

Epikarst Springs as Atmospheric CO₂ Sinks in a Tropical Karst Environment: Evidence from the Gunungsewu Karst, Indonesia

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ABSTRACT

Karst ecosystems, covering 15% of global land, serve as vital carbon sinks, especially in the epikarst zone. This study examines the carbon sink capacity of epikarst spring catchments using field data from August 2022 to July 2023. Applying the hydrochem-discharge method, discharge and dissolved bicarbonate (HCO₃⁻) concentrations were analyzed at two-week intervals. The results reveal that epikarst springs absorb atmospheric CO₂ at rates of 747.34–787.00 tons/km²/year, significantly surpassing non-epikarst springs (576.92 tons/km²/year). This sequestration capacity is driven by seasonal rainfall, discharge volume, and ion levels. Compared to other karst regions on Java Island, these springs demonstrate superior absorption, highlighting their critical importance in the global carbon cycle.

Keywords: epikarst springs; atmospheric CO₂ sequestration; Gunungsewu karst; dissolution processes

Introduction

According to Yoro and Daramola (2020), carbon dioxide (CO₂), as a greenhouse gas, accounts for 50% of the occurrence of global warming and climate change. The escalation of carbon dioxide emissions in the atmosphere exerts a detrimental influence on ecosystems, necessitating the implementation of a mechanism capable of regulating atmospheric carbon dioxide emissions (Kabir et al., 2023; Nunes, 2023). Chen et al. (2023) thus clarified that through the dissolution process of carbonate rocks, karst areas naturally absorb atmospheric carbon dioxide. Furthermore, Wu et al. (2023) clarify the difference between karst and other ecosystems, namely that in karst ecosystems all CO₂ generated from respiration is absorbed by the dissolution process whereas in non-karst ecosystems CO₂

emitted by respiration will remain as emissions in the atmosphere. In addition, the interaction of carbon dioxide (CO₂) from the atmosphere or soil with water (H₂O) will result in the formation of carbonic acid (H₂CO₃). The carbon value derived from titration of karst spring water represents approximately half of the total carbon, with the remaining half originating from the atmosphere and soil (Martin, 2017; Jiang, 2013).

Karst areas, which cover around 2.2×10⁷ km² globally (15% of the Earth's total surface area), have the capacity to sequester carbon on land at a rate of approximately 2.5 Pg C/year (Pu et al., 2015). The absorption of CO₂ by the dissolution of limestone accounts for +33% of worldwide forest carbon absorption, ±68% of carbon in soil, ±23% of the world's missing carbon

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sink, and $\pm 7.5\%$ - 8.3% of the total emissions produced by fossil fuels (Huang et al., 2024; Cao et al., 2018). Hence, it is imperative to acknowledge the significance of natural carbon absorption in this karst region into the foreseeable future, spanning hundreds of years or beyond (Xie et al., 2021).

Balazs (1968) estimates that Indonesia's karst region encompasses approximately 150,000 square kilometers. Karst areas are present on nearly all islands in Indonesia, including Sumatra, Java, Kalimantan, Sulawesi, and Papua. Additionally, Balazs (1971) elucidated that the Maros karst area in South Sulawesi and the Gunungsewu karst on Java Island are two karst areas in Indonesia that are considered prototypes of tropical karst. These areas are characterized by their unique topography. According to Haryono (2011)'s research, the estimated quantity of CO_2 that can be absorbed through the dissolution of carbonate rocks in Indonesia is 13,482 Gg/year.

Epikarst, also known as “karst layer skin”, refers to a thin zone that is typically found near the surface of karst topography (Bakalowicz, 2019; Fu et al., 2015). The epikarst zone is distinguished by the extensive formation of fractures, which is influenced by factors such as the type of limestone rock, climate, hydrology, and vegetation (Pardo-Igúzquiza et al., 2018; Bakalowicz, 2013). From an ecological perspective, epikarst is regarded as a “reservoir” of biodiversity (Kozel & Pipan, 2020). Epikarst represents the uppermost weathered and highly fractured part of the karstified rock mass, where porosity and permeability are generally higher than in the deeper carbonate rocks. This zone plays an important role in storing and redistributing infiltrating water, regulating recharge to the vadose zone, and enhancing water-rock interaction (Klimchouk, 2004). Because epikarst is also a zone where geological, hydrological, biological, and chemical processes interact, its characteristics can vary greatly among karst systems (Milanović, 2025). In this study, such characteristics are important because they help explain the diffuse flow, prolonged carbonate dissolution, and atmospheric CO_2 sequestration observed in epikarst springs.

Furthermore, epikarst serves as a vertical extension of the soil and functions as a storage site for organic matter accumulation (Srivastava et al., 2012). Specifically, it is where CO_2 derived from the decomposition of organic matter is stored, making it the primary factor in the dissolution of carbonate rocks (Chen et al., 2021). Jiang (2013) discovered that epikarst plays a significant role in the production, storage, and distribution of carbon dioxide in karst aquifers. Epikarst

functions as a reservoir for CO_2 , gradually replenishing the infiltration zone through a slow infiltration process (Cheng et al., 2023). Specifically, this gradual infiltration results in the mixing of air and water in tiny cavities and pores, leading to the downward movement of CO_2 -rich air into the soil system and its subsequent distribution across the infiltration zone (Williams, 2008; Trček, 2002). In this process, if there is a quick influx of water, whether from direct dispersion or point recharge, it will still have the ability to dissolve CO_2 (Jiang et al., 2013). Consequently, the carbonate rocks in the phreatic zone become more soluble (Jones, 2013). Hence, the storage of water in the epikarst plays a crucial role in the formation of karst landscapes and the capture of carbon, both in shallow and deep zones (Nannoni & Piccini, 2022; Yang et al., 2012).

Regarding the development of voids in karst aquifers, Fores et al. (2021) revealed that epikarst springs originate from water stored in undeveloped epikarst zones. Consequently, the flow in these springs is primarily recharged by slow-moving infiltration water (diffuse flow). The elevated levels of CO_2 in epikarst springs are a result of the extensive water-rock interaction process and the presence of mechanisms in the soil (Cahyadi et al., 2023a; Nurkholis et al., 2019). Conversely, non-epikarst springs have undergone significant void development resulting in faster and more turbulent water flow (Adji et al., 2017). As a consequence, there is a decrease in the absorption of carbon dioxide.

The Gunungsewu Karst area is characterized by the presence of epikarst springs in the Ponjong hydrogeological subsystem, which serve as the primary water source for the local people (Riyanto & Cahyadi, 2023). This subsystem exhibits a distinct pattern of groundwater movement in the direction of the west and south. It is noteworthy for its significant discharge and continuous flow throughout the year. The upstream part of this subsystem typically contains epikarst springs, while the downstream part is characterized by non-epikarst springs (Cahyadi et al., 2023b). The main objective of this study is to determine the carbon sink capacity of the epikarst spring catchment area. Furthermore, the carbon sequestration capacity of epikarst springs is compared to that of non-epikarst springs. At a broader scale, this study provides new evidence on the role of tropical karst systems in atmospheric CO_2 sequestration. The findings highlight how warm temperatures, seasonal rainfall, and epikarst hydrological processes can enhance carbonate dissolution and support natural carbon uptake in humid tropical environments.

Materials and Methods

Carbon sequestration studies were performed at three epikarst springs: Gedaren, Sulu, and Sumber Ponjong Springs, while the Seropan Underground River served as a non-epikarst spring sample (Figure 1). These four

sites are part of the Ponjong hydrogeological subsystem, Gunungsewu Karst. The Ponjong hydrogeological subsystem is characterized by perennial springs and underground drainage systems, where groundwater

movement is mainly influenced by the local karst conduit–fracture network, catchment morphology, and recharge conditions (Cahyadi et al., 2023b).

Gunungsewu Karst is a part of the Southern Mountains on Java Island. It consists of a sequence of hills that create a highland landscape in the southern region of Java. The area extends from Ciletuh Bay in West Java to the Blambangan Peninsula in East Java (Reinhart et al., 2023). The Gunungsewu Karst is composed of the Wonosari-Punung Formation (Tmwl), which is a type of Neogene limestone. This limestone is characterized by extensive coral reef formations in the southern region and multiple layers of limestone in the northern region. The formation is classified as Middle Miocene and Upper Pliocene in terms of its age, and it is esti-

mated to have a thickness exceeding 650 m, as reported by Hartawan et al. (2020). The terrain surrounding the main karst aquifer consists of several non-carbonate and mixed lithological units, including volcanic, volcanoclastic, siliciclastic, and Quaternary deposits. These surrounding formations form a contrasting geological setting because they are generally less soluble than limestone and tend to support more developed surface drainage.

The long-term rainfall data for 2002–2022 were used to describe the general climatic condition of the Gunungsewu Karst area. In addition, monthly rainfall data corresponding to the monitoring period were processed and used in the temporal analysis. These monitoring-period rainfall data were matched with the

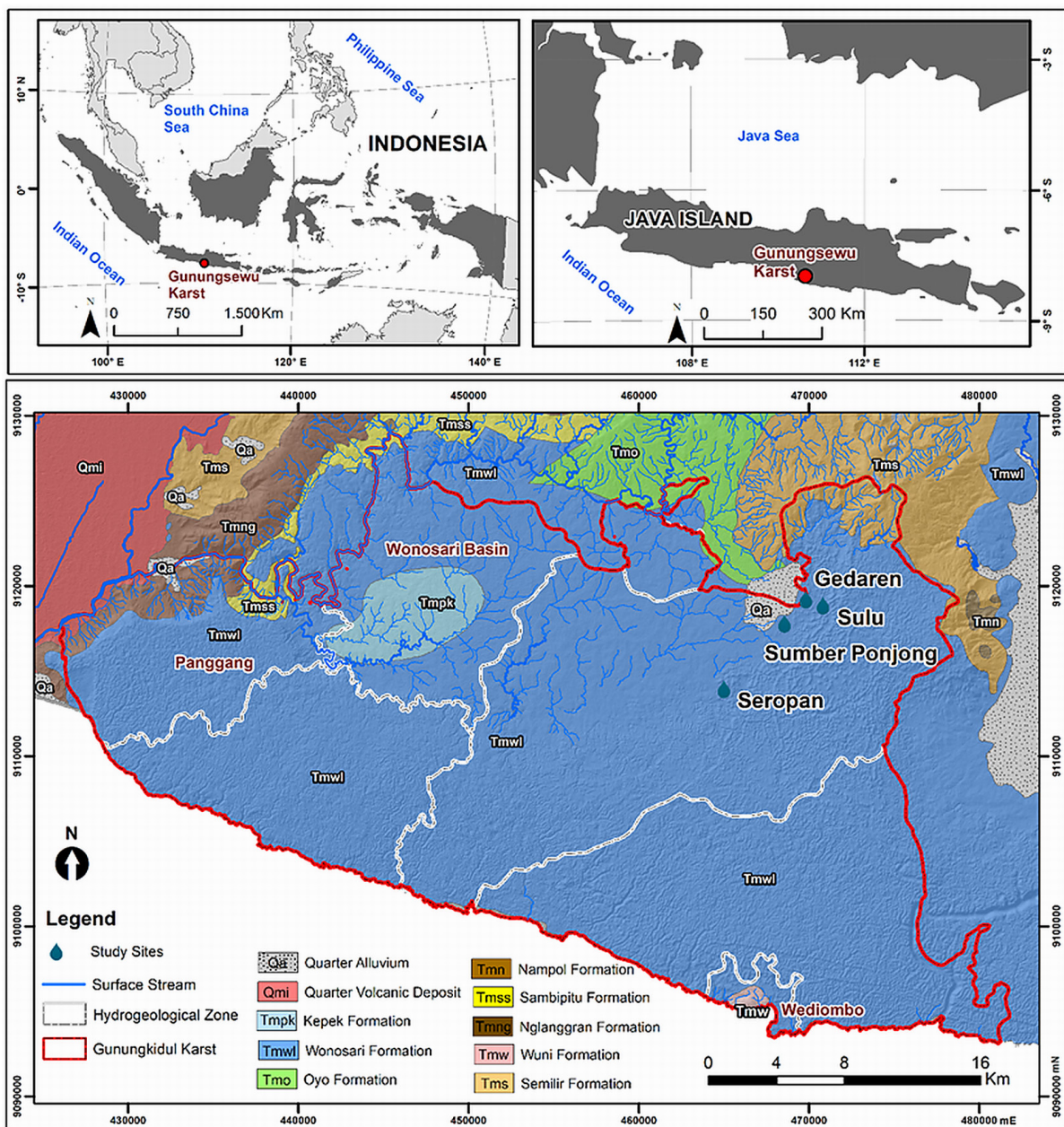


Figure 1. Location and geological setting of the studied epikarst springs and Seropan Underground River within the Gunungsewu Karst, Indonesia, including hydrogeological zones, surface rivers, and surrounding geological formations.

discharge, HCO_3^- concentration, and CO_2 sequestration records to evaluate the seasonal response of each spring system. Therefore, the long-term rainfall record represents the climatic background, whereas the monitoring-period rainfall data represent the hydrological forcing during the observation period.

The Gunungsewu Karst area has a distinct seasonal climate. Based on long-term data from 2002 to 2022, the area receives an average annual rainfall of about 2,355 mm, with rainfall mainly concentrated during the wet season. During the same period, the mean monthly air temperature was approximately 25.9 °C (Figure 2).

Temporal discharge data at each spring and the dissolved HCO_3^- concentration in mg/litre are required to calculate carbon sequestration accurately. The data were collected over one year, with samples collected every two weeks. The velocity-area method is employed to measure the discharge of springs and underground rivers, while a current meter is employed to measure the flow velocity. Meanwhile, the Alkalinity Test Kit MQuant® 1.11109 was employed to directly measure the dissolved HCO_3^- concentration in the field through titration. The catchment area is determined using the balance approach (Widyastuti et al., 2019) through evapotranspiration calculations:

$$V = (P - E) \times A \quad (1)$$

Where V is the discharge in volume (liter/year), P is precipitation (mm/year), E is evapotranspiration (mm/year), and A is the catchment area (m^2). The V value (total water volume) is obtained through the following equation (Widyastuti et al., 2019):

$$V = \left(\frac{Q(n)+Q(n+1)}{2} + \frac{Q(n+1)+Q(n+2)}{2} + \dots + \frac{Q(m-1)+Q(m)}{2} \right) \times \text{unit of time} \quad (2)$$

Where V is total volume (liter), Q is total discharge (liter/year), $Q(n)$ is the first discharge data (liter/second), $Q(m)$ is the last discharge data (liter/second), and Unit of time is the time lapse of each recording (second).

Next, the rate of atmospheric carbon sequestration was determined using the hydrochem-discharge method (Liu & Zhao, 2000) with the following formula:

$$F = 0.5 \times [\text{HCO}_3^-] \times Q \times (M_{\text{CO}_2}/M_{\text{HCO}_3}) \quad (3)$$

Where, F is the rate of atmospheric carbon sequestration (gram/year), HCO_3^- is the dissolved HCO_3^- (gram/liter), Q is the discharge (liter/year), M_{CO_2} is the Mr of CO_2 (44), and $M_{\text{HCO}_3^-}$ is the Mr of HCO_3^- (61.02). The F value in the formula given represents the quantity of carbon sequestration occurring in the catchment area of each spring/underground river. In order to convert carbon absorption into CO_2 absorption, a simple method is to use a stoichiometric equation with the formula:

$$\text{CO}_2 = F \times (\text{atomic weight } \text{CO}_2 / \text{atomic weight } \text{C}) \quad (4)$$

Where, CO_2 is the atmospheric CO_2 sequestration rate (ton/year), F is the atmospheric C sequestration rate (ton/year), atomic weight of CO_2 is 44, and atomic weight of C is 12.

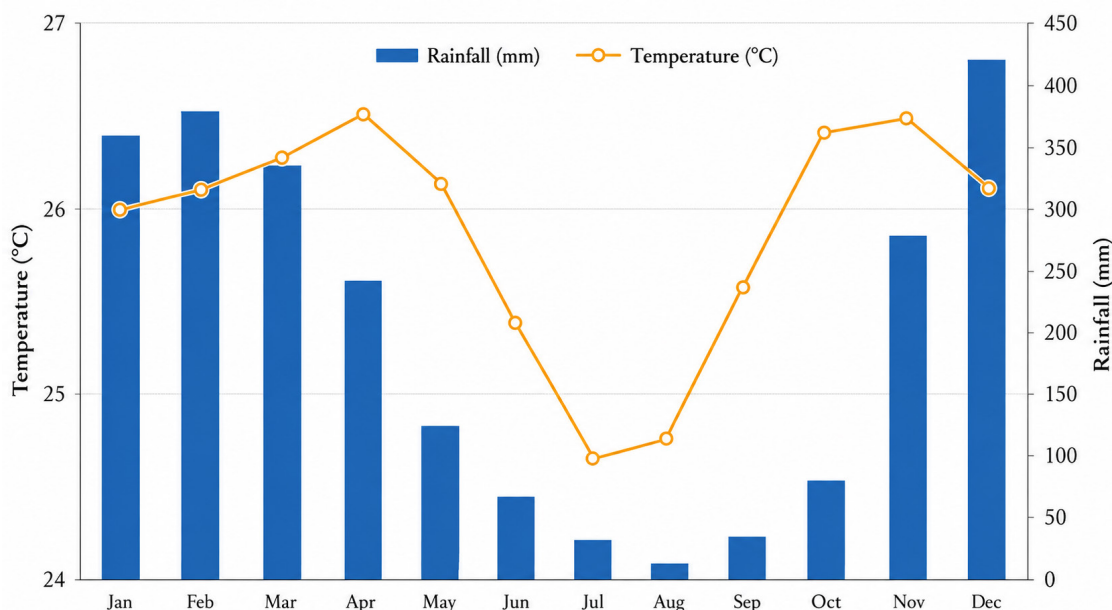


Figure 2. Long-term monthly rainfall and air temperature patterns in the Gunungsewu Karst area, based on climatic data used to describe the general climatic setting of the study area.

Results and Discussion

The sequestration of CO_2 is significantly affected by spring discharges and the concentration of dissolved bicarbonate ions (HCO_3^-). The discharge and HCO_3^- concentration measured at the spring outlet result from the accumulation of hydrological processes taking place in a water catchment area. The process of CO_2 absorption in karst springs begins with hydrological phenomena that include precipitation, infiltration, evapotranspiration, and the dissolution of carbonate rocks within a catchment area. Therefore, it is necessary to assess spring catchment requirements prior to estimating the absorption of atmospheric CO_2 . Figure 3 displays the outcomes of estimating the catchment area using the water balance method. The Seropan Underground River has the most extensive catchment area, totalling 10.91 km^2 . On the other hand, the Sumber Pongong Springs has the smallest catchment area, measuring only 0.69 km^2 .

The atmospheric carbon sequestration value obtained through the karstification process in epikarst and non-epikarst springs ranges from 157.33 to 214.62 $\text{tons}/\text{km}^2/\text{year}$, as determined by calculations and data analysis. Meanwhile, atmospheric CO_2 absorption values have a wider range of values, specifically from 576.92 to 787.00 $\text{tons}/\text{km}^2/\text{year}$ (Table 1). CO_2 absorption rates in the three epikarst springs (Gedaren, Sulu, and Sumber Pongong) are higher than that in the non-epikarst spring (Seropan).

Rainfall data for the monitoring period were processed and plotted together with discharge, HCO_3^- concentration, and CO_2 sequestration in Figure 4. This was done to ensure that the temporal variation of hydrochemical parameters could be interpreted in

relation to the actual rainfall conditions during the observation period, rather than only from the long-term climatic average. The rainfall pattern shows clear seasonal variability, with higher rainfall during the wet season and lower rainfall during the dry season. This seasonal pattern helps explain the observed changes in spring discharge, bicarbonate concentration, and CO_2 sequestration. Collectively, the four springs show HCO_3^- concentration values ranging from 276 to 408 mg/litre . The HCO_3^- concentration in Seropan River is the lowest among the three epikarst springs. This is because the epikarst springs are primarily characterised by a diffuse flow type, which is typically highly saturated, resulting in a higher HCO_3^- concentration. Seasonally, the average absorption of atmospheric CO_2 in Sulu, Sumber Pongong, and Seropan is greater during the dry season compared to the wet season (Figure 4). Here, due to the dilution effect of precipitation mechanism, high rainfall in the rainy season followed by an increase in spring discharge reduces HCO_3^- concentration and lowers CO_2 sequestration.

During the initial field measurement period, all springs exhibited significant fluctuation in CO_2 sequestration, particularly during the rainy season. The CO_2 levels during this time showed greater variability compared to the dry season. The temporal fluctuations in the rate at which atmospheric CO_2 is absorbed are primarily influenced by three key factors: rainfall, discharge, and the concentration of bicarbonate ions. In this scenario, the amount of rainfall is directly linked to the amount of discharge and is inversely linked to the concentration of HCO_3^- .

Table 1. CO_2 sequestration in epikarst and non-epikarst springs.

Location	Discharge (litre/year)	HCO_3^- (mg/litre)	Catchment area (km^2)	C ($\text{ton}/\text{km}^2/\text{year}$)	CO_2 ($\text{ton}/\text{km}^2/\text{year}$)
Gedaren	1,456,332,480.0	408.58	1.00	214.62	787.00
Sulu	1,733,709,124.8	392.39	1.16	211.21	774.52
Sumber Pongong	1,042,780,073.6	375.37	0.69	203.80	747.34
Seropan (non-epikarst)	17,235,370,080.0	275.97	10.9	157.33	576.92
Average				196.74	721.45

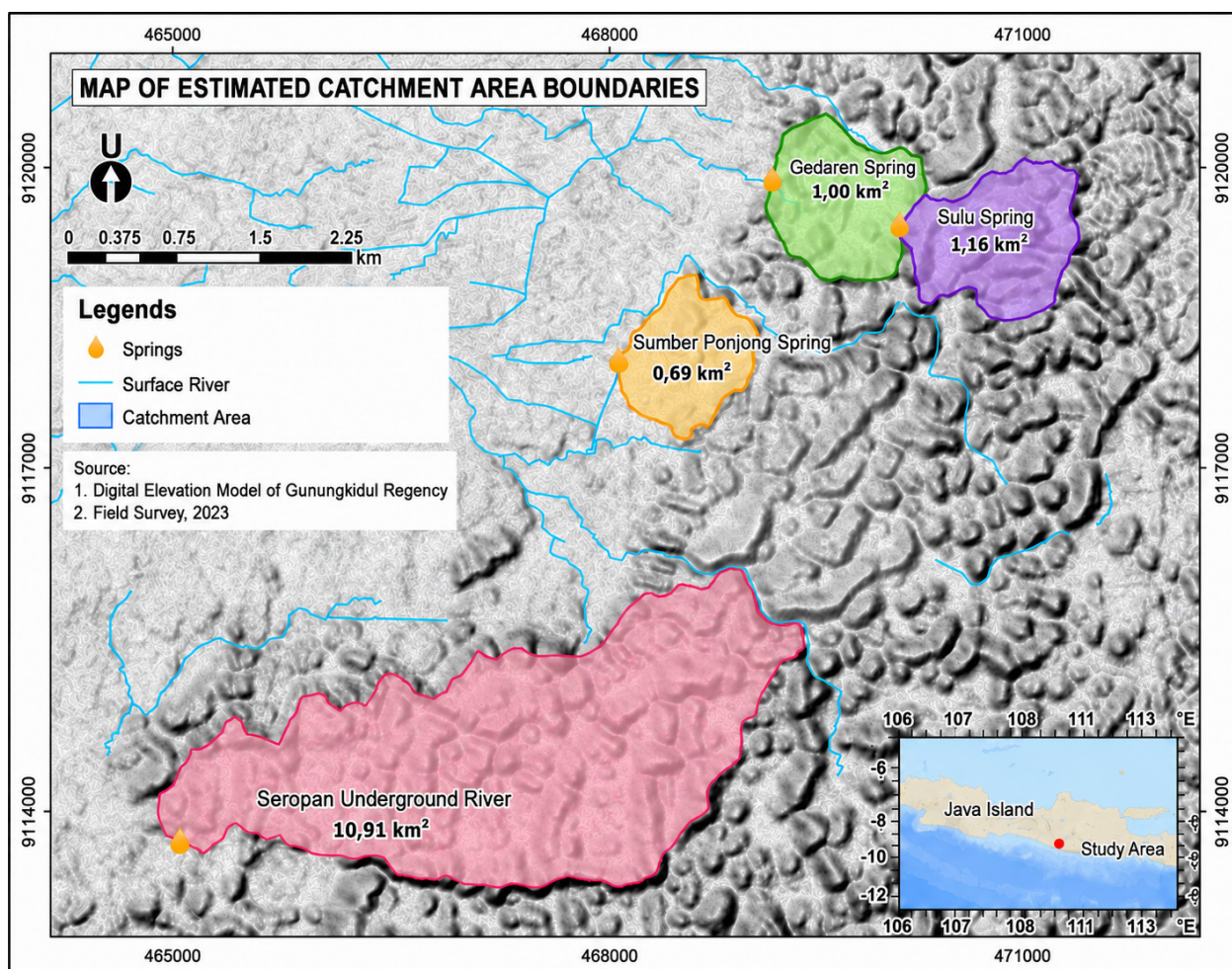


Figure 3. Estimated catchment boundaries of the studied epikarst springs and Seropan Underground River.

Nevertheless, there is no direct correlation between high rainfall and changes in discharge in epikarst springs. The phenomenon is attributed to a time delay, or time lag between precipitation and spring-discharge response that occurs in the catchment area. This delay is a result of the dominant diffuse flow characteristic of the epikarst spring type, which causes a slow response to rainfall (Adji et al., 2023). The duration of delay in the epikarst zone is affected by the changing intensity of rainfall, the thickness of the epikarst layer, the porosity, and the hydraulic conductivity (Aquilina et al., 2006; Zhang et al., 2013). It is evident that the rainy season reaches its peak in November 2022, while the flow discharge tends to be highest in January 2023. Despite the absence of rainfall in June 2023, the spring flow discharge can still be quantified as it originates from the accumulated rainwater from the preceding period.

The discharge observed at the springs in the study area is affected by the size of the spring catchment area. The larger the catchment area, the higher the capacity of water it can retain. The respective catchment areas of Gedaren, Sulu, Sumber, and Seropan Springs are 1.00 km², 1.16 km², 0.69 km², and 10.9 km², respectively. The size of the Seropan catchment area is directly correlated with the highest discharge value. Overall, the catchment area shows that Seropan has the highest at-

mospheric CO₂ absorption value, specifically 6,288.45 tons per year, while Sulu Springs follows with 899.39 tons per year. The Gedaren spring has a carbon dioxide absorption capacity of 786.68 tons per year, whereas the Sumber Ponjong spring has a capacity of 517.5 tons per year. These findings indicate that the Seropan catchment area has the highest capacity for absorbing atmospheric CO₂ among the three epikarst springs observed (Figure 5).

However, when viewed in units per km², epikarst springs have the greatest capacity to absorb CO₂ from the atmosphere. The epikarst zone, located in the upper soil layer, is directly influenced by vegetation and receives a large CO₂ input from respiration. This condition enhances CO₂ input to the epikarst zone. Meanwhile, the diffuse flow type in epikarst springs causes the water in this zone to move slowly, resulting in prolonged contact with carbonate rocks. This results in more saturated water and higher CO₂ absorption (Zeng et al., 2015). Furthermore, the epikarst zone is typically distinguished by a substantial layer of soil and abundant vegetation, which promotes elevated concentrations and pressures of CO₂ in the soil, consequently enhancing CO₂ absorption. The carbon cycle in the soil layer is recognized as a significant contributor to the process of karstification, despite its complexity re-

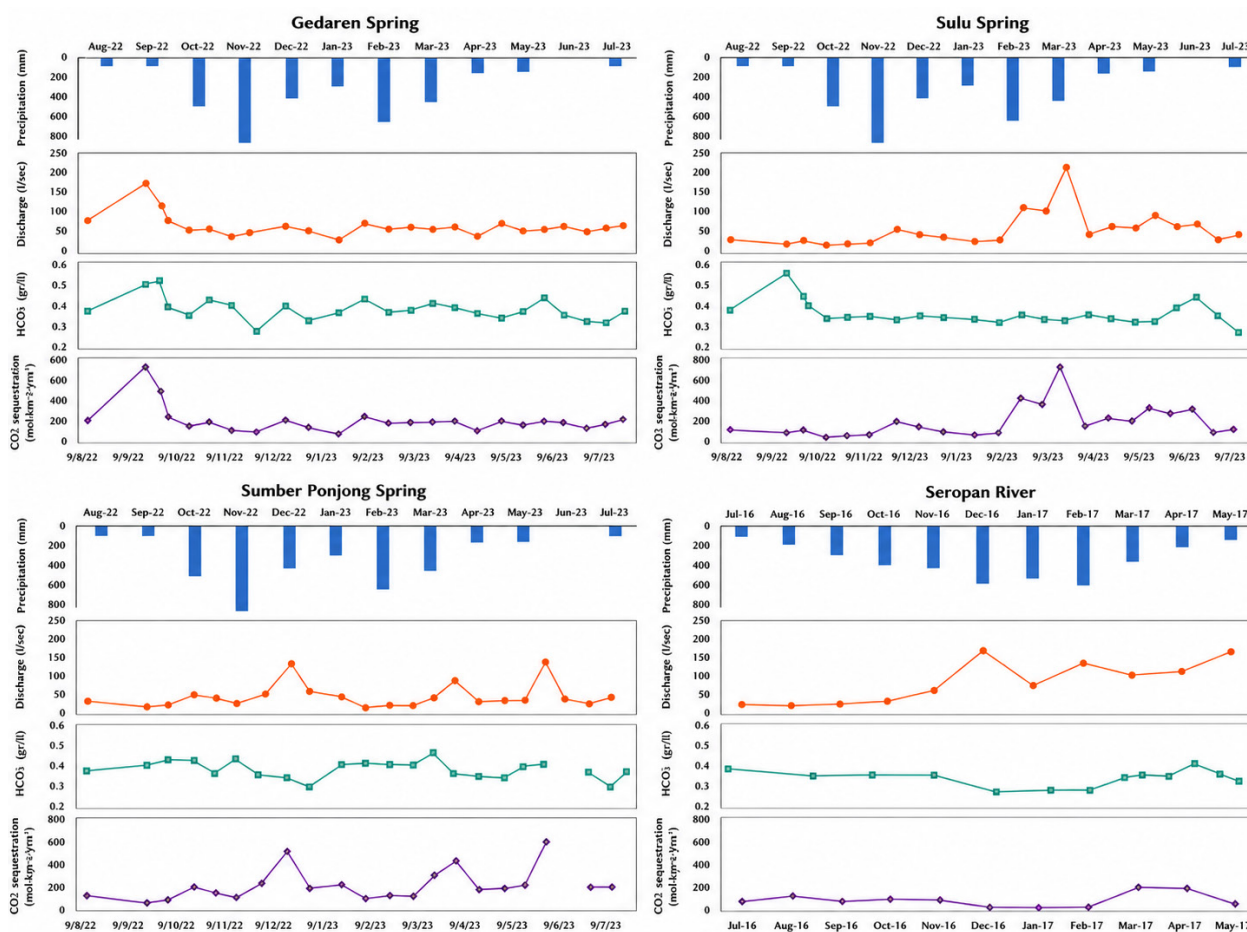


Figure 4. Temporal variations in precipitation, discharge, HCO_3^- concentration, and CO_2 sequestration at Gedaren, Sulu, Sumber Ponjong, and Seropan.

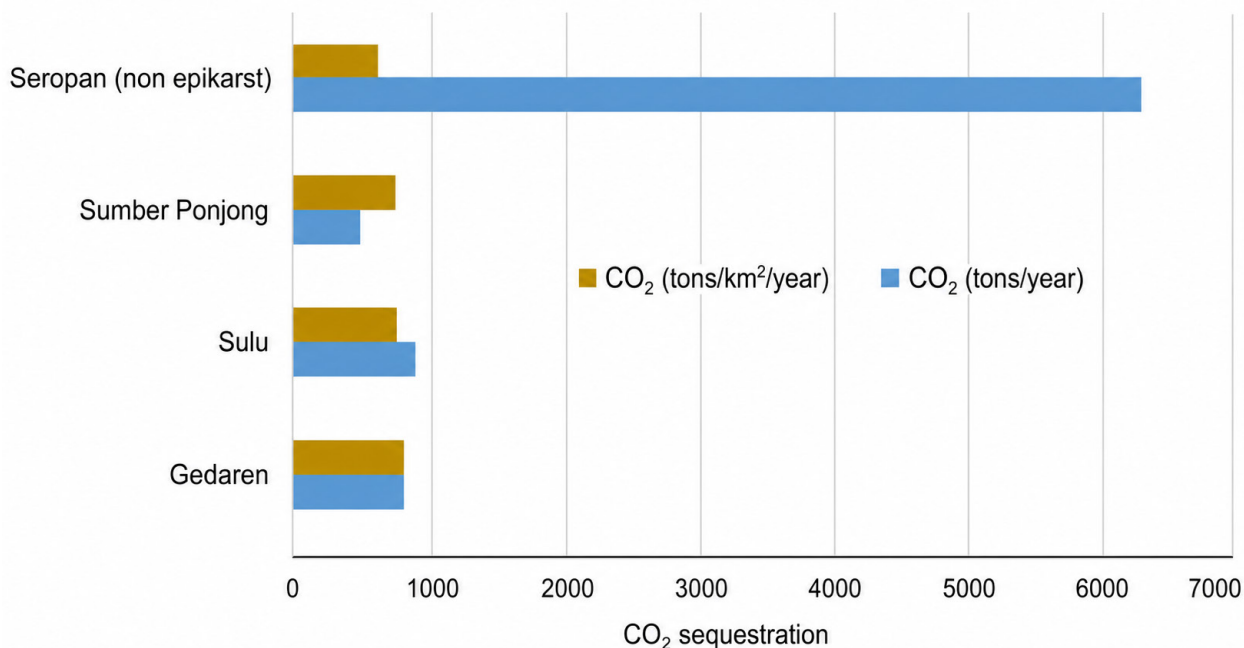


Figure 5. Comparison of total and area-normalized CO_2 absorption among epikarst springs and the non-epikarst Seropan Underground River.

sulting from soil limitations and moisture conditions (Jiang et al., 2013).

Figure 6 illustrates the conceptual position and function of epikarst in the Gunungsewu Karst system. The epikarst zone occurs near the surface, beneath the soil or regolith layer, and is characterized by intensive weathering, fractures, enhanced porosity, and higher permeability. Rainfall infiltrates diffusely into this zone, where part of the water may be temporarily stored, redistributed laterally, and then released slowly through epikarst springs such as Gedaren, Sulu, and Sumber Ponjong. In contrast, deeper conduit flow is represented by the underground river outlet, such as Seropan.

In the humid tropical setting of Gunungsewu, in-

tensive karstification, strong weathering, and active soil formation may promote a more developed and locally thicker epikarst. These conditions increase water storage, prolong water–rock interaction, and enhance carbonate dissolution, helping explain the higher area-normalized CO₂ sequestration observed in the epikarst springs.

Compared to other tropical karst areas in Indonesia, epikarst springs have a higher capacity for absorbing CO₂. In the Jonggrangan karst area of Central Java, Dwiputra (2019) conducted an estimation of the amount of CO₂ sequestration in three springs: Mudal, Anjani, and Kiskendo springs. Table 2 presents a comparison of CO₂ absorption in two tropical karst areas in Indonesia.

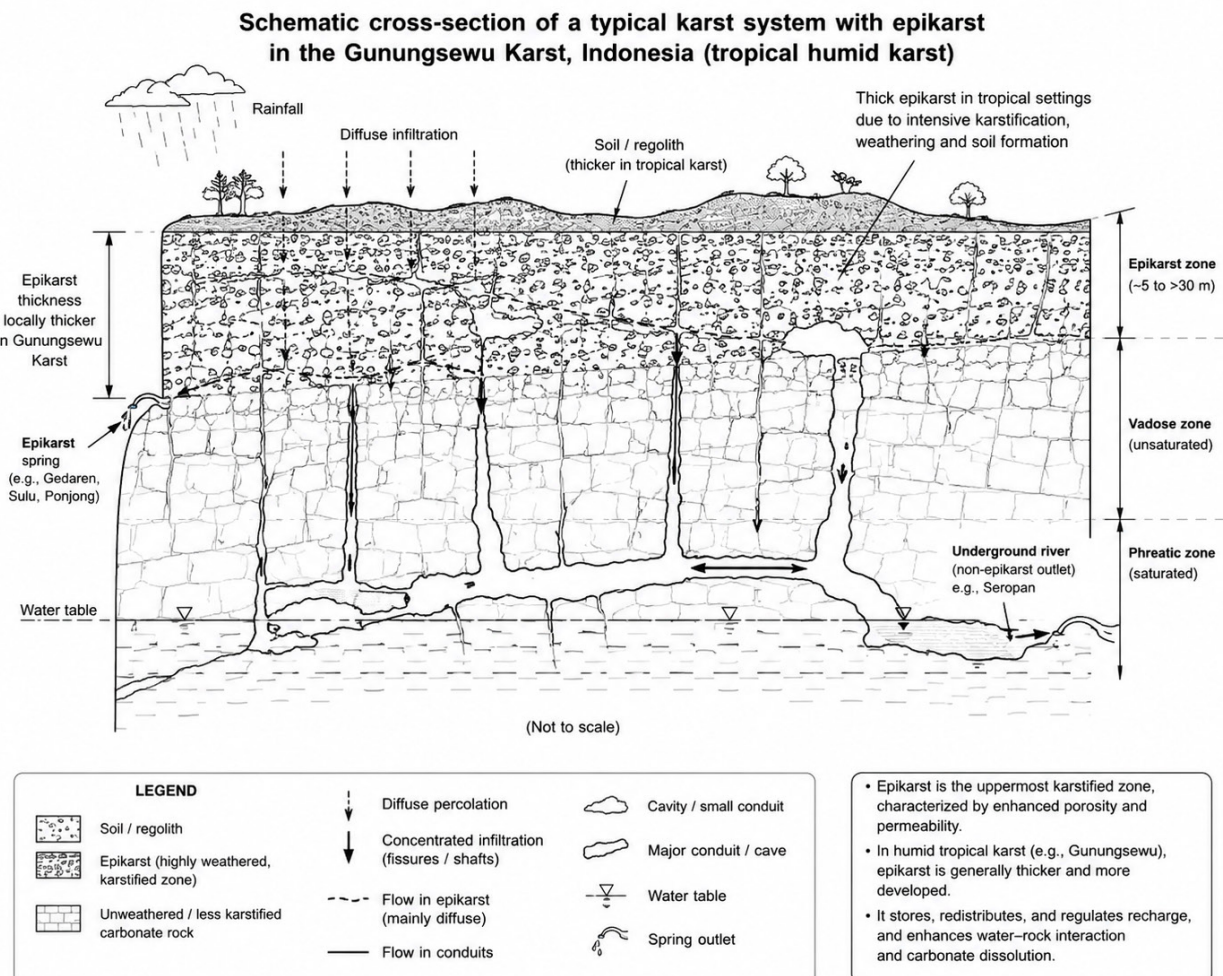


Figure 6. Conceptual cross-section of a typical tropical karst system in the Gunungsewu Karst, showing the position of the epikarst zone, diffuse infiltration, temporary storage, focused recharge, vadose and phreatic zones, epikarst springs, and the underground river outlet.

Table 2. CO₂ sequestration in Gunungsewu and Jonggrangan karst

Karst Area	Springs	Discharge (litre/ year)	HCO ₃ ⁻ (mg/litre)	Catchment area (km ²)	CO ₂ (ton/ km ² /year)
Gunungsewu (DIY province)	Gedaren (epikarst)	1,456,332,480.00	408.58	1.00	787.00
	Sulu (epikarst)	1,733,709,124.80	392.39	1.16	774.52
	Sumber Ponjong (epikarst)	1,042,780,073.60	375.37	0.69	747.34
	Seropan (non-epikarst)	17,235,370,080.00	275.97	10.9	576.92
Jonggran- gan-(Central Java province)	Mudal (non-epikarst)	10,379,559,298.60	290.00	7.05	564.48
	Anjani (non-epikarst)	4,818,823,835.75	210.00	4.00	334.47
	Kiskendo (non-epikarst)	8,627,129,496.38	260.00	6.90	429.79

The springs in the Jonggrangan karst are classified as non-epikarst springs. Generally, their absorption of CO₂ is lower than the epikarst springs found in the Gunungsewu karst. Furthermore, their absorption is even lower than that of the non-epikarst springs in Seropan. This comparison reveals that the catchment of epikarst springs plays a crucial role in the process of absorbing CO₂. This is due to the slow and diffuse flow in the aquifer, as well as the respiration mechanism of vegetation, which absorbs carbon dioxide from the air through the dissolution process. In addition, within the epikarst zone, carbon dioxide (CO₂) produced from the decomposition of organic material is retained, making it the main contributor to the dissolution of carbonate rocks.

The results of this study can also be placed in the broader context of karst carbon sink studies from other regions of the world. In subtropical karst regions of China, karst carbon sequestration has been shown to be strongly influenced by carbonate weathering, soil-vegetation processes, hydrological conditions, and human intervention in karst landscapes (Zhang et al., 2022). In contrast, high-alpine karst systems in Europe

show different hydrological behavior because recharge, storage, and solute transport are strongly affected by snowmelt, seasonal flow dynamics, and clearly defined catchment conditions (Frank et al., 2021). Studies from stratigraphically complex karst areas in South Korea also show that hydrochemical and isotopic approaches are useful for identifying differences in spring-water flow types and groundwater pathways (Yu et al., 2021). These comparisons indicate that the hydrochem-discharge method is broadly applicable, but its results must be interpreted according to local climatic and hydrogeological conditions.

Compared with these karst environments, the relatively high CO₂ absorption per unit area in the Gunungsewu epikarst springs highlights the important role of tropical epikarst systems. Warm and humid conditions, active soil respiration, vegetation cover, diffuse flow, and longer water-rock interaction may support higher bicarbonate production and carbonate dissolution. Therefore, the Gunungsewu results provide useful evidence from tropical karst and strengthen the view that epikarst springs can play an important role in natural atmospheric CO₂ sequestration.

Conclusions

This study confirms that epikarst is a crucial zone in the carbon sequestration mechanism in tropical karst areas. Epikarst springs in Gunungsewu have been shown to have a higher CO₂ absorption capacity per unit area than non-epikarst systems, ranging from 747.34 to 787.00 tons/km²/year, while Seropan only has 576.92 tons/km²/year. This high absorption indicates that the slow, diffuse flow character of epikarst creates more ideal conditions for carbonate dissolution and the absorption of atmospheric CO₂. This finding is further strengthened by the fact that the absorption value in Gunungsewu is also higher than that of several springs in Jonggrangan Karst, such as Mudal, Kiskendo, and Anjani. Therefore, epikarst not only functions as an important component of the karst hydrological system but also as a key element in karst's ecological

role as a natural carbon sink. Although Seropan's total CO₂ uptake is greater due to its larger catchment area, these results indicate that carbon uptake efficiency is more determined by the karst system's hydrogeological characteristics than by catchment area alone. Thus, epikarst should be a key focus in tropical karst carbon studies and climate change mitigation.

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