwater in Baleendah-Soreang, South Bandung, West Java Province. Ris. Geol. Pertamb. 33(1), 37–48. https://doi.org/10.55981/risetgeotam.2023.1235

Nugraha, R.S., Putra, D.P., 2019. Hidrokimia dan indikasi kontaminasi pada air tanah di lereng selatan Gunung Merapi, Sleman, D.I. Yogyakarta. Ris. Geol. Pertamb. 29(2), 215–226. http://dx.doi.org/10.14203/risetgeotam2019.v29.1027

Nugraha, G. U., Bakti, H., & Lubis, R. F. (2024). Adaptive preconditioning Krylov Subspace methods for efficient numerical groundwater flow modeling in steady-state conditions. Ris. Geol. Pertamb. 34(2), 131–152. https://doi.org/10.55981/risetgeotam.2024.1345

Nurysyifa, F., Kaswanto, R.L., 2019. Institutional study to support sustainable basin management in Cirasea sub-basin, upstream Citarum. Proc. SPIE 11372, 1137207. https://doi.org/10.1117/12.2540788

Pham, N.Q., Nguyen, G.T., 2024. Evaluating groundwater quality using multivariate statistical analysis and groundwater quality index. Civ. Eng. J. 10(3), 699–713. https://doi.org/10.28991/CEJ-2024-010-03-03

Prapanchan, V.N., Kumar, E., Subramani, T., Sathya, U., Li, P., 2023. A global perspective on microplastic occurrence in sediments and water. Water 15(11), 1987. https://doi.org/10.3390/w15111987

Putra, D.P.E., Halim, D., Widagdo, S.S., Atmaja, R.R.S., 2020. Degradation of groundwater quality due to saline water occurrence in Bayat District, Klaten, Indonesia. J. Degra. Min. Lands Manag. 8(1), 2525–2536. https://doi.org/10.15243/jdmlm.2020.081.2525

Rao, N.S., Das, R., Sahoo, H.K., Gugulothu, S., 2024. Hydrochemical characterization and water quality perspectives for groundwater management. Groundw. Sustain. Dev. 24, 101071. https://doi.org/10.1016/j.gsd.2023.101071

Razi, M.H., Wilopo, W., Putra, D.P.E., 2024. Hydrogeochemical evolution and water–rock interaction processes in the multilayer volcanic aquifer of Yogyakarta-Sleman Basin, Indonesia. Environ. Earth Sci. 83(6), 1–17. https://doi.org/10.1007/s12665-024-11477-6

Sabino, H., Silva, G.C., Costa, V.E., Menezes, J., 2023. Conceptual model of a semi-arid coastal aquifer using hydrogeochemical variation and isotopic fingerprints in Brazil. Environ. Monit. Assess. 195(3), 1–17. https://doi.org/10.1007/s10661-023-10913-7

Samal, K.P., Dhara, P., Tarai, A., 2023. Anthropogenic and geogenic contamination of groundwater: a review. YMER Digit. 22(4), 149–165. https://ymerdigital.eu/uploads/YMER220441.pdf

Shoedarto, R.M., Rahayudin, Y., Taufiqurrahman, A., Ferdiano, M.R., Nugraha, D.M., 2024. Heavy metal identification in water resources and the surrounding environment of the Cirasea riparian zone, Indonesia. Indones. J. Chem. 24(5), 1331–1348. https://doi.org/10.22146/ijc.93326

Singh, A.K., Gewali, L.P., 2010. A shape-similarity index for Stiff diagrams. Int. J. Appl. Environ. Sci. 5(4), 541–553. http://www.ripublication.com/ijaes.htm

Sridharan, M., Senthil Nathan, D., 2017. Groundwater quality assessment for domestic and agricultural purposes in Puducherry region. Appl. Water Sci. 7(7), 4037–4053. https://doi.org/10.1007/s13201-017-0556-y

Syamsiyah, N., Sadeli, A.H., Saidah, Z., Noor, T.I., 2025. Community participation in the development of sustainable villages in the Cirasea Sub-Watershed, Indonesia. Sustainability. 17(11), 4871. https://doi.org/10.3390/su17114871

Talabi, A.O., 2022. Groundwater distribution in urban settlement. Int. J. Curr. Sci. Res. Rev. 5(10), 3838–3856. https://doi.org/10.47191/ijcsrr/V5-i10-06

Times, I., 2018. Menurut World Bank: Citarum merupakan sungai terkotor di dunia [Internet]. https://science.idntimes.com/discovery/ekasupriyadi/menurut-world-bank-citarum-merupakan-sungai-terkotor-di-dunia-c1c2

Virnodkar, S.S., Jha, S.K., Gaikwad, V.P., Nemade, S.B., Desai, M.M., 2024. Impacts of agricultural practices on groundwater quality and its remediation methods: a review. Nanotechnol. Percept. 14, 2813–283. https://nano-ntp.com/index.php/nano