



RESEARCH ARTICLE

Spatial Variation of Physicochemical Characteristics of Auya River Water in Relation to Geological Conditions, Paniai Regency, Central Papua, Indonesia

Deserius Boma^{1,*}, Emi Sukiyah¹, Boy Yoseph Cahya Sunan Sakti Syah Alam¹

¹ Geological Engineering Study Program, Padjadjaran University, Jatinangor, Sumedang, Indonesia.

* Corresponding author : deserius25001@mail.unpad.ac.id

Tel.: +62-812-7044-4065

Received: Sep 18, 2026; Accepted: Sep 30, 2026.

DOI: 10.25299/jgeet.2026.11.3.30300

Abstract

This study aims to analyze the spatial variation of the physicochemical characteristics of Auya River water and its relationship to geological conditions in Paniai Regency, Central Papua. *In situ measurements* were conducted at 20 stations (ST01–ST20) from upstream to downstream for *Total Dissolved Solids* (TDS), pH, *Electrical Conductivity* (EC), and temperature. Based on field conditions, the stations were grouped into Intrusive Igneous Rock (ST01–ST05), Siltstone (ST06–ST10), and Sand (ST11–ST20). Data were analyzed using descriptive statistics, *One-Way ANOVA*, Welch ANOVA, Tukey HSD, Pearson correlation, and partial correlation by controlling for cumulative distance. The results showed TDS 25–153 mg/L, pH 6.50–7.77, EC 48–166 $\mu\text{S}/\text{cm}$, and temperature 16.80–20.20 $^{\circ}\text{C}$, with an increasing trend from upstream to downstream. *One-Way ANOVA* showed significant differences between groups for TDS, pH, EC, and temperature ($p < 0.001$). Tukey's test showed that all pairs of groups differed significantly in TDS, pH, and EC, while temperature between Intrusive Igneous Rock and Siltstone was not significantly different ($p = 0.073$). Pearson's correlation showed a very strong positive relationship between parameters ($r = 0.969$ – 0.985 ; $p < 0.001$), but the coefficient decreased after cumulative distance was controlled. These findings suggest that the physicochemical characteristics of the water form spatial gradients that coincide with changes in geological conditions. Because the geological groups are also arranged in an upstream–downstream sequence, these statistical differences are interpreted as geological–spatial associations, not evidence of an independent influence of lithology. Thus, variations in the Auya River water likely reflect the combined contributions of geological conditions, longitudinal position, solute accumulation, elevation, and environmental factors along the river course, which also need to be considered in hydrogeochemical interpretations.

Keywords: Auya River; Spatial Variation; Water Physicochemistry; Geological Conditions; Lithology; Longitudinal Gradient.

1. Introduction

River water is an important part of the hydrological system whose physicochemical characteristics can change spatially due to variations in environmental, hydrological, and geological conditions along the river basin. These changes can be observed through *Total Dissolved Solids* (TDS), pH, *Electrical Conductivity* (EC), and temperature. TDS describes the amount of dissolved substances, EC relates to the concentration of dissolved ions, pH reflects acid-base conditions, while temperature describes thermal conditions that also influence physical and chemical processes in water. These parameters have been used to evaluate the condition and spatial variation of water characteristics in various water systems (Irwan et al., 2017; Pohan et al., 2017; HAR et al., 2023; Ayuningrum et al., 2023; Yanidar et al., 2023; Ayu et al., 2024; Rumabar et al., 2024).

Physicochemical variations in water can also be related to geological conditions and the materials interacting with the water. Water contact with rocks, sediments, and weathered materials allows for chemical weathering, mineral dissolution, leaching, and ion exchange. These processes can release dissolved constituents, contributing to changes in TDS and EC, as well as acid-base balance, as reflected in pH (Bastia and Equeenuddin, 2019; Su et al., 2022; Goldrich-Middaugh et al., 2022; Ma et al., 2023; Raj and Maya, 2023). Conceptually, based on previous research,

differences in mineral composition and reactivity can result in different weathering responses; weathering of silicate minerals can release dissolved constituents gradually, while more soluble materials can contribute more rapidly to the water's ionic composition. These mechanisms are used as the basis for geochemical interpretation and are not intended to identify specific minerals in the Auya River geological material. The magnitude of this process is also influenced by the nature of the geological material, the level of weathering, the time of water–rock contact, and local hydrological conditions (Duan et al., 2023; Hartanto et al., 2023; Razi et al., 2024).

The relationship between geological conditions and water characteristics has been reported in various hydrogeological environments. Differences in lithology, weathering processes, and water–rock interactions can produce distinct hydrogeochemical characteristics (Dianardi et al., 2018; Mairizki et al., 2021; Maria et al., 2022; Gaur et al., 2022; Afrilita et al., 2024; Islam and Mostafa, 2024; Laratmase et al., 2024; Masitoh et al., 2025). These variations can also develop spatially and temporally as a result of the interaction of geological conditions, hydrological processes, and environmental factors (Listyani and Ridayati, 2024; Duan et al., 2024; Hidayat et al., 2025; Basharat et al., 2025). In this study, the relationship to geological conditions was primarily considered for TDS, EC, and pH through the release and dissolution processes of dissolved constituents. In contrast,

temperature is more influenced by elevation, solar radiation, vegetation, flow conditions, and measurement time and is therefore not assumed to be a direct response to lithology, although temperature changes can affect geochemical reaction rates and water conductivity.

The Auya River in the Obano area of Paniai Regency, Central Papua, flows through varying geological conditions. Previous research by Boma and Mote (2026) showed that TDS and pH of the Auya River vary across the river section, related to changes in lithology and weathering levels. This study provided initial empirical evidence regarding the relationship between geological conditions and water characteristics, but it only included six observation points and two main parameters: TDS and pH. Consequently, the spatial physicochemical patterns of water along the course have not been characterized in detail. Furthermore, lithological changes occur along the upstream-downstream gradient, so differences in water parameters cannot be fully separated from other spatial factors that change along the course. These limitations leave a gap in knowledge regarding variations in TDS, pH, EC, and temperature over a narrower spatial range and their relationship to the geological conditions of the Auya River.

This study was developed to address this gap through observations at 20 stations (ST01–ST20) and measurements of TDS, pH, EC, and temperature. The observation stations are located in river segments characterized by intrusive igneous rocks, siltstone, and sand, while the weathering level of outcrops is used as supporting geological information. Increasing the number of stations from six to 20 and the addition of EC and temperature allow for the evaluation of water physicochemical change patterns with more detailed spatial resolution. Statistical analysis is used to quantitatively evaluate spatial variations, parameter differences between lithological groups, and relationships between parameters, as is the approach used in spatial variation studies and hydrogeochemical characterization (Yanidar et al., 2023; Listyani and Ridayati, 2024; Basharat et al., 2025).

However, the lithological groups at the study site are arranged along the upstream–downstream gradient of the Auya River, so that differences in parameters between groups may reflect a combination of geological conditions and other spatial factors. Therefore, the differences found are not interpreted as evidence of a direct causal relationship between lithology and water characteristics, but rather as a spatial association between water physicochemical variations and geological conditions along the Auya River. Based on this framework, this study aims to analyze the spatial variations of TDS, pH, EC, and temperature; evaluate their differences in segments with different lithological conditions; analyze the relationships between parameters; and interpret the obtained patterns in relation to the geological conditions and weathering levels of outcrops in the Auya River, Paniai Regency, Central Papua, Indonesia.

2. Regional Geology

This research was conducted in Obano District, Paniai Regency, Central Papua Province. Regionally, the research area falls within the scope of Geological Map of the Enarotali Sheet, Irian Jaya, scale 1:250,000. Based on the map, the area around the Auya River is composed of several geological units with different ages and lithological characteristics, especially the Timepa Monzonite (Tmpt), the Kemelangan Group (JKk), and Lake Deposits (Ql)

(Harahap et al., 1990). This geological composition reflects the development of the region influenced by magmatic activity, sedimentation, deformation, and deposition of surface materials. This diversity of geological conditions is important in the study because the Auya River flows through or adjacent to different geological materials, allowing for interactions between water and rocks and sediments along the river flow.

The Timepa Monzonite (Tmpt) is a Pliocene unit associated with magmatic activity. This unit is composed of quartz diorite, monzonite, porphyry diorite, quartz andesite, and muscovite-biotite granite (Harahap et al., 1990). Based on the general characteristics of its constituent rocks, this unit can contain silicate minerals such as feldspar and quartz, accompanied by mafic minerals in certain rock types, while muscovite and biotite are the minerals explicitly mentioned in muscovite-biotite granite. When exposed at the surface, the minerals that make up igneous rocks can undergo physical and chemical weathering through processes such as hydrolysis, dissolution, and leaching. These processes conceptually allow for the release of dissolved components from the rocks into the water. However, because this study did not conduct direct mineralogical analysis at each station, the presence and proportion of specific minerals are not used as direct evidence regarding the minerals that control the water characteristics of the Auya River.

Another unit that developed in the study area is the Kemelangan Group (JKk) of Middle Jurassic–Paleocene age. According to Harahap et al. (1990), this unit is primarily composed of siltstone, which in the northern part has undergone deformation to develop into slate. In some parts, siltstone is found interbedded with sandstone, while mudstone is present locally. In general, clastic sedimentary rocks such as siltstone and sandstone can be composed of quartz, clay minerals, feldspar, and rock fragments in varying proportions. The local presence of mudstone also indicates the possible presence of carbonate material in certain parts of the unit. However, the actual mineral composition and proportions at the observation location have not been determined through direct mineralogical analysis, so the mineralogical characteristics are used as a framework for geological interpretation, not as a result of mineral identification in the study samples.

The characteristics of siltstone are important in the context of this study because it is a fine-grained clastic sedimentary rock that has undergone lithification. Relatively fine grain size, mineral composition, degree of cementation, fracturing, and weathering can influence the extent and intensity of contact between the rock and water. During weathering, the minerals and materials composing siltstone can undergo leaching and dissolution, potentially releasing dissolved components into the aquatic system. These processes provide a geological basis for evaluating the possible association between the presence of siltstone and variations in TDS, EC, and pH measured in the Auya River. However, this relationship remains interpreted as an association based on geological conditions and spatial patterns, rather than as evidence of a direct causal relationship.

The younger geological unit, the Lake Deposit (Ql), is Holocene in age and composed primarily of mud and sand (Harahap et al., 1990). Unlike the Timepa Monzonite and the Kemelangan Group, which consist of consolidated rocks, the material in the Lake Deposit is relatively unconsolidated surface sediment. In this study, the term "sand" is used to describe loose, sand-sized sediment found at the

observation site and is regionally associated with the presence of younger surface deposits. Sand material has different physical characteristics compared to intrusive igneous rocks and siltstones, particularly in terms of grain size, porosity, permeability, and the contact conditions between water and sediment grains. These differences in characteristics can influence the exchange of material between the solid and water phases, although the extent of the contribution to water composition remains dependent on the mineral composition and local environmental conditions.

Based on field conditions, geological materials at the observation stations in this study are grouped into three main categories, namely Intrusive Igneous Rock, Siltstone, and Sand. This grouping needs to be distinguished from the nomenclature of regional geological units. Timepa Monzonite (Tmpt), Kemelangan Group (JKk), and Lake Deposits (Ql) are regional geological units according to Harahap et al. (1990), while Intrusive Igneous Rock, Siltstone, and Sand are geological material groups used to classify conditions at the observation stations. Intrusive Igneous Rock and Siltstone are rock materials that have been consolidated, while Sand is loose sedimentary material that has not undergone lithification. This distinction is important so that the classification of materials at the research stations is not directly equated with the names of formations or stratigraphic units on regional geological maps.

The differences in the properties of rocks and sediments provide conditions that allow for interactions between water and geological materials through weathering, dissolution, leaching, hydrolysis, and ion exchange. The release of ions and dissolved materials from rocks and sediments is potentially reflected in changes in Total Dissolved Solids (TDS) and Electrical Conductivity (EC), while reactions between water and minerals or weathered materials can be related to changes in pH. Temperature is interpreted more carefully because in addition to being related to physicochemical processes, this parameter can be influenced by other spatial factors, such as elevation, solar radiation, vegetation cover, discharge, and flow characteristics. Therefore, geological conditions in this study are treated as one of the factors associated with water physicochemical variations, not as the sole controlling factor.

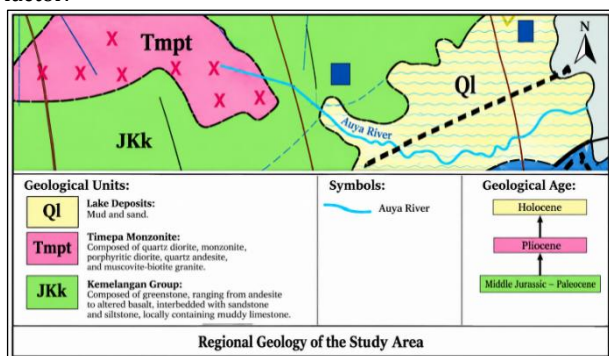


Fig 1. Regional Geology of the Research Area
Source: Regional geological map sheet Enarotali (1990)

Regional geological information from Harahap et al. (1990) was then used as a framework to understand the distribution of rock and sediment units around the Auya River and to support the interpretation of observation results at 20 stations. (ST01–ST20). The geological map of the research area needs to clearly show Auya River flow,

ST01–ST20 locations, boundaries between geological units, map scale, and north direction. Since the geological material groups at the observation stations are also arranged along an upstream–downstream gradient, variations in TDS, pH, EC, and temperature in the Intrusive Igneous Rock, Siltstone, and Sand groups are interpreted as geological–spatial associations. This approach allows the relationship between geological conditions and physicochemical characteristics of water to be evaluated without assuming that differences in water parameters are entirely due to differences in lithology.

3. Research Methods

This study used an observational quantitative approach to analyze the spatial variation of the physicochemical characteristics of Auya River water in relation to geological conditions. Data collection was conducted in Obano District, Paniai Regency, Central Papua, from late July to early August 2026. A total of 20 observation stations (ST01–ST20) were determined *purposely* following the direction of river flow from upstream to downstream by considering changes in geological conditions, spatial representation, the presence of outcrops or geological materials, and location accessibility. The coordinates and elevation of each station were determined using a Garmin eTrex 10 GPS. The elevation of the observation locations ranged from 2,185 m at ST01 to 1,769 m at ST20, while the cumulative distance from ST01 ranged from 0.000–8.032 km and was used to represent the longitudinal position along the river flow.

Based on field observations, stations were grouped into three geological condition groups, namely Intrusive Igneous Rock (ST01–ST05; n = 5), Siltstone (ST06–ST10; n = 5), and Sand (ST11–ST20; n = 10). The difference in the number of stations between groups follows the distribution and length of the geological material zones encountered along the research track. The Sand Zone covers a longer section of the track and is therefore represented by a greater number of stations. The weathering conditions of the outcrops were visually classified based on color changes, surface conditions, and physical changes of the material into Slightly Weathered (ST01–ST04), Moderately Weathered (ST05–ST15 and ST20), and Highly Weathered (ST16–ST19). Weathering data were used as supporting geological information in the interpretation of the results and were not treated as the main factor in the inferential statistical analysis.

The physicochemical parameters of water were measured directly (*in situ*) at each station using the Water Quality Tester 5-in-1 Model EZ-9909, including Total Dissolved Solids (TDS; mg/L), pH, Electrical Conductivity (EC; $\mu\text{S}/\text{cm}$), and temperature ($^{\circ}\text{C}$). The instrument was prepared and calibrated according to the instrument usage procedures before measurement. The sensor was cleaned before use at the next station to minimize cross-contamination. Measurements were made by placing the sensor in river water, then the TDS, pH, EC, and temperature values were recorded after the instrument readings stabilized. The same measurement procedure was applied at all stations to maintain consistency and comparability of data between locations.

Data were analyzed using IBM SPSS Statistics 27 with a significance level of $\alpha = 0.05$. Descriptive statistics were used to determine the minimum, maximum, mean, and standard deviation values of TDS, pH, EC, and temperature, both overall and by geological condition group. Prior to inferential analysis, the distribution of data in each group was examined using the Shapiro–Wilk test, while

homogeneity of variance was evaluated using the Levene test. Differences in the average physicochemical parameters between the Intrusive Igneous Rock, Siltstone, and Sand groups were analyzed using *One-Way ANOVA*. Given the unbalanced group sizes ($n = 5, 5, \text{ and } 10$), *Welch ANOVA* was used as a robustness analysis to evaluate the consistency of the results against the imbalance in group size and possible differences in variance. The Levene test results showed a $p \text{ value} > 0.05$ for all parameters so that the assumption of homogeneity of variance was met. If the ANOVA showed a significant difference ($p < 0.05$), the analysis was continued using the *Tukey HSD post-hoc* to identify significantly different group pairs. This approach also ensures that ANOVA significance is not immediately interpreted as evidence that all pairs of groups are different.

The relationships between TDS, pH, EC, and temperature parameters were analyzed using a two-way Pearson correlation at a significance level of $\alpha = 0.05$ and visualized through a scatterplot with a linear regression line. Because the geological condition groups are arranged along an upstream-downstream gradient, the correlations between parameters are potentially influenced by the same spatial trend. Therefore, partial correlations controlling for cumulative distance from ST01 were used to evaluate the relationships between parameters after accounting for the linear component of longitudinal position. Elevation was used as an additional sensitivity analysis to evaluate the stability of the relationships between parameters with respect to topographic gradients. This analysis was used to distinguish directly observed relationships between parameters from those that may be influenced by spatial position along the river.

Interpretation of results was carried out by integrating geological conditions, weathering levels, elevation, cumulative distance, physicochemical characteristics of water, and statistical analysis results. In the sampling design of this study, the Intrusive Igneous Rock, Siltstone, and Sandstone groups coincided with the upstream, middle, and downstream sections of the Auya River, respectively. This condition caused geological factors and longitudinal position to be unable to be completely separated as independent factors. Therefore, differences in TDS, pH, EC, and temperature between groups were interpreted as geological-spatial associations, not as evidence of a causal relationship or independent influence of lithology on water characteristics. This interpretative framework was used to maintain consistency between the observational design, statistical analysis, research results, and conclusions.

4. Results And Discussion

4.1. Field Data and Geological Conditions of Observation Stations

Field observations were conducted at 20 stations (ST01–ST20) sequentially distributed along the main flow of the Auya River, Obano District, Paniai Regency, Central Papua. The distribution of stations follows the flow direction from the upstream in the northwest to the downstream approaching Lake Paniai (Figure 2). The upstream section has a relatively steeper relief indicated by tighter contours with an elevation of around 2,300–2,500 m, while the downstream section exhibits a gentler relief with an elevation of around 1,700–1,800 m. The arrangement of stations following the flow direction provides a spatial framework for evaluating changes in geological conditions and physicochemical characteristics of water from upstream to downstream.

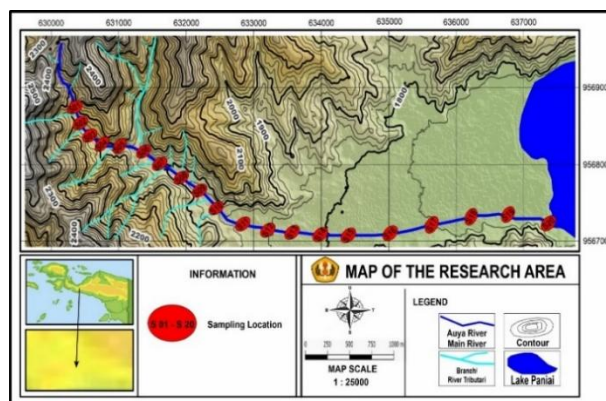


Fig 2. Map of research locations and distribution of observation stations ST01–ST20 along the Auya River.

Source: Map of research locations, processed by the author (2026).

The results of field geological observations indicate that the research stations can be grouped into three main geological material groups, namely Intrusive Igneous Rock at ST01–ST05, Siltstone at ST06–ST10, and Sand at ST11–ST20. This grouping is based on the geological material found at each observation location and is used as the basis for grouping data in statistical analysis. The term **Siltstone** at ST06–ST10 refers to fine-grained clastic sedimentary rocks that have undergone lithification, not loose silt sediment. Meanwhile, Sand at ST11–ST20 is loose sedimentary material that has not been consolidated. This distinction is important because Intrusive Igneous Rock and Siltstone are consolidated rocks, while Sand is unconsolidated sedimentary material.



Fig 3. Photo of an intrusive igneous rock sample

In the upstream section (ST01–ST05), the geological conditions of the field are dominated by Intrusive Igneous Rocks. In this group, the degree of weathering of the outcrops varies from slightly weathered in ST01–ST04 to moderately weathered in ST05. The physicochemical characteristics of the water in this section show a TDS of 25–48 mg/L, pH 6.50–6.73, EC 48–83 $\mu\text{S}/\text{cm}$, and temperature 16.80–17.71 $^{\circ}\text{C}$. The relatively lower parameter values in the upstream section describe the initial conditions of the water at the series of research stations before the flow enters the river section associated with the next geological material.

In the middle section (ST06–ST10), the geological material observed was siltstone with a moderate level of weathering. The transition from intrusive igneous rock to siltstone was spatially followed by an increase in TDS to 70–93 mg/L and EC to 86–118 $\mu\text{S}/\text{cm}$. The pH value ranged from 6.72–7.08, while the water temperature ranged from 17.57–18.47 $^{\circ}\text{C}$. These conditions indicate that changes in

geological material groups from the upstream to the middle section coincided with changes in the physicochemical characteristics of the water. However, because lithological changes occur in the direction of the upstream–downstream position, this pattern at the field observation stage was treated as a spatial association and has not been interpreted as a direct result of lithological changes.



Fig 4. Photo of a siltstone sample

In the downstream section (ST11–ST20), the material encountered is dominated by sand, which is loose, unconsolidated sediment. The level of weathering recorded in the environment around the station is generally in the moderate weathering category, while highly weathered conditions are found in ST16–ST19. In this group, TDS ranges from 108–153 mg/L, pH 7.20–7.77, EC 125–166 $\mu\text{S}/\text{cm}$, and temperature 18.42–20.20 $^{\circ}\text{C}$. Compared to the stations in the upstream and middle sections, the downstream section shows generally higher TDS, EC, pH, and temperature values.



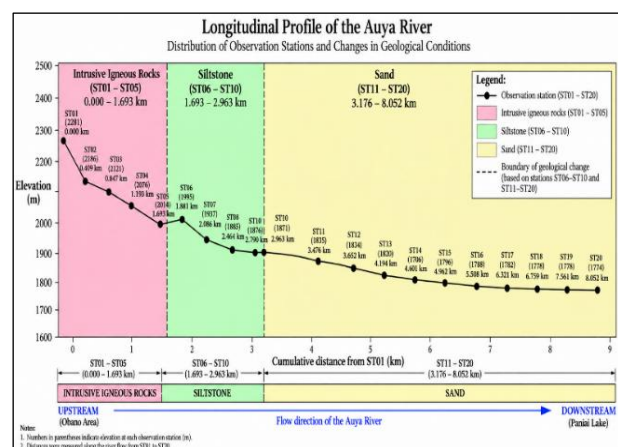
Fig 5. Photo of sand sample

Overall, the field data showed a spatial pattern of increasing TDS from 25 mg/L at ST01 to 153 mg/L at ST20, while pH ranged from 6.50–7.77, EC between 48–166 $\mu\text{S}/\text{cm}$, and temperature between 16.80–20.20 $^{\circ}\text{C}$. The increase in these parameters occurred simultaneously with changes in geological material from Intrusive Igneous Rock at ST01–ST05, Siltstone at ST06–ST10, to Sand at ST11–ST20. However, this pattern does not directly indicate a causal relationship because the geological material groups are also arranged along an upstream–downstream gradient. Thus, the field data showed a spatial correspondence between changes in geological conditions and variations in the physicochemical characteristics of the Auya River water, which was further evaluated through statistical analysis.

Table 1. Physicochemical characteristics of water and geological conditions of ST01–ST20

Station	Position	TDS	pH	EC	Temperature	Geological Materials	Outcrop Weathering
ST01	Upstream	25	6.50	48	16.80	Intrusive Igneous Rock	A little weathered
ST02	Upstream	31	6.55	56	17.00	Intrusive Igneous Rock	A little weathered
ST03	Upstream	36	6.64	64	17.24	Intrusive Igneous Rock	A little weathered
ST04	Upstream	42	6.58	72	17.49	Intrusive Igneous Rock	A little weathered
ST05	Upstream	48	6.73	83	17.71	Intrusive Igneous Rock	Moderate weathering
ST06	Middle	70	6.72	86	17.57	Siltstone	Moderate weathering
ST07	Middle	76	6.89	100	17.80	Siltstone	Moderate weathering
ST08	Middle	81	6.80	102	18.04	Siltstone	Moderate weathering
ST09	Central	87	7.08	115	18.22	Siltstone	Moderate weathering
ST10	Central	93	6.94	118	18.47	Siltstone	Moderate weathering
ST11	Downstream	108	7.20	126	18.42	Sand	Moderate weathering
ST12	Downstream	113	7.41	141	18.68	Sand	Moderate weathering
ST13	Downstream	118	7.23	125	18.79	Sand	Moderate weathering
ST14	Downstream	123	7.49	149	19.10	Sand	Moderate weathering
ST15	Downstream	128	7.35	134	19.21	Sand	Moderate weathering
ST16	Downstream	133	7.63	153	19.47	Sand	Very weathered
ST17	Downstream	138	7.53	161	19.76	Sand	Very weathered
ST18	Downstream	143	7.68	153	19.84	Sand	Very weathered
ST19	Downstream	148	7.64	166	20.15	Sand	Very weathered
ST20	Downstream	153	7.77	161	20.20	Sand	Moderate weathering

Source: Field research data ST01–ST20 (2026).



4.2. Spatial Variation of Physicochemical Characteristics of Auya River Water

The results of descriptive statistical analysis showed variations in the physicochemical characteristics of water at 20 observation stations along the Auya River. *Total Dissolved Solids* (TDS) values ranged from 25–153 mg/L with an average of 94.70 ± 41.93 mg/L. The pH value ranged from 6.50–7.77 with an average of 7.118 ± 0.427 , while the *Electrical Conductivity* (EC) ranged from 48–166 $\mu\text{S}/\text{cm}$ with an average of 115.65 ± 37.57 $\mu\text{S}/\text{cm}$. The water temperature ranged from 16.80–20.20 °C with an average of 18.50 ± 1.05 °C. This range of values indicates that the physicochemical conditions of the Auya River water are not uniform, but experience spatial changes from upstream to downstream.

Table 2. Descriptive statistics of the physicochemical characteristics of Auya River water

Parameter	N	Minimum	Maximum	Average	Elementary School
TDS (mg/L)	20	25	153	94.70	41.93
pH	20	6.50	7.77	7.118	0.427
EC ($\mu\text{S}/\text{cm}$)	20	48	166	115.65	37.57
Temperature (°C)	20	16.80	20.20	18.50	1.05

Source: Results of research data processing using IBM SPSS Statistics 27 (2026).

TDS showed a clear increasing trend along the flow direction. The lowest value of 25 mg/L was found at ST01 in the upstream section and generally increased to 153 mg/L at ST20 in the downstream section. A similar trend was seen for EC, which increased from 48 $\mu\text{S}/\text{cm}$ at ST01 and reached a maximum value of 166 $\mu\text{S}/\text{cm}$ at ST19. The similarity of TDS and EC patterns indicates that the concentrations of dissolved materials and ions tend to be higher downstream than upstream. Hydrogeochemically, this pattern may be related to the accumulation of dissolved substances during water travel, increased contact time between water and rocks and sediments, and possible input of materials from tributaries and the environment along the flow. However, the available data do not yet allow for the relative contributions of each of these processes to be determined separately.

The pH value also shows an increasing trend from upstream to downstream, but with fluctuations at some stations. At ST01, the pH was recorded at 6.50 and increased to 7.77 at ST20. The upstream section generally exhibits slightly acidic to near-neutral conditions, while the downstream section tends to be neutral to slightly alkaline. The non-linear pattern, such as decreases and increases in pH between adjacent stations, suggests that the acid-base conditions of the water are likely influenced by a combination of geochemical processes and local environmental conditions, so that pH changes cannot be explained solely by station location or geological material type.

Water temperature shows an increasing trend from 16.80 °C at ST01 to 20.20 °C at ST20. This increase occurs simultaneously with the change in position from upstream to downstream and a decrease in elevation along the Auya River profile. Based on the longitudinal profile, the elevation decreases from approximately 2,185 m above sea level at ST01 to 1,769 m above sea level at ST20. Therefore, temperature variations are not directly associated with changes in lithology because they can also be influenced by elevation, sunlight intensity, vegetation cover, flow

conditions, water depth, discharge, and microclimate conditions along the river.

Spatially, changes in physicochemical characteristics occur simultaneously with changes in geological conditions observed in the field. ST01–ST05 in the upstream section are associated with Intrusive Igneous Rock, ST06–ST10 in the middle section with Siltstone, while ST11–ST20 in the downstream section is dominated by Sand. Locations associated with Siltstone and Sand generally show higher TDS, EC, pH, and temperature values than locations with Intrusive Igneous Rock. This pattern indicates a spatial relationship between changes in geological conditions and the physicochemical characteristics of the Auya River water.

However, these relationships need to be interpreted with caution because the distribution of geological material groups follows an upstream–downstream gradient. With this sampling design, the influence of along-stream position cannot be independently separated from differences in geological conditions. Increases in TDS, EC, pH, and temperature at different site groups cannot be attributed solely to lithological changes because distance from the headwaters, elevation reduction, solute accumulation, tributary input, and other hydrological and environmental conditions may contribute to the observed patterns. Therefore, differences in parameters between geological groups in this study are better understood as geologic–spatial associations, rather than as evidence of a direct causal relationship between lithology and water physicochemical characteristics.

Overall, the descriptive statistics show a spatial gradient in the physicochemical characteristics of the Auya River water from upstream to downstream, primarily in the form of an increase in TDS and EC and a tendency towards increasing pH and temperature. This gradient coincides with a change in geological material from intrusive igneous rock to siltstone and sandstone and a decrease in elevation along the course. These results provide a basis for subsequent statistical analysis to evaluate differences in physicochemical characteristics between geological location groups. However, any statistical differences found should be interpreted in the context of the relationship between geological conditions and spatial position and should not be used as evidence that lithology is the sole factor controlling variations in the Auya River water.

4.3. Spatial Variation of Physicochemical Characteristics of Water in Relation to Geological Conditions

Descriptive statistics show variations in the physicochemical characteristics of water in different geological condition groups along the Auya River. Based on field observations, ST01–ST05 in the upstream section are associated with Intrusive Igneous Rock, ST06–ST10 in the middle section with Siltstone, while ST11–ST20 in the downstream section is dominated by Sand. The average values of TDS, pH, EC, and temperature show an increasing trend from the Intrusive Igneous Rock location group towards Siltstone and Sand (Table 3). However, because the three groups are also arranged sequentially following the upstream–downstream gradient, differences between groups need to be interpreted as part of the river's spatial variation and do not directly indicate the influence of lithology independently.

TDS showed a clear increasing trend between the site groups. The average TDS in Intrusive Igneous Rock was 36.40 ± 9.02 mg/L with a range of 25–48 mg/L, then

increased to 81.40 ± 9.02 mg/L in Siltstone with a range of 70–93 mg/L, and reached 130.50 ± 15.14 mg/L in Sand with a range of 108–153 mg/L. This pattern indicates that dissolved material concentrations were generally higher at the middle and downstream stations compared to the upstream stations. Although differences in geological materials can provide different conditions for water–rock or water–sediment interactions, the increase in TDS cannot be directly attributed to changes in lithology because the position of the stations also changes systematically from upstream to downstream. Accumulation of dissolved material during water travel, increased distance and time of contact with materials along the flow, input from tributaries, and local hydrological conditions may also contribute to this pattern.

Table 3. Descriptive statistics of the physicochemical characteristics of water in geological condition groups

Geological conditions	N	TDS (mg/L)	pH	EC (μ S/cm)	Temperature ($^{\circ}$ C)
Intrusive Igneous Rock	5	36.40 ± 9.02	6.600 ± 0.089	64.60 ± 13.63	17.248 ± 0.365
Siltstone	5	81.40 ± 9.02	6.886 ± 0.137	104.20 ± 12.85	18.020 ± 0.351
Sand	10	130.50 ± 15.14	7.493 ± 0.193	146.90 ± 14.75	19.362 ± 0.623

Source: Results of research data processing using SPSS (2026).

EC showed a trend in the same direction as TDS. The average EC increased from 64.60 ± 13.63 μ S/cm in intrusive igneous rocks to 104.20 ± 12.85 μ S/cm in siltstone and 146.90 ± 14.75 μ S/cm in sand. The similarity of TDS and EC patterns indicates that the increase in dissolved material content along the river coincided with an increase in the water's ability to conduct electrical current. This is consistent with the EC character related to the presence of dissolved ions in water. However, the higher EC value in the sand group cannot be interpreted as directly producing higher ion concentrations, because the group is located downstream and has received the cumulative influence of processes occurring along the flow.

The pH value also shows a spatial increase. The average pH in the intrusive igneous rocks is 6.600 ± 0.089 , increasing to 6.886 ± 0.137 in the siltstone and 7.493 ± 0.193 in the sand. Overall, the pH ranges from 6.50–7.77, indicating a change in water conditions from slightly acidic to slightly alkaline. pH variations may be related to various geochemical reactions that occur during water contact with rocks, sediments, and weathered materials. Regional geological conditions indicate the presence of igneous rocks in the Timepa Monzonite and sedimentary rocks in the form of siltstone, sandstone, and local muddy limestone in the Kemelangan Group (Harahap et al., 1990). This material diversity provides a geological basis for the possibility of water–rock interactions. However, because the mineral and geochemical composition of rocks at each station has not been directly analyzed, the processes of mineral dissolution, hydrolysis, and ion release in this study are treated as possible mechanisms and not as processes that have been directly proven.

Water temperature shows an increasing pattern from an average of 17.248 ± 0.365 $^{\circ}$ C in Intrusive Igneous Rock to 18.020 ± 0.351 $^{\circ}$ C in Siltstone and 19.362 ± 0.623 $^{\circ}$ C in Sand. This temperature increase occurs simultaneously with the change in station position from upstream to downstream. The longitudinal profile of the Auya River shows a decrease in elevation from 2,185 m above sea level

at ST01 to 1,769 m above sea level at ST20. Therefore, temperature variations cannot be directly related to geological conditions. In addition to elevation, water temperature can be influenced by the intensity of sunlight, vegetation cover, measurement time, water depth, discharge, flow velocity, and river morphology.

Descriptively, the four parameters show an average sequence of Intrusive Igneous Rock < Siltstone < Sand. However, the sequence coincides with the spatial arrangement of upstream (ST01–ST05) → middle (ST06–ST10) → downstream (ST11–ST20). This condition indicates that geological factors and position along the flow cannot be separated independently in the sampling design. Thus, the higher parameter values in the Siltstone and Sand groups cannot be considered solely as a result of lithological differences. Downstream processes, including accumulation of dissolved substances along the flow, elevation reduction, input from the surrounding environment, and changes in hydrological conditions, need to be considered together with geological conditions in explaining the variations found.

Based on these results, descriptive statistics indicate a spatial gradient in the physicochemical characteristics of Auya River water that coincides with the change in geological conditions from Intrusive Igneous Rock to Siltstone and Sandstone. This finding supports an association between geological conditions and water physicochemical variations, but cannot yet be used to conclude a direct cause-and-effect relationship. Water–rock interaction mechanisms such as weathering, leaching, and geological mineral dissolution may contribute to changes in water characteristics, but their contribution cannot be specifically determined without direct mineralogical or geochemical evidence. Therefore, the results at this stage are used to describe the geological-spatial association, while the significance of differences between groups is further evaluated through ANOVA and *post-hoc* tests.

4.4 Differences in Physicochemical Characteristics of Water Between Geological Condition Groups

Before performing *One-Way ANOVA*, the data were tested to meet the assumptions of normality and homogeneity of variance. The Shapiro–Wilk test showed that the data in each geological condition group had a *p*-value > 0.05. For example, the *p*-values for TDS in the Intrusive Igneous Rock, Siltstone, and Sand groups were 0.979; 0.979; and 0.892, respectively. Similar results were obtained for the parameters pH, EC, and temperature, so there was insufficient evidence to reject the assumption of normality. Furthermore, the Levene test produced *p*-values of 0.168 for TDS, 0.164 for pH, 0.772 for EC, and 0.112 for temperature. All of these values were greater than 0.05, so the assumption of homogeneity of variance was met. Based on the results of testing these assumptions, *One-Way ANOVA* was used to evaluate the mean differences between geological condition groups, followed by a Tukey HSD *post-hoc* test to identify significantly different pairs of groups.

The *One-Way ANOVA* results showed significant differences in the averages among the three geological condition groups for TDS ($F(2,17) = 96.174$; $p < 0.001$), pH ($F(2,17) = 57.923$; $p < 0.001$), EC ($F(2,17) = 59.276$; $p < 0.001$), and temperature ($F(2,17) = 30.870$; $p < 0.001$). The Welch test results as a robust test also provided consistent results, with values of 106.768 for TDS, 70.543 for pH, 55.026 for EC, and 32.130 for temperature, all at $p < 0.001$. However, the significance of the ANOVA only indicates that there is a difference in at least one group average and does

not indicate that all pairs of groups are significantly different. Therefore, the interpretation of differences between groups was further based on the results of the Tukey HSD *post-hoc* test.

Table 4. One-Way ANOVA results of physicochemical characteristics of water between geological condition groups

Parameter	F	df	p	Interpretation
TDS	96,174	2;17	<0.001	There are differences between groups
pH	57,923	2;17	<0.001	There are differences between groups
EC	59,276	2;17	<0.001	There are differences between groups
Temperature	30,870	2;17	<0.001	There are differences between groups

Source: Results of research data processing using SPSS (2026).

Table 5. Results of the Tukey HSD *post-hoc* test between geological condition groups

Parameter	Group pairs	Average difference	p	Interpretation
TDS	Intrusive Igneous Rock–Siltstone	45.00 mg/L	<0.001	Significant
	Intrusive Igneous Rock–Sand	94.10 mg/L	<0.001	Significant
	Siltstone–Sandstone	49.10 mg/L	<0.001	Significant
pH	Intrusive Igneous Rock–Siltstone	0.286	0.031	Significant
	Intrusive Igneous Rock–Sand	0.893	<0.001	Significant
	Siltstone–Sandstone	0.607	<0.001	Significant
EC	Intrusive Igneous Rock–Siltstone	39.60 µS/cm	0.001	Significant
	Intrusive Igneous Rock–Sand	82.30 µS/cm	<0.001	Significant
	Siltstone–Sandstone	42.70 µS/cm	<0.001	Significant
Temperature	Intrusive Igneous Rock–Siltstone	0.772 °C	0.073	Not significant
	Intrusive Igneous Rock–Sand	2,114 °C	<0.001	Significant
	Siltstone–Sandstone	1,342 °C	0.001	Significant

Source: Results of research data processing using SPSS (2026). Significance level $\alpha = 0.05$.

post-hoc test showed that TDS differed significantly across all pairs of geological condition groups. The average difference in TDS between Intrusive Igneous Rock and Siltstone was 45.00 mg/L ($p < 0.001$), between Intrusive Igneous Rock and Sand was 94.10 mg/L ($p < 0.001$), and between Siltstone and Sand was 49.10 mg/L ($p < 0.001$). Based on descriptive statistics, the average TDS increased from 36.40 mg/L in the Intrusive Igneous Rock group to 81.40 mg/L in Siltstone and 130.50 mg/L in Sand. Thus, the differences in TDS identified through ANOVA were

supported by significant differences across all pairs of groups.

The same pattern was found in pH. The mean difference between Intrusive Igneous Rock and Siltstone of 0.286 was significant at $p = 0.031$, while the difference between Intrusive Igneous Rock and Sand of 0.893 and between Siltstone and Sand of 0.607 were each significant at $p < 0.001$. The mean pH value increased from 6.600 in Intrusive Igneous Rock to 6.886 in Siltstone and 7.493 in Sand. These results indicate that all three pairs of groups have statistically significant differences in pH.

EC also showed significant differences across all pairs of groups. The mean difference between Intrusive Igneous Rock and Siltstone was 39.60 µS/cm ($p = 0.001$), between Intrusive Igneous Rock and Sand was 82.30 µS/cm ($p < 0.001$), and between Siltstone and Sand was 42.70 µS/cm ($p < 0.001$). The mean EC increased from 64.60 µS/cm in Intrusive Igneous Rock to 104.20 µS/cm in Siltstone and 146.90 µS/cm in Sand. The trend of EC in the same direction as TDS indicates that locations with higher dissolved material content generally also have higher electrical conductivity.

In contrast to TDS, pH, and EC, *post-hoc* results on temperature showed that not all pairs of groups differed significantly. The average temperature difference between Intrusive Igneous Rock and Siltstone of 0.772 °C was not significant at the $\alpha = 0.05$ level ($p = 0.073$). In contrast, the difference between Intrusive Igneous Rock and Sand of 2.114 °C was significant ($p < 0.001$), as was the difference between Siltstone and Sand of 1.342 °C ($p = 0.001$). Thus, the significance of the ANOVA on temperature was primarily related to the difference between the Sand group and the other two groups, while the temperature between Intrusive Igneous Rock and Siltstone groups did not show a statistically significant difference.

Although TDS, pH, and EC showed significant differences across all pairs of groups, these results need to be interpreted in the context of the spatial distribution of the observation stations. The Intrusive Igneous Rock group is located at ST01–ST05 in the upstream section, Siltstone at ST06–ST10 in the middle section, and Sand is found at ST11–ST20 in the downstream section. Thus, changes in geological conditions occur simultaneously with changes in position along the stream. This configuration means that the influence of geological conditions cannot be separated independently from the upstream–downstream gradient. Therefore, the differences identified through ANOVA and Tukey HSD indicate the presence of statistical associations between physicochemical characteristics of water, geological conditions, and spatial position, are not evidence that lithology directly causes changes in water parameters.

The increase in TDS and EC from the upstream to downstream location groups may be related to the accumulation of dissolved substances during water travel, input from tributaries and the surrounding environment, and the interaction of water with rocks and sediments along the flow. Changes in pH may also involve geochemical reactions during water contact with geological materials. However, without direct mineralogical, geochemical, or dissolved ion composition data, specific mechanisms such as mineral dissolution, hydrolysis, leaching, or ion release cannot be determined based on these statistical results. These mechanisms are therefore considered geochemically probable processes, not directly proven causes.

Temperature variations require careful interpretation because, in addition to the lack of significant differences between intrusive igneous rocks and siltstones, water

temperature is influenced by various environmental factors. The longitudinal profile of the Auya River shows a decrease in elevation from approximately 2,185 m above sea level at ST01 to 1,769 m above sea level at ST20. In addition to elevation, solar radiation, vegetation cover, water depth, discharge, flow velocity, measurement time, and river morphology can contribute to temperature variations. Therefore, the temperature differences found in the downstream sand group cannot be interpreted as a direct result of the type of geological material.

Overall, the results of ANOVA and Tukey HSD show that TDS, pH, and EC differ significantly in all pairs of Intrusive Igneous Rock, Siltstone, and Sand groups, whereas Temperatures differed significantly between Intrusive Igneous Rock–Sand and Siltstone–Sand, but not between Intrusive Igneous Rock–Siltstone. These findings demonstrate statistically significant variations in physicochemical characteristics between groups of locations with different geological conditions. However, because the geological condition groups are also arranged along an upstream–downstream gradient, the results of this study are more appropriately interpreted as a geological–spatial relationship to the physicochemical variations of the Auya River water, rather than as a direct causal relationship between lithology and water characteristics.

4.5 Relationship between Physicochemical Parameters of Water and the Effect of Spatial Gradients

Pearson correlation analysis was used as an initial bivariate analysis to evaluate the relationships between TDS, pH, EC, and temperature at 20 observation stations. The results showed that all parameter pairs were strongly and significantly positively correlated ($r = 0.969–0.985$; $p < 0.001$). However, because all four parameters generally increased from ST01 to ST20, the magnitude of the correlation could potentially be influenced by a shared spatial trend from upstream to downstream. To evaluate the influence of spatial gradients on the relationships between parameters, the relationship patterns were examined through scatterplots and partial correlations by controlling for cumulative distance from ST01. Elevation was used as an additional sensitivity analysis.

4.5.1 Pearson Correlation and Scatterplot Diagram

Table 6. Pearson correlation results between physicochemical parameters of Auya River water

Parameter pairs	Pearson r	p	Interpretation
TDS–pH	0.972	< 0.001	Very strong positive; significant
TDS–EC	0.985	< 0.001	Very strong positive; significant
TDS–Temperature	0.975	< 0.001	Very strong positive; significant
pH–EC	0.973	< 0.001	Very strong positive; significant
pH–Temperature	0.969	< 0.001	Very strong positive; significant
EC–Temperature	0.971	< 0.001	Very strong positive; significant

Source: Results of processing research data ST01–ST20 (2026).

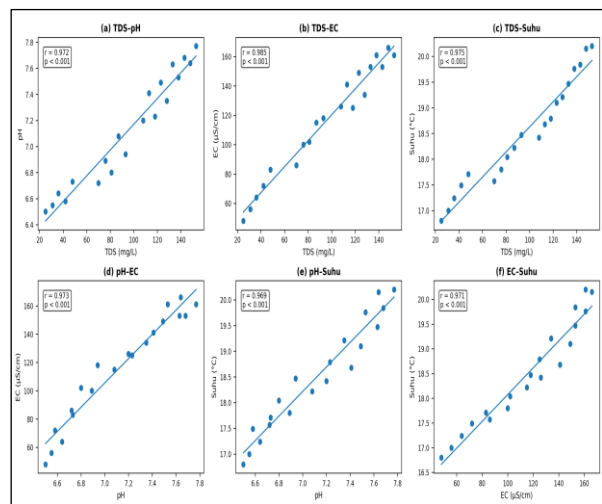


Fig 7. Distribution diagram of the relationship between the physicochemical parameters of Auya River water: (a) TDS–pH, (b) TDS–EC, (c) TDS–temperature, (d) pH–EC, (e) pH–temperature, and (f) EC–temperature. The lines indicate linear regression. Source: ST01–ST20 research data; visualization based on Pearson correlation analysis (2026).

Figure 7 shows a positive correlation pattern across all parameter pairs. However, a strong linear pattern in a scatterplot does not necessarily indicate a causal relationship. Because the observation points are also arranged along an upstream–downstream gradient, this pattern needs to be compared with a partial correlation to evaluate the linear contribution of spatial position.

4.5.2 Pearson Comparison with Partial Correlation

Table 7. Pearson comparison and partial correlation after controlling for cumulative distance and elevation

Partner	Pearson r	p	Partial r Distance	p	Partial r Elevation	p
TDS–pH	0.972	<0.001	0.587	0.006	0.831	<0.001
TDS–EC	0.985	<0.001	0.851	<0.001	0.833	<0.001
TDS–Temperature	0.975	<0.001	0.573	0.008	0.809	<0.001
pH–EC	0.973	<0.001	0.711	<0.001	0.851	<0.001
pH–Temperature	0.969	<0.001	0.294	0.208	0.807	<0.001
EC–Temperature	0.971	<0.001	0.759	<0.001	0.769	<0.001

Note: $N = 20$; the main partial correlation controls the cumulative distance from ST01. Elevation control is presented as a sensitivity analysis. Source: Results of research data processing (2026).

Comparison of Pearson's partial correlations shows that all coefficients decrease after cumulative distance from ST01 is controlled. This pattern suggests that the very high Pearson correlations partly reflect a shared spatial trend. However, the magnitude of the decrease differs across pairs, and five of the six relationships remain significant after controlling for the linear component of upstream–downstream distance.

The TDS–EC relationship was the most consistent. The Pearson coefficient of $r = 0.985$ ($p < 0.001$) decreased to a partial $r = 0.851$ ($p < 0.001$) after controlling for distance,

but remained very strong and significant. Physicochemically, this pattern is consistent with a relationship between dissolved materials and water electrical conductivity. These results are still treated as statistical associations and not evidence of causality.

The TDS–pH relationship decreased from $r = 0.972$ to partial $r = 0.587$ ($p = 0.006$), while TDS–temperature decreased from $r = 0.975$ to partial $r = 0.573$ ($p = 0.008$). Both remained significant, but the decrease in coefficients suggests that some of the initial Pearson correlation strength was related to the tendency of the parameters to change together along the upstream–downstream gradient.

The pH–EC relationship decreased from $r = 0.973$ to partial $r = 0.711$ ($p < 0.001$), while the EC–temperature relationship decreased from $r = 0.971$ to partial $r = 0.759$ ($p < 0.001$). Both pairs remained strongly positive after controlling for distance. Thus, spatial gradients contributed to the initial correlation, but did not fully explain either relationship.

The most significant change occurred in pH–temperature. The initially very strong Pearson correlation ($r = 0.969$; $p < 0.001$) decreased to a partial $r = 0.294$ and was not significant ($p = 0.208$) after distance was controlled. This finding suggests that the very strong bivariate pH–temperature relationship is primarily related to the tendency of both parameters to change simultaneously along the spatial gradient. After the linear component of distance was accounted for, there was insufficient statistical evidence for an independent linear pH–temperature relationship at $\alpha = 0.05$.

Elevation control yielded partial correlations that remained significant for all pairs (partial $r = 0.769$ – 0.851 ; $p < 0.001$). The differences in results between distance and elevation control indicate that the two variables represent different aspects of the spatial gradient. Because parameter changes follow the spatial sequence from ST01 to ST20, cumulative distance was used as the primary control, while elevation was treated as a sensitivity analysis.

4.5.3 Implications for Interpretation of Geological Conditions

Neither Pearson's correlation nor partial correlation results are used as independent evidence that lithology controls the physicochemical characteristics of water. Geological conditions also vary spatially, with intrusive igneous rocks at ST01–ST05 in the upstream section, siltstone at ST06–ST10 in the middle section, and sand at ST11–ST20 in the downstream section. Thus, changes in geological conditions coincide with the upstream–downstream gradient. A more appropriate interpretation is that variations in TDS, pH, EC, and temperature are related to spatial gradients and changes in geological conditions along the Auya River, without establishing a direct causal relationship.

Overall, this analysis suggests that very high initial correlations need to be considered alongside the possible influence of downstream trends. Once distance is controlled, the strength of all correlations diminishes, and the pH–temperature relationship becomes insignificant. Therefore, the discussion clearly distinguishes between correlation, spatial gradient, and causation.

4.6 Relationship between Physicochemical Variations of Water with Geological Conditions and Spatial Gradients

The results of this study indicate a consistent spatial pattern in the physicochemical characteristics of Auya River

water that coincides with changes in geological conditions along the study area. Intrusive Igneous Rock groups are found at ST01–ST05 in the upstream section, Siltstone at ST06–ST10 in the middle section, while Sand is found at ST11–ST20 in the downstream section. This distribution indicates that the geological condition groups are arranged along an upstream–downstream gradient and are not distributed independently along the river. Therefore, differences in water characteristics between groups in this study are interpreted as geological–spatial associations, not as evidence that lithology independently controls the physicochemical characteristics of water.

Descriptively, all parameters show an average increase from the Intrusive Igneous Rock group towards Siltstone and Sand. In the Intrusive Igneous Rock group, the average TDS was 36.40 mg/L, pH 6.600, EC 64.60 $\mu\text{S}/\text{cm}$, and temperature 17.248 °C. In the Siltstone group, the average value increased to TDS 81.40 mg/L, pH 6.886, EC 104.20 $\mu\text{S}/\text{cm}$, and temperature 18.020 °C. The highest value was found in the Sand group, with an average TDS of 130.50 mg/L, pH 7.493, EC 146.90 $\mu\text{S}/\text{cm}$, and temperature 19.362 °C. This pattern produces the sequence Intrusive Igneous Rock < Siltstone < Sand for all observed parameters. However, since the sequence of these geological groups also coincides with the upstream < middle < downstream positions, this pattern cannot be attributed solely to differences in geological materials.

Differences between groups were supported by ANOVA results showing significant differences for TDS ($F(2,17) = 96.174$; $p < 0.001$), pH ($F(2,17) = 57.923$; $p < 0.001$), EC ($F(2,17) = 59.276$; $p < 0.001$), and temperature ($F(2,17) = 30.870$; $p < 0.001$). Tukey's *post-hoc analysis* showed that all pairs of groups differed significantly for TDS, pH, and EC. For temperature, significant differences were found between Intrusive Igneous Rock–Sand and Siltstone–Sand, while Intrusive Igneous Rock–Siltstone showed no significant differences. Thus, statistical analysis confirmed differences between geological/spatial condition groups, but could not determine whether these differences were independently caused by lithology because the geological groups also represent different positions along the flow.

This pattern is also seen in the longitudinal distribution of parameters. TDS generally increased from 25 mg/L at ST01 to 153 mg/L at ST20, EC from 48 to 161 $\mu\text{S}/\text{cm}$, pH from 6.50 to 7.77, and temperature from 16.80 to 20.20 °C. At the same time, elevation generally decreased from 2,185 m at ST01 to 1,769 m at ST20, with a cumulative distance based on inter-station coordinates reaching approximately 8.03 km. This condition indicates that changes in physicochemical parameters occur simultaneously with changes in position along the river, elevation, and geological conditions. Thus, spatial gradients are an important component in explaining the observed patterns.

The influence of spatial trends on the relationships between parameters is also evident from the comparison of Pearson correlations and partial correlations. The initial Pearson correlations showed a very strong positive relationship for all parameter pairs ($r = 0.969$ – 0.985 ; $p < 0.001$). After cumulative distance from ST01 was controlled, all coefficients decreased. The TDS–EC relationship remained the strongest (partial $r = 0.851$; $p < 0.001$), followed by EC–temperature ($r = 0.759$; $p < 0.001$) and pH–EC ($r = 0.711$; $p < 0.001$). The TDS–pH ($r = 0.587$; $p = 0.006$) and TDS–temperature ($r = 0.573$; $p = 0.008$) relationships also remained significant, while pH–temperature decreased to $r = 0.294$ and was no longer significant ($p = 0.208$). The decrease in all coefficients after

controlling for distance indicates that the upstream-downstream trend contributed to the high initial Pearson correlation. Therefore, the correlation between parameters should not be used as independent evidence that geological conditions control the physicochemical characteristics of water.

The weathering conditions of the outcrops exhibit a similar spatial pattern. Slight weathering is primarily found at ST01-ST04 in the upstream section, while moderate weathering conditions dominate at subsequent stations. Because these changes in weathering levels also follow the spatial sequence of stations, their association with increases in TDS, EC, pH, and temperature cannot be separated independently from the upstream-downstream gradient. Therefore, weathering levels in this study are more appropriately treated as supporting geological characteristics accompanying changes in conditions along the river, rather than as independently confirmed causal factors.

Geochemically, changes in geological conditions still provide a relevant framework for interpreting variations in water characteristics. Water contact with rocks and sedimentary materials theoretically allows for leaching, dissolution of mineral components, ion exchange, and release of dissolved materials, which could contribute to variations in TDS, EC, and pH. However, these mechanisms cannot be directly confirmed because this study did not measure the mineral composition of the rocks or the composition of dissolved ions in the water. Therefore, water-rock interactions are treated as a possible geochemical mechanism, not as a process that has been proven by research data.

In addition to geological conditions, processes occurring along the flow also need to be considered. The movement of water from upstream to downstream can be accompanied by changes in contact time with geological materials and sediments, as well as input of materials from the environment along the flow. Hydrological factors and local environmental conditions also potentially contribute to parameter variations. Specifically, changes in temperature, elevation, vegetation cover, solar radiation, discharge, depth, and flow characteristics can influence observed patterns. Therefore, increases in parameters downstream cannot be attributed exclusively to changes in geological groups.

Overall, the results of this study indicate that spatial variations in the physicochemical characteristics of Auya River water are associated with changes in geological conditions along the course. The Intrusive Igneous Rock group in the upstream section shows lower average parameters, Siltstone in the middle section shows intermediate values, while Sand in the downstream section shows the highest average values. Although these differences are supported by ANOVA and *post-hoc analysis*, the distribution of geological groups that follows an upstream-downstream gradient means that the contribution of geological conditions cannot be separated independently from spatial position and other river processes. Therefore, the results of this study indicate a relationship between spatial variations in water physicochemical characteristics and changes in geological conditions, without interpreting it as evidence of a causal relationship or independent lithological control.

5. Conclusion And Recommendations

Research at 20 stations along the Auya River showed spatial variations in the physicochemical characteristics of

water from upstream to downstream. TDS, pH, EC, and temperature generally showed an increasing trend from ST01 to ST20. Based on geological condition groups, Intrusive Igneous Rock in the upstream had lower average parameter values, Siltstone in the middle showed intermediate values, while Sand in the downstream showed higher average values. ANOVA results showed significant differences in TDS, pH, EC, and temperature between geological/spatial condition groups ($p < 0.001$). Tukey's *post-hoc test* showed that all pairs of groups were significantly different for TDS, pH, and EC, while temperature between Intrusive Igneous Rock and Siltstone groups did not show significant differences.

Pearson correlation analysis showed a very strong and significant positive relationship between the physicochemical parameters. However, after the cumulative distance from ST01 was controlled through partial correlation, all correlation coefficients decreased. Most relationships remained significant, especially TDS-EC, while the pH-temperature relationship was no longer significant. These results indicate that the upstream-downstream spatial gradient contributed to the high bivariate correlations obtained in the initial analysis. Therefore, the relationships between parameters in this study are interpreted as statistical associations and do not indicate a causal relationship.

Overall, the spatial variation in the physicochemical characteristics of the Auya River water is related to changes in geological conditions along its course. However, the intrusive igneous rock, siltstone, and sandstone groups are also arranged sequentially in the upstream, middle, and downstream sections. Thus, the contribution of geological conditions cannot be separated independently from the influence of position along the river. Statistical differences between groups cannot be used as evidence that lithology directly controls the physicochemical characteristics of the water. The results of this study more precisely indicate an association between changes in water characteristics, spatial gradients, and accompanying geological conditions along the Auya River.

Interpretation of the research results is limited by the spatial relationship between geological groups and river locations, the relatively limited number of observation stations, and the unequal group sizes. This study also did not include analysis of major ions in water or direct characterization of the mineralogical and elemental composition of rocks, so the water-rock interaction mechanism cannot be confirmed geochemically. Furthermore, the weathering level of the outcrops is still classified qualitatively, while water temperature can be influenced by environmental factors such as elevation, vegetation cover, solar radiation, discharge, depth, and measurement time.

Further research is recommended using a more representative number and distribution of stations so that similar geological conditions can be observed at different spatial locations. Water chemistry analysis needs to be complemented by measurements of major ions and other hydrogeochemical parameters. Rock characterization using X-Ray Diffraction (XRD) And X-Ray Fluorescence (XRF) is needed to obtain direct information on the mineralogical and elemental composition of rocks. Integration of rock mineralogical and geochemical data with water chemistry, quantified weathering rates, and spatial and environmental variables is expected to more directly examine the mechanisms of water-rock interactions and distinguish the

contribution of geological conditions from the influence of upstream–downstream gradients.

Acknowledgements

The author expresses his deepest gratitude to the Indonesian Endowment Fund for Education (LPDP) for the scholarship and financial support provided during his studies. This support provided the author with the opportunity to complete his studies. Through the LPDP scholarship, the author also had the opportunity to broaden his horizons, improve his academic abilities, and develop his knowledge throughout his studies.

The author also expresses his appreciation and gratitude to the Dean of the Faculty of Geological Engineering, Padjadjaran University, and the Geological Engineering Study Program, Padjadjaran University, for their academic support and facilities provided during the lectures. Adequate facilities and infrastructure, a conducive academic atmosphere, and the support of competent lecturers have assisted the author in the learning process and deepened his knowledge in the field of geology.

The author would like to express his sincere gratitude to his supervisor for his time, attention, guidance, and various suggestions and corrections provided during the preparation of this article. This guidance provided a significant contribution to improving the content and quality of the article, leading to its successful completion. The preparation of this article is part of the academic requirements for completing the study. Therefore, the guidance and support provided by the supervisor played a significant role in the completion of this scientific work.

The author also expresses his gratitude to all parties who have provided assistance and support, both directly and indirectly, during the educational process, implementation of research, and completion of this article.

References

- Afrilita, Yoni, DR, Pratomo, SU, 2024. A hydrogeochemistry analysis for quality determination of shallow karstic groundwater in Western Tuban, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 9. doi:10.25299/jgeet.2024.9.04.15926.
- Ayu, D., Mirino, T., Alfius, B., 2024. Analysis of water quality parameters of the Kampung Salak River, Sorong City, Southwest Papua. *Casuarina: Journal of Environmental Engineering* 1, 13–16. doi:10.33506/ceej.v1i2.3394.
- Ayuningrum, VR, Yushardi, Nurdin, EA, Astutik, S., Ikhsan, FA, 2023. Mapping the distribution of irrigation river water quality on agricultural land on the Karst slopes of Mount Sadeng, Puger District, Jember Regency. *JPIG (Journal of Geography Education and Science)* 8, 1–11. doi:10.21067/jpig.v8i1.7558.
- Basharat, U., Zhang, W., Abbasi, A., Mahroof, S., Han, C., Khan, SH, Li, S., 2025. Integrated assessment of groundwater hydrogeochemistry and quality using multivariate statistical analysis, self-organizing maps, and water quality indices in District Bagh, AJK, Pakistan. *Ecotoxicology and Environmental Safety* 301, 118515. doi:10.1016/j.ecoenv.2025.118515.
- Bastia, F., Equeenuddin, SM, 2019. Chemical weathering and associated CO₂ consumption in the Mahanadi River basin, India. *Journal of Asian Earth Sciences* 174, 218–231. doi:10.1016/j.jseaes.2018.12.010.
- Boma, D., Mote, D., 2026. Lithological control on variations in total dissolved solids (TDS) and pH of Auya River water, Obano Area, Paniai Regency, Central Papua. *Journal of Geoscience, Engineering, Environment, and Technology* 11, 108–116. doi:10.25299/jgeet.2026.11.1.27493.
- Dianardi, K., Jumhari, Hadian, MSD, Waliyana, TY, 2018. Characteristics of groundwater on the eastern slope of Mount Ciremai, Kuningan Regency, West Java, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 3, 187–192. doi:10.24273/jgeet.2018.3.4.1606.
- Duan, X., Sun, Z., Li, S., Jiang, Z., Liao, H., 2023. Hydrogeochemical characteristics and environmental quality assessment of karst groundwater in the Mengzi Basin of Yunnan Province, China. *Water* 15, 2126. doi:10.3390/w15112126.
- Duan, L., Zhang, W., Qiu, Y., Chen, S., Wang, D., Luo, Y., Qu, S., Gao, R., Xue, B., Wang, G., Liu, T., 2024. Identifying the spatio-seasonal pattern of hydrochemical evolution and surface water-groundwater interaction in a large urban river basin, Northwest China. *Science of the Total Environment* 944, 173989. doi:10.1016/j.scitotenv.2024.173989.
- Gaur, N., Sarkar, A., Dutta, D., Gogoi, BJ, Dubey, R., Dwivedi, SK, 2022. Evaluation of water quality index and geochemical characteristics of surface water from Tawang, India. *Scientific Reports* 12, 11698. doi:10.1038/s41598-022-14760-3.
- Goldrich-Middaugh, GM, Ma, L., Engle, MA, Ricketts, JW, Soto-Montero, P., Sullivan, PL, 2022. Regional drivers of stream chemical behavior: Leveraging lithology, land use, and climate gradients across the Colorado River, Texas USA. *Water Resources Research* 58. doi:10.1029/2022WR032155.
- HAR, R., Aprisal, Berd, I., Hutasoit, LM, Tanjung, DA, 2023. Testing of pH, conductivity, total dissolved solids, salinity, and turbidity around the Batang Arau River, Padang City, West Sumatra. *BioLink: Journal of Environmental, Industrial and Health Biology* 10, 25–34. doi:10.31289/biolink.v10i1.9642.
- Hartanto, FV, Putranto, TT, Setiawan, T., 2023. Analysis of the influence of lithology distribution on hydrogeochemistry in unconfined aquifers in the Jakarta Groundwater Basin (CAT). *Journal of Environment and Geological Hazards* 14, 136–148. doi:10.34126/jlbg.v14i3.495.
- Hidayat, H., Yoseph, B., Muda Iskandarsyah, TYW, 2025. Characteristics of groundwater hydrochemistry and stable isotopes ($\delta^{18}\text{O}$ & $\delta^2\text{H}$) in Cadasari, Banten, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 10. doi:10.25299/jgeet.2025.10.02.21531.
- Hynek, SA, McDowell, WH, Bhatt, MP, Orlando, JJ, Brantley, SL, 2022. Lithological control of stream chemistry in the Luquillo Mountains, Puerto Rico. *Frontiers in Earth Science* 10, 779459. doi:10.3389/feart.2022.779459.
- Irwan, M., Alianto, Toja, YT, 2017. Physicochemical conditions of river water flowing into Sawaibu Bay, Manokwari Regency. *Indopacific Journal of Aquatic Resources* 1, 81–92. doi:10.30862/jsai-fpik-unipa.2017.Vol.1.No.1.23.
- Islam, MZ, Mostafa, MG, 2024. Assessment of hydrogeochemical characteristics, water quality, and health risk of groundwater in Chapai-Nawabganj District, Bangladesh. *H2Open Journal* 7, 375–396. doi:10.2166/h2oj.2024.030.
- Laratmase, L., Kusumayudha, SB, Harjanto, A., 2024.

- Geochemical correlation of volcanic rocks and groundwater quality in the Todoko-Ranu Complex, Sahu District, West Halmahera, North Maluku, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 9. doi:10.25299/jgeet.2024.9.3.15295.
- Listyani, TRA, Ridayati, 2024. Spatial and seasonal variation of doline water hydrochemistry in West Gunungsewu Karst Area, Yogyakarta Special Region, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 9. doi:10.25299/jgeet.2024.9.2.6033.
- Ma, B., Huang, X., Cui, X., Liang, Journal of Hydrology 625, 129991. doi:10.1016/j.jhydrol.2023.129991.
- Mairizki, F., Putra, AY, Putri, WA, Ferdiansyah, 2021. Hydrogeochemical and characteristics of groundwater in Teluk Nilap Area, Rokan Hilir, Riau. *Journal of Geoscience, Engineering, Environment, and Technology* 6. doi:10.25299/jgeet.2021.6.4.8136.
- Maria, R., Muda Iskandarsyah, TYW, Rachmat Suganda, B., Hendarmawan, 2022. Hydrogeochemical characteristics and the impact of anthropogenic activity on groundwater quality in the Banjara Sub Urban Area, West Java, Indonesia. *Journal of Civil Engineering* 29, 217–226. doi:10.5614/jts.2022.29.3.2.
- Masitoh, F., Rusydi, AN, Taryana, D., 2025. Hydrogeochemistry and shallow groundwater quality assessment in Penguluran Basin, East Java, Indonesia. *Indonesian Journal on Geoscience* 12, 343–365. doi:10.17014/ijog.12.3.343-365.
- Pohan, DAS, Budiyo, B., Syafrudin, S., 2017. Analysis of river water quality to determine its designation from an environmental perspective. *Journal of Environmental Science* 14, 63–71. doi:10.14710/jil.14.2.63-71.
- Prasad, R.K., Singh, N.D., Singh, S.K., Jain, V., 2025 . Lithological controls on chemical weathering signatures in the semi-arid climatic regime: Study based on tropical small scale catchments. *Geomorphology* 470, 109521.
- Raj, V.T., Maya, K., 2023. Rock–water interaction, chemical weathering and solute transport of two rivers draining contrasting climate gradients in the Western Ghats, India. *Earth Surface Processes and Landforms* 48, 1969–1989. doi:10.1002/esp.5598.
- Razi, MH, Wilopo, W., Putra, DPE, 2024. Hydrogeochemical evolution and water–rock interaction processes in the multilayer volcanic aquifer of Yogyakarta-Sleman Groundwater Basin, Indonesia. *Environmental Earth Sciences* 83, 164. doi:10.1007/s12665-024-11477-6.
- Rumabar, AMF, Gaspersz, RS, Moisi, G., 2024. Determination of water quality status of the Dosay River, Jayapura Regency using the pollution index method. *Jurnal Ilmiah Wahana Pendidikan* 10, 1064–1072. doi:10.5281/zenodo.13325054.
- Su, C., Liu, Y., Cheng, Z., Wang, W., Zheng, Z., 2022. Hydrochemical processes and controls on the hydrochemistry of river water in the Muling-Xingkai Plain, Northeast China. *Frontiers in Environmental Science* 10, 1010367. doi:10.3389/fenvs.2022.1010367.
- Yanidar, R., Hartono, DM, Moersidik, SS, Andres, Y., 2023. Mapping the spatial variation of rivers water quality using multivariate analysis: A case study of Greater Jakarta, Indonesia. *Indonesian Journal of Urban and Environmental Technology* 6, 1–19. doi:10.25105/urbanenvirotech.v6i1.16198.



© 2026 Journal of Geoscience, Engineering, Environment and Technology. All rights reserved. This is an open access article distributed under the terms of the CC BY-SA License (<http://creativecommons.org/licenses/by-sa/4.0/>).