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# Spatial Variation in Water Quality at Karst Springs in South Malang: Geological Control and Flow Type

**Nelya Eka Susanti[1*], Kurniawan Sigit Wicaksono[2], Didik Suprayogo[2], Zaenal Kusuma[2]**
[1]Doctoral Student Program, Faculty of Agriculture, Brawijaya University, Malang, 65145, Indonesia
[2]Department of Soil Science, Faculty of Agriculture, Brawijaya University, Malang, 65145, Indonesia

**[*]Corresponding Author: nelyaeka@unikama.ac.id**

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## ABSTRACT

The karst region of southern Malang, East Java, Indonesia, is underlain by carbonate rocks of the Wonosari and Mandalika Formations, forming a complex aquifer system shaped by dissolution processes and water–rock interactions. This study assessed spatial variations in groundwater quality at four major springs: Umbulan, Durmo, Bendo, and Sendang Biru. *In situ* measurements using a portable multiparameter device recorded pH values of 7.17–7.45, electrical conductivity (EC) of 604.3– 805.7µS/ cm, and total dissolved solids (TDS) of 278.3– 364.7mg/ L. Laboratory analyses showed turbidity values of 0.58–4.78 NTU and $CaCO_3$ concentrations of 380–446.7mg/ L. Pearson correlation analysis revealed a positive relationship between EC and $CaCO_3$ ($r = 0.721$), highlighting the role of carbonate dissolution in controlling groundwater ionic composition. Conversely, a moderately strong negative correlation was observed between turbidity and $CaCO_3$ ($r = –0.687$). The elevated turbidity at Sendang Biru Spring suggests additional sediment input, likely linked to recharge zone disturbances. Overall, the results indicate that hydrogeochemical dynamics in the Southern Malang karst are strongly influenced by carbonate dissolution, groundwater flow path characteristics, and local anthropogenic impacts.

## INTRODUCTION

Karst aquifers are vital but vulnerable groundwater systems due to their high permeability, complex underground drainage systems, and rapid hydrological response to rainfall **(Hartmann *et al*., 2014; Banusch *et al*., 2022)**. Formed through the dissolution of carbonate rocks, these aquifers consist of conduit and diffuse flow systems that regulate water storage, transport, and quality. Conduit flow allows for rapid water movement but minimal filtration, while diffuse flow provides slower transmission and greater hydrochemical stability **(Xiao *et al*., 2021; Yu *et al*., 2021)**. Globally, karst systems face major challenges in water resource management due to their vulnerability to land use change, deforestation, pollution, and climate variability **(Hartmann *et al*.,**

**2014)**. The distinctive characteristics of karst aquifers, which include secondary porosity, rapid groundwater flow, and low filtration capacity, make them highly susceptible to contamination and fluctuations in water flow. This issue is evident in various karst regions around the world, from Europe to Southeast Asia, where anthropogenic pressures exacerbate the degradation of water quality and availability.

Similar conditions also occur in South Malang, one of Indonesia's tropical karst zones. In tropical regions, these aquifers supply water for domestic, agricultural, and industrial use, but are increasingly threatened by land use change, deforestation, and climate variability **(Vilhar *et al*., 2022; Zhang *et al*., 2023)**. Rainwater and contaminated surface runoff can quickly enter the system without adequate filtration, posing a risk to groundwater quality. These global hydrogeological challenges are clearly reflected in this region. In other words, South Malang is a local representation of global karst issues, but it is unique because of its direct connection to the Indian Ocean coastal region. The interaction between carbonate dissolution processes in the recharge zone and coastal dynamics makes this research important, not only for the regional context but also as a contribution to the international discourse on the sustainability of tropical karst aquifer systems.

The Southern Karst of Malang, East Java, is formed from limestone of the Wonosari and Mandalika Formations, creating dolines, ponors, caves, and underground rivers. The high infiltration capacity and complex underground flow network supply major springs such as Umbulan Spring, Durmo Spring, Bendo Spring, and Sendang Biru Spring, which serve as critical water sources for the surrounding communities. Each of these springs exhibits varying hydrogeochemical characteristics, reflecting differences in the depth of the flow system, water residence time, and the intensity of interaction with the host rock. The direct hydrological connectivity of this region with the Indian Ocean enhances its ecological importance but also increases its vulnerability to contamination, as surface pollutants can quickly infiltrate and move through the channel system with limited natural retention **(Cholet *et al*., 2017; Giese *et al*., 2018)**.

Recent research highlights that water quality in tropical karst springs is strongly influenced by the dominant flow type, local lithology, and land use pressure **(Cahyadi *et al*., 2025)**. Water sources dominated by channel flow tend to exhibit higher temporal variability and higher levels of turbidity or pollutants, while water sources dominated by diffuse flow often maintain more stable hydrochemical conditions **(Banusch *et al*., 2022)**. However, in the Southern Malang Karst Area, despite its importance both hydrologically (water supply) and socioeconomically (community use), comprehensive and structured research has not been extensively conducted to examine how differences in water flow types (conduit flow and diffuse flow) and local geological conditions influence variations in water chemistry at springs. Most existing studies focus on general hydrogeological mapping or seasonal water quality assessment, without integrating flow path analysis **(Cahyadi *et al*., 2020; Yogafanny & Legono, 2021)**. This is important because the unique characteristics of karst aquifer systems make them highly vulnerable to contaminants, both in terms of water quantity and quality **(Jakada *et al*., 2019; Yogafanny & Legono, 2021)**. Researchers note that surface contamination can quickly enter the soil through ponors in this area, necessitating a more comprehensive analytical approach to understand the spatial influence and local geological controls on water quality **(Nurani, 2017; Cahyadi *et al*., 2020)**.

This research gap becomes increasingly critical given the growing environmental pressures on the Southern Malang Karst recharge zone, where ongoing deforestation, agricultural intensification, and tourism expansion have the potential to reduce infiltration capacity, accelerate soil erosion, and increase the risk of groundwater contamination **(Willenbrink, 2021; Ruiz *et al*., 2022)**. Additionally, the lack of sustainable water quality monitoring and stream characterization limits the ability of local stakeholders to design effective management interventions. The sustainability of these sources is highly dependent on the protection of recharge zones, control of deforestation, and regular monitoring of water quality and quantity. Studies and conservation of these springs are crucial to ensuring water resilience in tropical karst areas vulnerable to land-use change and climate change. This research fills this research gap by explicitly linking water quality parameters to flow type (conduit and diffuse) and local geological controls, providing novelty to water quality studies in tropical karst systems and contributing to the development of more appropriate water conservation and management strategies in tropical karst ecosystems.

To address this issue, this study evaluated the spatial variation of hydrogeochemical parameters in four main springs in the southern karst of Malang, explicitly linking these differences to the dominance of conduit and diffuse flow and local geological settings. By integrating field measurements, laboratory analyses, and statistical correlations, this study provides new insights into how flow mechanisms and lithological controls influence groundwater chemistry in tropical karst systems. This study aimed to evaluate spatial variations in water quality at four main springs: Umbulan Spring, Durmo Spring, Bendo Spring, and Sendang Biru Spring. The findings of this study contribute to targeted conservation strategies and sustainable groundwater management in Southern Malang and similar vulnerable karst landscapes.

## MATERIALS AND METHODS

### 1. Research location

The research location is in the southern part of Malang, East Java, Indonesia, which geomorphologically is part of a tropical karst zone that developed on Miocene Middle to Late carbonate rocks of the Wonosari Formation. This formation consists of massive layered limestone with a high degree of dissolution, forming a complex karst aquifer network with heterogeneous groundwater circulation characteristics. Geographically, the location is situated at coordinates of approximately 8°15’–8°30’ S and 112°30’–112°45’

E, with elevations ranging from 50 to 300 metres above sea level. The area has a humid tropical climate with two dominant seasons: the rainy season from November to March and the dry season from April to October, which significantly influence the hydrological dynamics of the karst system.

The study focused on four main springs scattered across the active karst zone, namely Sumber Umbulan, Sumber Bendo, Sumber Durmo, and Sumber Sendang Biru. The selection of these four points is based on their spatial distribution, which represents variations in morphology, land cover, potential anthropogenic disturbances around the recharge zone, and generally has springs that flow throughout the year, and represents different underground flow systems **(**conduit vs diffuse**)**. The research location map is shown in Fig. (1).

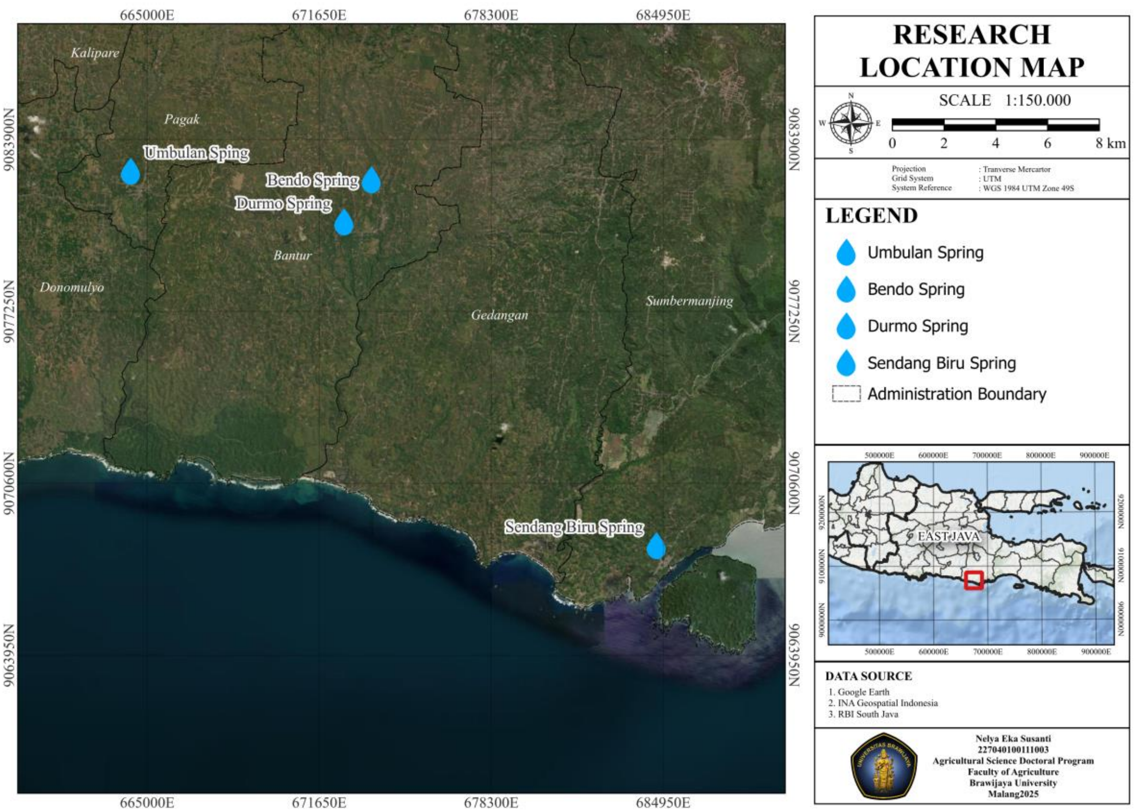



**Fig. 1.** Research location

## 2. Research design and data collection

The water quality parameters measured in this study include pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, and calcium carbonate ($CaCO_3$) content. All measurements were conducted at the four karst water sources in the southern Malang region during the dry season in April, May, and June 2025. Water samples were collected during the dry season to ensure more stable measurement results and minimise the influence of weather conditions or fluctuating water flow rates, which are common during the rainy season. Each month, three replicates of sampling were conducted at each spring, with sampling times consistently in the morning (07:00–09:00 WIB) to reduce daily variability due to changes in temperature and anthropogenic activities. Thus, the total number of samples obtained during the study was 36 samples (4 springs × 3 months × 3 replicates).

The pH, electrical conductivity (EC), and total dissolved solids (TDS) parameters are measured *in situ* using a portable multi-parameter water quality testing device (accuracy ±0.01 pH, ±1 μS/cm EC, ±1 mg/L TDS) with automatic temperature compensation. The detection limits (LOD) of this instrument are 0.01 pH units, 1 μS/cm for EC, and 1 mg/L for TDS. Before use, the device is calibrated using recommended standard solutions, namely pH buffers 4.01, 6.86, and 9.18 for pH calibration, and a standard solution of 1413 μS/cm for EC/TDS calibration. The calibration process is performed routinely before each sample collection to maintain the accuracy and precision of the results. All measurements are performed by directly immersing the instrument's electrode into the spring water and waiting until the reading stabilises.

The use of this portable device was chosen considering the limited access to laboratories at the research site and the need for rapid, efficient, and repeated water quality monitoring. Although the device has limitations in terms of accuracy when compared to full-scale laboratory instruments, data validity is maintained through strict calibration procedures and consistent comparison of results between locations. This approach aligns with methods used in previous studies in tropical and semi-arid regions facing similar challenges in accessibility and technical resource limitations **(Giambastiani *et al*., 2020; Smith & Johnson, 2022)**.

Turbidity was analyzed in the laboratory using a bench-top turbidimeter (LOD: 0.01 NTU), while calcium carbonate ($CaCO_3$) concentration was determined by EDTA titration according to **APHA (2017)** standards. All *in situ* parameters (pH, temperature, electrical conductivity (EC), and total dissolved solids (TDS)) were measured directly at the spring site at the same time as water samples were collected for laboratory analysis (turbidity and $CaCO_3$ concentration). Thus, the *in situ* and laboratory data originate from identical hydrological conditions, enabling direct comparison between field measurements and laboratory analyses. This approach ensures that variations in water quality parameters observed are not influenced by differences in measurement timing, sample transport, or changing environmental conditions after sampling.

**3. Research framework and methodological steps**

This study followed a systematic methodology, as shown in Fig. (2). The methodological framework consisted of the following main stages:

1) Identification of problems based on water quality issues in the South Malang Karst Area.
2) Development of hypotheses based on the Geohygrological Process Model approach.
3) Selection of research areas and determination of samples.

4) Data collection through measurements of pH, EC, TDS, turbidity, and calcium carbonate ($CaCO_3$) content.
5) Data processing in this study was conducted quantitatively using descriptive statistical analysis and correlation analysis between parameters.
6) Interpretation of results, discussing findings related to previous studies and theoretical implications.
7) Conclusions and policy recommendations. Providing insights into practical implications and detailed water management strategies in tropical karst areas.

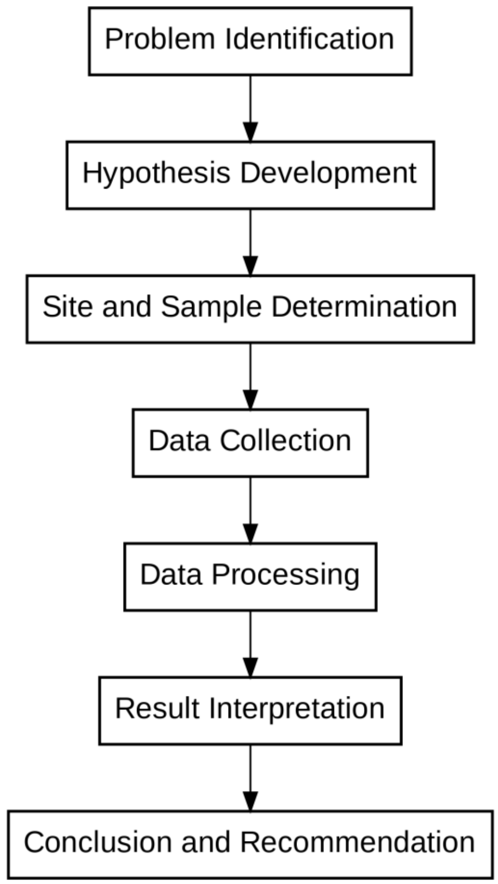



**Fig. 2**. Research process framework

Each stage in this research process was systematically designed to ensure the validity, reliability, and robustness of the findings. The process began with the identification of the problem, namely the low level of understanding of spatial variations in water quality in karst areas influenced by geological controls and types of underground flow. Next, a hypothesis was developed that differences in lithology, fracture structure, and flow type (diffuse or conduit) contribute to differences in the physical-chemical characteristics between springs. The site selection and sampling stage focused on four karst springs in Southern Malang with distinct geological characteristics: Sumber Durmo, Sumber Bendo, Sumber Umbulan, and Sumber Sendang Biru. Data collection was conducted through *in situ* measurements and water sampling for laboratory analysis, with primary parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, and calcium carbonate ($CaCO_3$) content.

The data obtained was then entered into the data processing stage, using a descriptive statistical analysis approach to identify the distribution of values for each parameter. Pearson's correlation analysis was used to evaluate the relationship between hydrogeochemical parameters. All statistical analyses were performed using IBM SPSS Statistics v.26 and Microsoft Excel 2019 with a significance level of $P < 0.05$. Statistical measures, including minimum, maximum, mean, and standard deviation values, were used to describe the general characteristics of each water source.

Next, the results were interpreted through a correlation analysis between water quality parameters using Pearson's correlation coefficient. Significant correlations between certain parameters are interpreted as indications of geochemical processes or the influence of local geological conditions on the chemical properties of water. Based on this interpretation, initial conclusions and recommendations are drawn regarding the influence of geological control and flow type on karst water quality. These findings are expected to serve as a basis for further research and support sustainable water resource management in karst areas.

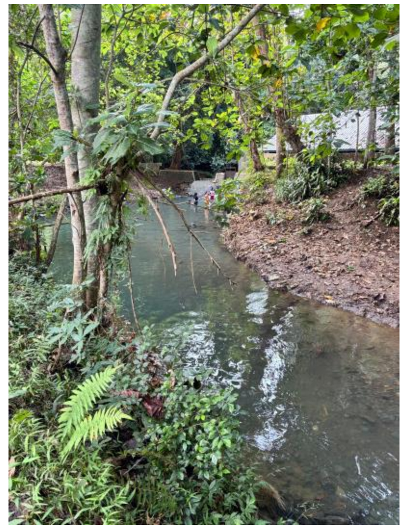
## RESULTS AND DISCUSSION

The four springs analyzed in this study are located in the southern Malang karst region, East Java Province, Indonesia. Geomorphologically, this region is part of a tropical karst zone that developed on Tertiary carbonate rocks, with a complex aquifer system that is vulnerable to changes in land use in the recharge zone. Each spring has distinct topographical, geological, and land-use characteristics, which contribute to the observed differences in water quality. The current conditions of the four springs analysed are shown in Fig. (3).

(a)

(b)

(c)



(d)

**Fig. 3.** Current Condition of Spring Water: (a) Sumber Umbulan, (b) Sumber Bendo, (c) Sumber Durmo, (d) Sumber Sendang biru

Measurements of water quality parameters at four karst springs in the South Malang region show striking spatial variations between locations (Table 1). These differences indicate heterogeneity in the groundwater flow system and local geological conditions that influence the hydrogeochemical characteristics of each spring.

**Table 1.** Summary of water quality parameters (Mean ± SD, n = 3)

| Spring | pH (±SD) | TDS (mg/L ±SD) | EC (µS/cm ±SD) | Turbidity (NTU ±SD) | $CaCO_3$ (mg/L ±SD) |
|---|---|---|---|---|---|
| Bendo | 7.45 ± 0.11 | 364.67 ± 75.12 | 805.67 ± 17.90 | 0.89 ± 0.69 | 446.67 ± 11.55 |
| Durmo | 7.33 ± 0.12 | 353.00 ± 65.83 | 785.33 ± 4.73 | 0.58 ± 0.11 | 433.33 ± 46.19 |
| Umbulan | 7.18 ± 0.07 | 325.00 ± 78.89 | 745.33 ± 20.84 | 1.03 ± 0.06 | 402.33 ± 20.40 |
| Sendang Biru | 7.39 ± 0.16 | 278.33 ± 81.70 | 604.33 ± 71.45 | 4.78 ± 1.91 | 380.00 ± 40.00 |

Note: Values represent mean ± standard deviation, based on n = 3 replicates per month. Total number of samples = 36.

To provide a comprehensive overview of the relationships between the measured hydrogeochemical parameters, a Pearson correlation matrix was compiled (Table 2). This matrix summarises the correlation coefficients (r) between pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, and calcium carbonate ($CaCO_3$) concentration at all sampling points and periods.

**Table 2.** Pearson correlation coefficients between water quality parameters

| Parameter | pH | TDS | EC | Turbidity | $CaCO_3$ |
|---|---|---|---|---|---|
| **pH** | 1.000 | 0.324 | 0.115 | -0.029 | 0.157 |
| **TDS** | 0.324 | 1.000 | 0.679 | -0.485 | 0.332 |
| **EC** | 0.115 | 0.679 | 1.000 | -0.903 | 0.721 |
| **Turbidity** | -0.029 | -0.485 | -0.903 | 1.000 | -0.687 |
| **$CaCO_3$** | 0.157 | 0.332 | 0.721 | -0.687 | 1.000 |

Note: Values represent Pearson correlation coefficients (r) among parameters (n = 12).

The Pearson correlation matrix provides a comprehensive overview of the relationships between water quality parameters in four karst springs. The correlation results show a consistent pattern between relevant hydrogeochemical variables and the dynamics of carbonate dissolution and precipitation. For example, electrical conductivity (EC) is positively correlated with $CaCO_3$ (r = 0.721), indicating that an increase in the concentration of dissolved calcium carbonate is in line with an increase in the number of ions in the water. This correlation confirms that $Ca^{2+}$ and $HCO_3^-$ resulting from carbonate dissolution are the main contributors to high EC values.

In addition, the negative relationship between turbidity and $CaCO_3$ (r = -0.687) indicates that an increase in suspended particles tends to be opposite to carbonate chemical stability, possibly due to hydrological disturbances or external inputs from surface activities. This relationship is important to highlight that physical dynamics (e.g., suspended particles) do not always move in tandem with carbonate chemical dynamics. Correlations between other parameters, such as between pH and $CaCO_3$, show relatively moderate but still significant patterns for understanding the balance between carbonate dissolution and precipitation.

**pH stability and calcium carbonate dissolution dynamics in Karst Springs**

The pH measurements at the four karst springs in South Malang showed a relatively stable range, between 7.17 and 7.45 (Fig. 4). These values confirm the neutral to slightly alkaline conditions also reported in other tropical karst systems, such as in Vietnam and Thailand **(Limbert *et al.*, 2020)**. However, the relatively narrow variation at the study site differs from findings in the Gunungkidul karst area (Indonesia), where agricultural intensification has caused wider pH fluctuations **(Cahyadi *et al*., 2023)**. This suggests that, although carbonate buffering processes remain dominant, pH stability in Southern Malang appears to be influenced by land use conditions and the distinct characteristics of coastal aquifer flow compared to continental karst systems. Thus, these results not only confirm the role of carbonate buffering capacity as described in the literature **(Han *et al*., 2009; Wang *et al*., 2016)** but also highlight the local context of Southern Malang as a tropical coastal karst with distinctive hydrogeological dynamics.

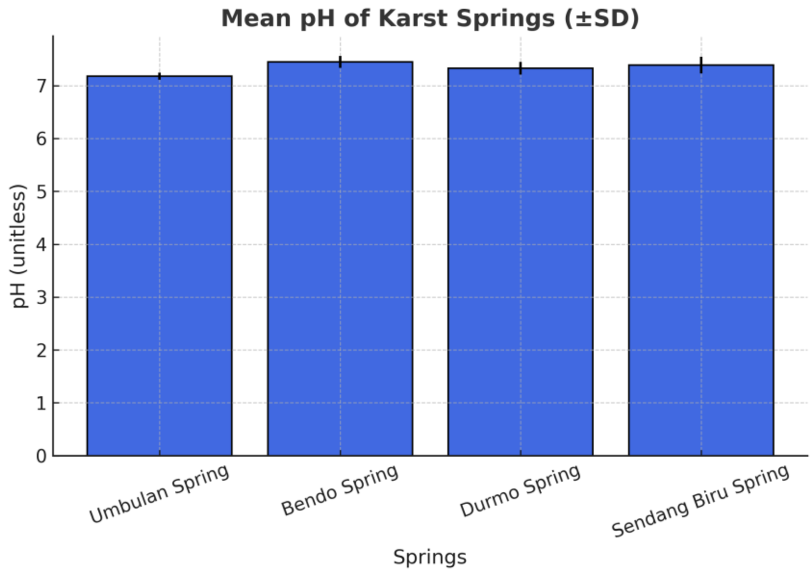



**Fig. 4.** Water pH Values

The existing spatial pattern shows differences where the relatively low pH at Sumber Umbulan indicates more intensive dissolution activity, while the higher pH at Sumber Bendo indicates the potential for $CaCO_3$ precipitation. This phenomenon is consistent with findings in tropical karst regions of Thailand **(Jiang *et al.*, 2020)**, but differs from studies in Gunungkidul, Indonesia, where intensified agriculture has resulted in more extreme pH fluctuations **(Cahyadi *et al.*, 2023)**. The stability of pH in the neutral to alkaline range in Southern Malang also reflects the effectiveness of the carbonate buffering system in coping with seasonal variations. This indicates that external acid loads from anthropogenic activities remain limited, unlike the case in Brazilian karst regions reported by **Souza *et al.* (2023)**, where organic inputs from land use increase carbonate dissolution rates. Thus, the results of this study confirm that local carbonate lithology plays a crucial role in maintaining water chemical quality, while also highlighting regional differences in the hydrogeochemical dynamics of tropical karst systems.

**Electrical conductivity (EC) as an indicator of carbonate dissolution intensity**

The electrical conductivity (EC) values obtained from the four springs ranged from 604.3 to 805.7μS/ cm, with the highest value found in the Sumber Bendo spring (805.7μS/ cm), as shown in Fig. (5). High EC values indicate high levels of dissolved ions, which are directly correlated with the dissolution of carbonates due to water contact with carbonate rocks over extended residence times **(Ford & Williams, 2007; Hartmann *et al.*, 2014)**.

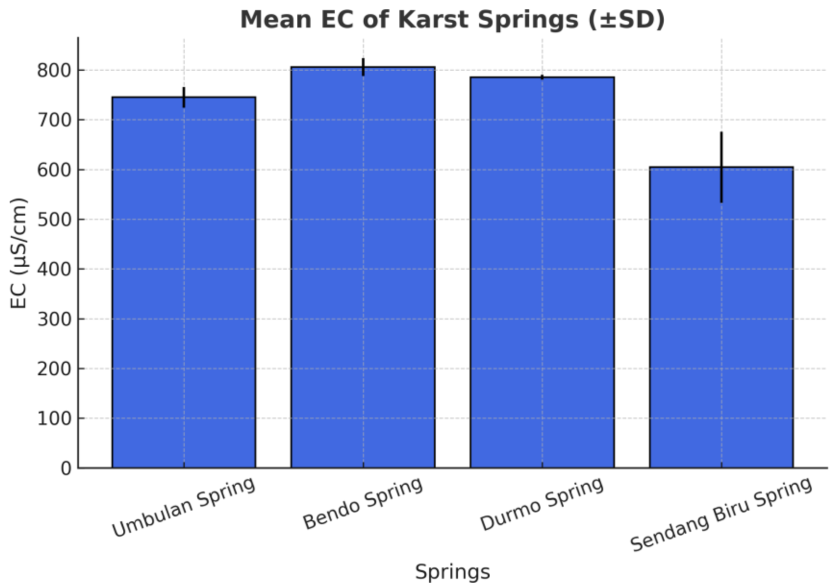



**Fig. 5.** Electrical conductivity **(**EC**)** values

The influence of bicarbonate ions ($HCO_3^-$) and calcium ions ($Ca^{2+}$) on electrical conductivity (EC) in karst systems, such as the tropical karst system at Baron Spring, has been well documented. These ions significantly influence the hydrochemical characteristics and processes occurring in karst aquifers. In karst systems, groundwater composition is often stable, with EC levels primarily determined by the dissolution of carbonate rocks, which release $HCO_3^-$ and $Ca^{2+}$ into the water. This relationship suggests that fluctuations in electrical conductivity can serve as an effective indicator of changes in dissolved ion concentrations, particularly in relatively undisturbed karst areas **(Chang *et al*., 2021; Xiao *et al*., 2021)**. Conversely, the lower average EC value at Sumber Sendang Biru **(**522 μS/cm**)** indicates a relatively short flow path with lower rock interaction, likely due to the dominance of diffusive flow **(Goldscheider & Drew, 2007)**.

**$CaCO_3$ concentration and its relationship with EC**

The $CaCO_3$ content in the four springs ranged from 380 to 446.7mg/ L, as shown in Fig. (6). The high concentration of $CaCO_3$ in the Durmo and Bendo springs reinforces the indication of the dominance of the carbonate dissolution process.

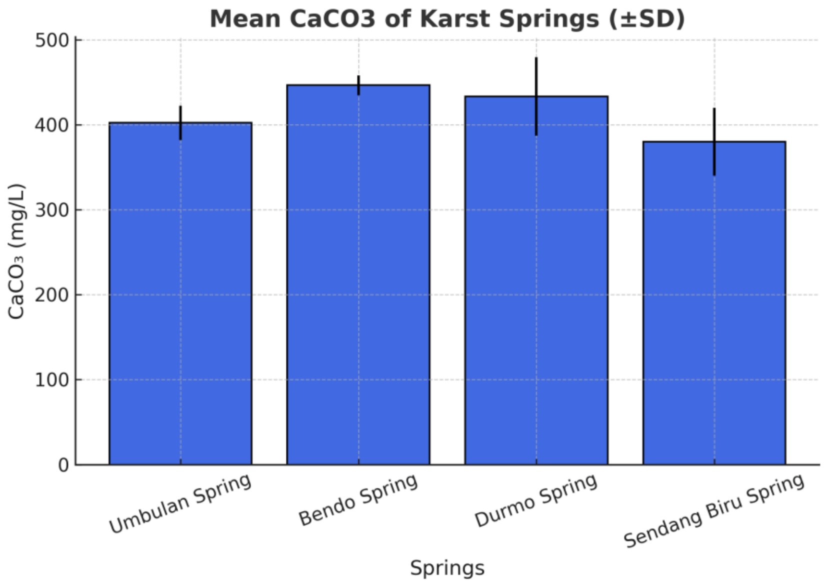



**Fig. 6.** $CaCO_3$ values

Pearson's correlation analysis shows a positive relationship between $CaCO_3$ and EC (r = 0.721), indicating that variations in carbonate ion content play an important role in controlling water conductivity in the karst springs of South Malang. This correlation not only confirms the dominant role of carbonate dissolution but also indicates that the ionic charge in the local karst system is relatively controlled by carbonate lithology rather than external inputs. These findings are consistent with reports from tropical karst in Southern China **(Han *et al.*, 2009)** and Florida **(Gulley *et al.*, 2015)**, but the more moderate correlation level compared to the study in Vietnam **(Jiang *et al.*, 2020)**, with r > 0.85, indicates distinctive hydrodynamic variations. Thus, the relationship between $CaCO_3$ and EC in this study underscores the role of carbonate buffering in Southern Malang, while also highlighting the uniqueness of hydrogeochemical responses in coastal tropical karst compared to continental systems.

**Turbidity as an indicator of rapid response to surface variations**

Turbidity shows significant spatial variation, with the highest values recorded at Sumber Sendang Biru, while other springs are relatively low, as shown in Fig. (7). The high turbidity at Sumber Sendang Biru is not only influenced by anthropogenic activities around the spring, but also by the hydrological characteristics of karst, which is highly responsive to seasonal changes. During the rainy season, rapid infiltration in the epikarst zone carries suspended particles into the groundwater system, resulting in increased turbidity at the spring outlet. This confirms that the turbidity at Sumber Sendang Biru does not originate from surface runoff, but rather from internal sediment transport triggered by rainfall dynamics and soil moisture in the seasonal recharge zone.

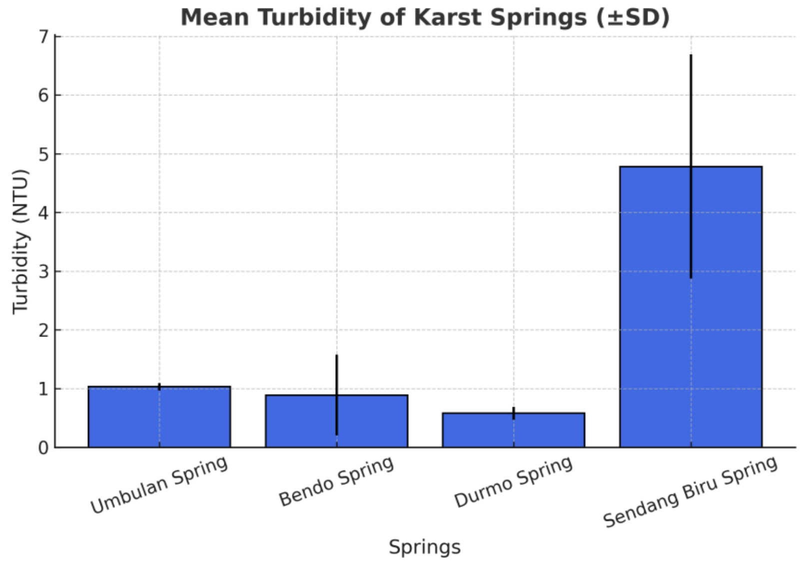



**Fig. 7.** Turbidity values

The unit map of the Sumber Sendang Biru Catchment Area (Fig. 8) shows the dominance of non-forest areas in the recharge zone, including moorland and intensive agricultural activities. This land use distribution explains why this source has the highest turbidity value compared to other springs. The spatial pattern on the map supports the water quality measurement results, where anthropogenic pressure and intensified land use are proven to be correlated with turbidity spikes, especially during the rainy season.

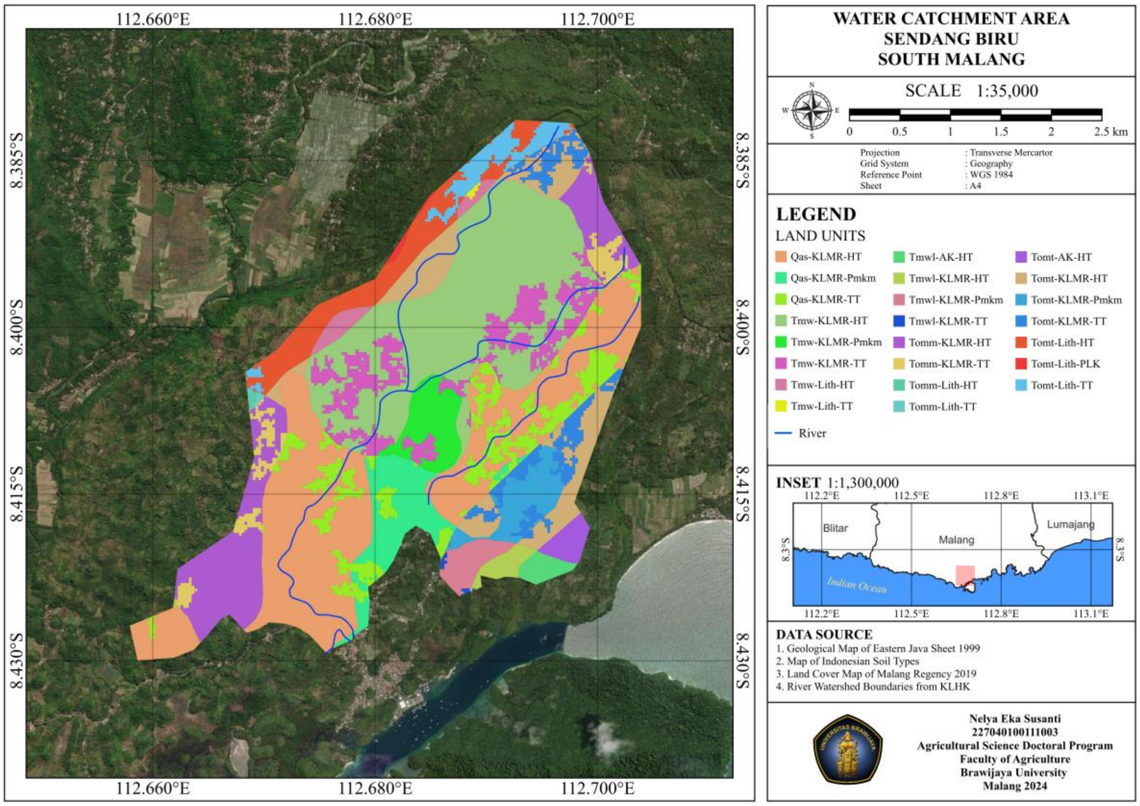



**Fig. 8**. Sendang Biru water catchment area

The Sendang Biru catchment area (DTA) map in Fig. (8) shows the diversity of land units and land use distribution that has a direct impact on water quality, particularly turbidity parameters. In the upper to middle parts of the DTA, the land units are dominated by forested areas (shown in green and purple), which act as natural recharge zones and relatively maintain the stability of hydrogeochemical conditions. Conversely, in the middle to lower reaches, especially those near the coastline, there are land units dominated by settlements, ponds, and rice fields (colored brown and light blue). This zone indicates higher anthropogenic pressure. The spatial pattern correlation can explain the field findings of a surge in turbidity values at the Sendang Biru Spring.

The results of Pearson's correlation analysis show a fairly strong negative correlation between turbidity and $CaCO_3$ (r = –0.687). This correlation indicates that an increase in turbidity values tends to be followed by a decrease in $CaCO_3$ concentration, and vice versa. This relationship pattern reflects the characteristic hydrological dynamics of karst aquifer systems, which are highly influenced by water flow paths, residence time, and seasonal conditions.

This phenomenon also supports previous findings that water quality characteristics in karst environments are greatly influenced by the contribution of quickflow and baseflow, which vary temporally **(Hartmann *et al.*, 2014)**. During the rainy season or periods following high rainfall, the role of quickflow increases significantly, causing spring water to become more turbid and $CaCO_3$ content to decrease. Conversely, during the dry season or periods of low rainfall, water reaching the springs is dominated by baseflow originating from the saturated zone, which has high clarity and higher dissolved mineral content, including $CaCO_3$.

In karst systems, turbidity dynamics serve as an important indicator of water quality, particularly in relation to rainfall events. Research indicates that rainfall significantly increases turbidity in karst aquifers characterized by strong surface connections and rapid flow pathways **(Kadić *et al*., 2023; Mueller *et al.*, 2023)**. Thus, the negative relationship between turbidity and $CaCO_3$ not only indicates the physico-chemical dynamics of water but also reflects the structural and functional conditions of the karst system itself. This correlation can be utilized as an indirect indicator to evaluate the dominance of flow pathways and the level of hydrological disturbance in karst recharge systems, particularly in the context of land cover change and anthropogenic pressure in recharge zones.

**Variations in total dissolved solids (TDS) and their implications for water quality**

The results of the Total Dissolved Solids (TDS) concentration study at four main spring locations in the South Malang karst area show significant variations in TDS values, ranging from 278.33 to 364.67 ppm, as shown in Fig. (9). The Bendo Spring has the highest average TDS value, while the Sendang Biru Spring has the lowest average TDS value. This distribution aligns with findings from similar hydrogeological environments, where factors such as the dissolution of carbonate minerals, particularly calcium carbonate ($CaCO_3$), and the characteristics of underground flow pathways substantially influence TDS concentrations **(Anggraeni *et al.*, 2022)**. Furthermore, the observed TDS values indicate that the chemical properties of these springs are strongly influenced by the mineral composition of the surrounding rocks and the duration of water residence in the karst system, as longer residence times generally facilitate greater mineral dissolution, thereby increasing TDS levels **(Moldovan *et al*., 2021; Anggraeni *et al.*, 2022)**.

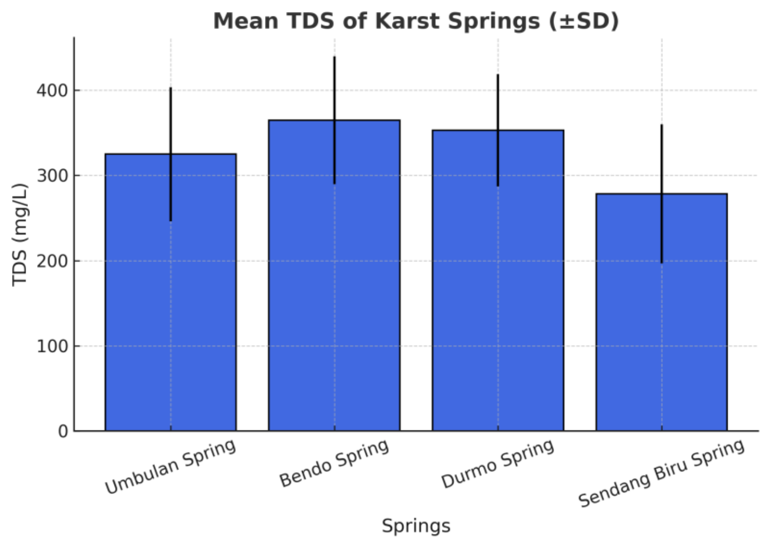



**Fig. 9.** Total dissolved solids **(**TDS**)** values

The correlation between TDS values and electrical conductivity (EC) shows a strong relationship characteristic of karst waters, where increased mineral content contributes to higher TDS and EC measurements. These observations emphasize that the chemical characteristics of water are strongly influenced by geological composition, which acts through mechanisms such as branching flow paths and the duration of water interaction with rocks **(Fashina *et al.*, 2022)**.

**Implications for Karst water resource management and sustainability**

Overall, the variation in water quality parameters reflects the dynamics of the karst aquifer system, which is strongly influenced by local geological conditions, flow morphology, and land use activities in the catchment area. Understanding these spatial dynamics is crucial as a foundation for sustainable management of karst water resources, particularly in addressing the growing anthropogenic pressures in tropical regions. The findings of this study underscore the importance of conserving catchment areas and controlling land use activities in karst recharge zones. Conservation of water catchment areas, particularly in karst recharge zones, is an integral part of groundwater resource sustainability. Karst aquifers are unique geological formations characterised by high porosity and permeability, enabling efficient groundwater recharge through the dissolution of easily soluble rocks such as limestone. However, this rapid recharge rate also poses significant risks related to contamination and depletion of this important water source due to anthropogenic activities such as urbanisation and land use change **(Li *et al*., 2019; Cao *et al*., 2025)**.

The current water quality stability in the study area indicates that the carbonate buffering mechanism is still functioning effectively in maintaining the chemical balance of groundwater. This system allows for the neutralisation of pH changes through reactions between calcium carbonate and natural acid compounds, thereby maintaining water quality within a stable range. However, high turbidity levels at some observation points indicate pressure from anthropogenic activities on the surface, such as land conversion, intensive agriculture, and infrastructure development around the recharge zone. If this pressure is not controlled, it could disrupt the natural capacity of the karst system to filter and stabilize water in the long term, potentially leading to degradation of the hydrogeological system.

Therefore, adaptive and conservation-based land use management in karst recharge areas is crucial. Uncontrolled land use in recharge zones can increase erosion rates, increase surface runoff, and shorten the contact time between water and carbonate rocks, which ultimately reduces infiltration effectiveness and natural dissolution capacity. Several studies have shown that rapid and unplanned urbanization is one of the main factors driving the degradation of karst water recharge systems, altering the nature of groundwater flow, and accelerating the decline in groundwater quality and availability **(Li *et al*., 2019; Cao *et al*., 2025)**.

An integrated approach is needed in karst area management, including the implementation of protected zones, regular water quality monitoring, and restrictions on development in recharge areas, so that the ecological and hydrological functions of the karst system are maintained sustainably **(Fattah *et al.*, 2025)**. Thus, the carbonate buffering system, which is the foundation of the hydrogeochemical stability of this area, can continue to function optimally in the face of increasing environmental pressures.

## CONCLUSION

This study revealed that the water quality of karst springs in Southern Malang remains relatively stable, with pH values ranging from neutral to slightly alkaline, and a significant correlation was observed between $CaCO_3$ concentrations and electrical conductivity (EC). However, turbidity spikes were most pronounced at the Sendang Biru spring, strongly influenced by anthropogenic activities around the recharge area and the intrinsic hydrological characteristics of karst systems, which respond rapidly to rainfall. These findings highlight that karst water quality is shaped by the interplay between geochemical processes, geological settings, and land-use pressures. Based on these results, water quality monitoring should be prioritized at Sendang Biru, especially during the rainy season, to provide early detection of potential water quality deterioration. Furthermore, land-use management in recharge zones should focus on vegetation conservation and regulating anthropogenic activities to minimize sediment and nutrient transport into the subsurface aquifer. In the long term, integrating GIS-based monitoring systems with water quality sensors could serve as a strategic approach to ensuring the sustainability of karst water resources.

Despite providing valuable initial insights, this study has limitations, as sampling was conducted only during the dry season and restricted to four major springs. Consequently, the full extent of temporal variability throughout the year and broader spatial dynamics has yet to be captured. Future research should therefore incorporate multi-seasonal monitoring, expand the number of sampling sites with replication, and integrate detailed land-use data with karst hydrological modeling. Such efforts would strengthen the understanding of how human activities, aquifer dynamics, and water quality interact within tropical karst systems.

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## REFERENCES

**Anggraeni, T.; Putra, D. and Taufiq, A. (**2022**)**. Groundwater quantity and quality of springs of karst region in Pacitan Regency, East Java. In *Proceedings of the International Conference on Environmental and Sustainability Contexts in Science, Technology, and Business* **(**pp. 389–394**)**. Atlantis Press. https://doi.org/10.2991/978-94-6463-086-2_47.

**Banusch, S.; Somogyvári, M.; Sauter, M.; Renard, P. and Engelhardt, I. (**2022**)**. Stochastic modeling approach to identify uncertainties of karst conduit networks in carbonate aquifers. Water Resources Research, 58**(**8**)**, e2021WR031710. https://doi.org/10.1029/2021WR031710.

**Cahyadi, A.; Adji, T.; Haryono, E.; Widyastuti, M.; Aji, A.; Naufal, M. and Riyanto, I. (**2020**)**. Temporal variation of tropical karst groundwater suitability for irrigation in Gremeng Resurgence, Gunungsewu Karst Area, Indonesia. E3s Web of Conferences, 202, 04004. https://doi.org/10.1051/e3sconf/202020204004.

**Cahyadi, A., Riyanto, I. A. and Adji, T. N (2023).** Suitability of water from tropical epikarst spring for irrigation in the Gunungsewu karst area, Indonesia. *IOP Conference Series: Earth and Environmental Science, 1268***(**1**)**, 012008. https://doi.org/10.1088/1755-1315/1268/1/012008.

**Cahyadi, A., Riyanto, I. A., Acintya, R., Singgih, A. and Putra, R. D. (**2025**)**. Characterization of water pollution in tropical epikarst spring in Gunungsewu karst area, Java Island, Indonesia. *Turkish Journal of Engineering, 9*(3), 433–446. https://doi.org/10.31127/tuje.1524600.

**Cao, H.; Qian, J.; Chen, H.; Liu, C.; Lyu, M.; Gao, S. and Hu, C. (**2025**)**. Managed aquifer recharge and exploitation impacts on dynamics of groundwater level and quality in northern China karst area: Quantitative research by multi-methods. *EGUsphere Discussion.* https://doi.org/10.5194/egusphere-2025-281.

**Chang, Y.; Hartmann, A.; Liu, L.; Jiang, G. and Wu, J. (**2021**)**. Identifying more realistic model structures by electrical conductivity observations of the karst spring. *Water Resources Research, 57(4)*. e2020WR028587. https://doi.org/10.1029/2020WR028587.

**Cholet, C.; Charlier, J.; Moussa, R.; Steinmann, M. and Denimal, S. (**2017**)**. Assessing lateral flows and solute transport during floods in a conduit-flow-dominated karst system using the inverse problem for the advection–diffusion equation. *Hydrology and Earth System Sciences, 21*(7), 3635–3653. https://doi.org/10.5194/hess-21-3635-2017.

**Fashina, L.; Luffman, I.; Joyner, T. and Nandi, A. (**2022**)**. Geospatial assessment of karst spring water quality in northeast Tennessee, USA. *Geosciences, 12*(8), 303. https://doi.org/10.3390/geosciences12080303.

**Fattah, M.; Hakim, L.; Soemarno, S. and Purwanti, P. (**2025**)**. Water Quality Assessment for Coastal Tourism Suitability in Kampung Mandar, Banyuwangi Regency. *Egyptian Journal of Aquatic Biology & Fisheries, 29*(3), 391–408. https://doi.org/10.21608/ejabf.2025.426904.

**Ford, D. and Williams, P. (**2007**)**. *Karst Hydrogeology and Geomorphology*. John Wiley & Sons.

**Giambastiani, Y., Giusti, R., Cecchi, S., Palomba, F., Manetti, F., Romanelli, S. and Bottai, L. (2020).** Evaluation of different irrigation strategies in Central Italy: The Pesa River Basin case study. *Journal of Water and Land Development, 46*(1), 195–205. https://doi.org/10.24425/jwld.2020.134200.

**Giese, M.; Reimann, T.; Bailly-Comte, V.; Maréchal, J.; Sauter, M. and Geyer, S. (**2018**)**. Turbulent and laminar flow in karst conduits under unsteady flow conditions: interpretation of pumping tests by discrete conduit-continuum modeling. *Water Resources Research, 54*(3), 1918-1933. https://doi.org/10.1002/2017wr020658.

**Goldscheider, N. and Drew, D. (**2007**)**. *Methods in Karst Hydrogeology*. Taylor & Francis.

**Gulley, J.; Martin, J.; Moore, P.; Brown, A.; Spellman, P. and Ezell, J. (**2015**)**. Heterogeneous distributions of $CO_2$ may be more important for dissolution and karstification in coastal eogenetic limestone than mixing dissolution. *Earth Surface Processes and Landforms, 40*(8), 1057-1071. https://doi.org/10.1002/esp.3705.

**Han, G.; Tang, Y. and Wu, Q. (**2009**)**. Hydrogeochemistry and dissolved inorganic carbon isotopic composition on karst groundwater in Maolan, southwest China. *Environmental Earth Sciences*, *60***(**4**)**, 893-899. https://doi.org/10.1007/s12665-009-0226-y.

**Hartmann, A.; Goldscheider, N.; Wagener, T.; Lange, J. and Weiler, M. (**2014**)**. Karst water resources in a changing world: Review of hydrological modeling approaches. *Reviews of Geophysics, 52***(**3**)**, 218–242. https://doi.org/10.1002/2013RG000443.

**Jakada, H.; Chen, Z.; Luo, M.; Zhou, H.; Wang, Z. and Habib, M. (**2019**)**. Watershed characterization and hydrograph recession analysis: A comparative look at a karst vs. non-karst watershed and implications for groundwater resources in Gaolan River Basin, southern China. *Water*, 11**(**4**)**, 743. https://doi.org/10.3390/w11040743.

**Jiang, G., Chen, Z., Siripornpibul, C., Haryono, E., Nguyen, N. X., Oo, T. and Vongphachanh, S. (**2020**)**. The karst water environment in Southeast Asia: Characteristics, challenges, and approaches. *Carbonates and Evaporites, 35**(4)**, 1–16.* https://doi.org/10.1007/s13146-020-00600-w.

**Kadić, A.; Denić-Jukić, V. and Jukić, D. (**2023**)**. Exceeding turbidity versus karst spring discharge during single rainfall events: the case of the Jadro spring. *Water*, *15***(**14**)**, 2589. https://doi.org/10.3390/w15142589.

**Li, W.; Sun, Q.; Wang, W.; Qu, S.; Zhang, Z. and Xu, Q. (**2019**)**. Effective water quantity of multi-source water recharging aquifers in Yufuhe River based on groundwater and surface water semi-coupled modelling. *Water Supply, 19***(**8**)**, 2280–2287. https://doi.org/10.2166/ws.2019.109.

**Limbert, H., Limbert, D., Ponta, G. M. L., Nguyen Xuan, N., Stoiciu, F. and Mocioiu, A.-M. (2020).** Preliminary hydrogeological observations in Phong Nha–Kẻ Bàng National Park and Tu Lân Karst Area, Quang Binh Province, Vietnam. *Carbonates and Evaporites, 35**(3)**, 67–78.* https://doi.org/10.1007/s13146-020-00600-w.

**Moldovan, A.; Török, A.; Mirea, I.; Micle, V.; Moldovan, O. and Levei, E. (**2021**)**. Health risk assessment in southern Carpathians small rural communities using karst springs as a drinking water source. *International Journal of Environmental Research and Public Health, 18***(**1**)**, 234. https://doi.org/10.3390/ijerph18010234.

**Mueller, Y.; Goldscheider, N.; Eiche, E.; Emberger, H. and Goeppert, N. (**2023**)**. From cave to spring: understanding transport of suspended sediment particles in a fully phreatic karst conduit using particle analysis and geochemical methods. *Hydrological Processes, 37***(**10**)**, e14979. https://doi.org/10.1002/hyp.14979.

**Nurani, I. (**2017**)**. Karakter budaya gua kidang hunian prasejarah kawasan karst pegunungan utara jawa. *Berkala Arkeologi Sangkhakala, 19***(**1**)**, 1. https://doi.org/10.24832/sba.v19i1.19.

**Ruiz, M. C., Domínguez, E., García-Ruiz, M. J. and Aguilera, H. (2022).** Land cover changes and their influence on recharge in a karstic aquifer (Spain). *Land*, *12*(1), 128. https://doi.org/10.3390/land12010128.

**Smith, R., & Johnson, E. (2022)**. Real-time Data Collection in ecosystems: Advancements and Challenges. *Remote Sensing of Ecosystems*, 11(5), 204-215.

**Souza, R.; Travassos, L.; Heredia, O.; Paparas, M.; Sicilia, S.; Patat, F. and Bautista, F. (**2023**)**. First steps to understanding intrinsic vulnerability to contamination of karst aquifers in various South American and Caribbean countries. *Acta Carsologica*, *52*(1), 101–112. https://doi.org/10.3986/ac.v52i1.10516.

**Vilhar, U., Kermavnar, J., Kozamernik, E., Petrič, M. and Ravbar, N. (2022).** The effects of large-scale forest disturbances on hydrology – An overview with special emphasis on karst aquifer systems. *Earth-Science Reviews*, *235*, 104243. https://doi.org/10.1016/j.earscirev.2022.104243.

**Wang, G.; Qafoku, N.; Lawter, A.; Bowden, M.; Harvey, O.; Sullivan, C. and Brown, C. (**2016**)**. Geochemical impacts of leaking $CO_2$ from subsurface storage reservoirs to an unconfined oxidizing carbonate aquifer. *International Journal of Greenhouse Gas Control*, *44*, 310-322. https://doi.org/10.1016/j.ijggc.2015.07.002.

**Willenbrink, E. (2021).** Communication networks as a catalyst for holistic understanding of human–karst interactions. *Sustainability*, *13*(6), 3360. https://doi.org/10.3390/su13063360.

**Xiao, S.; Zeng, C.; Lan, J.; Di, Y.; He, J.; Xiao, H. and Wang, J. (**2021**)**. Hydrochemical characteristics and controlling factors of a typical dolomite karst basin in the humid subtropical zone. *Geofluids*, *2021*, 8816097. https://doi.org/10.1155/2021/8816097.

**Yogafanny, E. and Legono, D. (**2021**)**. Assessment of groundwater vulnerability using the COP method to support the groundwater protection in the karst area. *IOP Conference Series Earth and Environmental Science*, *930*(1), 012036. https://doi.org/10.1088/1755-1315/930/1/012036.

**Yu, S. (2021).** *Hydrochemical and Isotopic Difference of Spring Water*. *Frontiers in Earth Science*, *9*, 712865. https://doi.org/10.3389/feart.2021.712865**.**

**Zhang, J., Liesch, T., Chen, Z. and Goldscheider, N. (2023).** Global analysis of land-use changes in karst areas and the implications for water resources. *Hydrogeology Journal*, *31*(4), 1197–1208. https://doi.org/10.1007/s10040-023-02650-5.