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Dynamics of Underground River Development by Allogenic Recharge in the Tropical Gunungsewu Karst Area, Indonesia

Ahmad Cahyadi*, Eko Haryono, Tjahyo Nugroho Adji, Margaretha Widyastuti

[1]*Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Indonesia*

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Abstract

Dissolving cavities in a water-holding rock (karst aquifer) are tied to how water is stored and released. However, cavity development by allogenic water is rarely studied. This research was intended to analyze the dynamic development of dissolution cavities in tropical karst areas influenced by allogenic recharge, using Beton Spring as an example. These dynamics were determined from water corrosiveness or aggressiveness based on the calcium carbonate saturation index, dissolution rate, and cavity development rate according to wall retreats. We found that water becomes more corrosive at the start of the rainy season due to the piston effect. The dissolution rate in the Karst Drainage Basin of Beton (Beton KDB) was estimated at 33.60 m^3/km^2/year or faster than in KDBs without allogenic recharges. Further, the mean rate of solutional wall retreat was calculated at 0.02 cm/year, or greater than the global average of approximately 0.01 cm/year.

Keywords: dissolution rate, saturation index, wall retreat, allogenic recharge, tropical karst

1. Introduction

Karst areas, which have special water features because of rock dissolution [1], are crucial for providing clean water for humans. They can supply up to 25% of total freshwater needs worldwide [2] [3] [4]. Andreo [5] and Drew [6] confirmed that many large in European cities, such as Paris, London, Vienna, Montpellier, Rome, and Bristol, rely on karst aquifers to supply freshwater for their residents. Further, Drew [6] and Leibundgut et al. [7] stated that in 1990, around 100 million people in China extracted water from these sources.

The development of underground drainage and dissolution cavities significantly affects a karst area's hydrological system and storage capacity [8]. As Hartmann et al. [9] explained, a karst landscape has three types of flow: (1) micropores or diffuses formed during rock formation, (2) fissures or cracks developed due to tectonic processes, and (3) conduits shaped by karstification. Tunnelling by karstification induces the development of secondary porosity, which changes rock permeability [10] and how water is recharged, stored and flows [9].
Drew [11] explained that dissolution cavities are formed depending on three major factors: (1) chemical driving forces, consisting of rain, temperature, and the partial pressure of carbon dioxide (P_{CO2}), (2) physical driving forces, represented by relief or height difference, and (3) hydrogeological settings, including tectonic conditions, thickness of soluble rocks, lithology, and stratigraphic characteristics. Chemical reactions are the primary process responsible for karst formation which is closely related to the availability of carbon dioxide (CO_2) in the water

* Email: ahmad.cahyadi@ugm.ac.id

[12] [13]. Similarly, White [14] stated that at least five regional factors control the dissolution of carbonate rocks: (1) CO_2 availability in water flows supplied by groundwater recharge, (2) flow system characteristics, consisting of open and closed systems, (3) mineral saturation at resurgence points or springs, (4) the proportion of allogenic and autogenic recharge (i.e., diffuse infiltration and internal runoff) in the aquifer, and (5) geological conditions of rocks, purity, dolomite-to-calcite ratio, and the presence of other rocks.

In a karst aquifer system, recharge (water sources) types greatly influence the development of underground rivers [15]. Allogenic supplies flow from outside the karst landscape through ponors and are generally more corrosive or aggressive compared to autogenic recharges from within karst regions. Moreover, allogenic water with large discharges is often responsible for forming the main tunnel system of underground rivers. Fast and large flood discharges exert forces that change the development of dissolution cavities more significantly and faster than regular groundwater level fluctuations in saturated zones [13]. Cahyadi et al. [16] stated that allogenic recharge in the Karst Drainage Basin of Beton (Beton KDB) contributed to shaping the single conduit of the main underground river system. However, very few studies have been concentrated on allogenic recharges [16] [17] [18] [19].

Dissolution rates vary geographically according to predominant climates. Compared to regions at higher latitudes, the tropics are characterized by high rainfall increasing water aggressiveness in dissolving rocks. The contrasting seasonal characters bring about different physical and hydrogeochemical variations in karst groundwater. In addition, several previous studies discovered that seasonal variations in tropical karst areas, such as in Indonesia, can lead to different flow characteristics [20] [21] [22] [23] [24]. Therefore, investigations into hydrogeochemical variations and their effects on the development of dissolution cavities in these areas become necessary.

This research looked at the dynamic cavity development in tropical karst regions influenced by allogenic recharges, using Beton KDB as a case study. These dynamics are viewed and discussed from three aspects: flow aggressiveness, dissolution rate, and wall retreat. These parameters are important because they provide insights into the processes contributing to karst aquifers' conduit development. These three methods were chosen due to the ease of data collection. The results obtained can be quite, detailed compared to direct measurement and interpretation of multitemporal geophysical data. Flow aggressiveness refers to the ability of the water to dissolve and erode the rock, dissolution rate measures the rate at which the water dissolves the rock, and wall retreat refers to the widening of the conduit as the rock is dissolved. ical karsts, especially in KDBs, are influenced by allogenic recharge. The findings should give us a better understanding of how underground rivers in tropical karsts, especially those in KDBs affected by allogenic rivers (recharge), develop over time.

Figure 1: Beton Spring as the inlet of Beton Reservoir (left, yellow arrow) and Beton Spring (right)

2. Study Area

This research focused on Beton KDB, with measurements conducted at Beton Spring (Gunungkidul Regency, Yogyakarta). It is one of the springs that generates a reasonably large discharge in the Gunungsewu Karst Area (Indonesia) (Figure 2). Beton KDB plays an essential role in supplying water for agriculture and fisheries in the region. Beton spring is the inlet of Beton Reservoir which irrigates paddy fields located in Ponjong and Karangmojo District, Gunungkidul Regency.

The regional geology is composed of predominant tertiary volcanic rocks (andesitic tuffs, sandstones, agglomerates, claystone, siltstone, shale, and andesitic to basaltic breccias) and tertiary limestones that form the karst landscape. Limestones lie on top of strongly denudated volcanic rocks in the south, and the lithological contact creates an allogenic river originating from an ancient volcanic zone that feeds groundwater into the Gunungsewu Karst Area. This allogenic river enters Beton KDB and then resurfaces at Beton Spring.

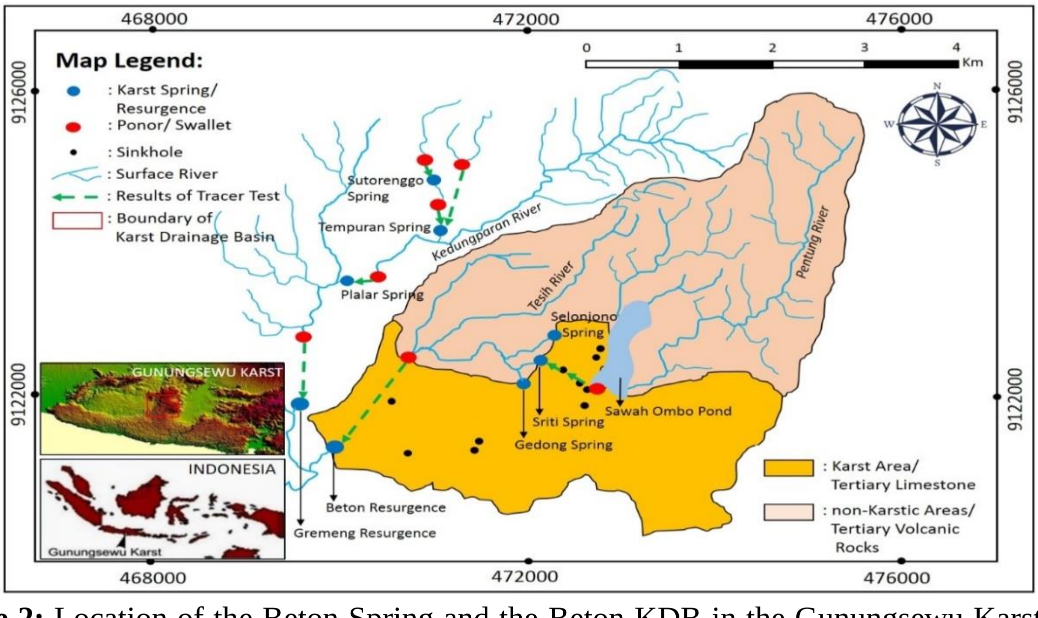

Figure 2: Location of the Beton Spring and the Beton KDB in the Gunungsewu Karst Area, Indonesia

3. Data and Methods

The research equipment included alkalinity and calcium test kits (Figure 3) to measure bicarbonate and calcium in allogenic river flows and springs or resurgence points directly in the field, the 1:25,000 Indonesian Topographic Maps (RBI), geological maps created based on field survey results and data processing with GIS programs to calculate the karst area, and a water level data logger to record real-time discharge.

Figure 3: Alkalinity (Left) and Calcium (Right) Test Kit

Water level data were converted into flow discharges using the rating curves generated automatically every 15 minutes. The rating curve is generated by analyzing the relationship between water level and flow discharge. Both data were generated from 24 field measurements over one year every two weeks and 11 measurements during floods (two flood events) in the wet season. Hydrogeochemical data were obtained by analyzing water samples collected biweekly from February 2019 to May 2020. Interval water sampling in karst areas where conduit flow has developed according to Currens [25] and Field [26] would be best and most efficient if done every two weeks. Field measurements were taken for Temperature, Alkalinity, Calcium, pH, Total Dissolved Solid (TDS) and Electrical Conductivity (EC). Other significant elements, such as Magnesium, Sodium, Potassium, Chloride and Sulfate were analyzed in the laboratory. Sampling is done with a polyethene bottle of one litre of water. All the data were then used to analyze water aggressiveness (using the saturation index), dissolution rate, and the rate at which the underground river tunnels developed (wall retreats).

In karst aquifers, the saturation index (SI) measures the extent to which groundwater chemically reacts with certain minerals in carbonate rocks and can, , explain the degree of water corrosiveness or aggressiveness. SI shows three phases of mineral saturation in groundwater: unsaturated, in-equilibrium (balanced), and supersaturated. Groundwater unsaturated with calcium carbonate ($CaCO_3$) potentially dissolves carbonate rocks upon contact, whereas supersaturated groundwater tends to precipitate $CaCO_3$. SI values were calculated from the physical and chemical parameter data inputted into AquaChem software and then classified according to the provisions in Table 1. The SI equation used was as follows equation 1 [27].

$$\mathrm{I\ CaCO_3} = Log_{10} \frac{[CO_3^-][Ca^{2+}]}{\mathrm{Ksp}\ CaCO_3} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where SI $CaCO_3$ is the $CaCO_3$ saturation index, [CO_3] is the carbonate ion concentration, [Ca] is calcium ion concentration, and Ksp $CaCO_3$ is the solubility product for $CaCO_3$ (given as $10^{-8.48}$).

Table 1: Classification of water aggressiveness according to the $CaCO_3$ saturation index values

SI $CaCO_3$	Water Aggressiveness	Hydrogeochemical Process
Negative (<0)	Unsaturated	$CaCO_3$ dissolution
0	In equilibrium	Groundwater neither precipitates nor dissolves $CaCO_3$
Positive (>0)	Supersaturated	$CaCO_3$ precipitation (crystallized or solidified)

Source: Appelo and Postma [28]

Equations 2 and 3 were used to calculate the degree of karst dissolution in KDBs affected predominantly by allogenic and autogenic systems, respectively [13] [29]. While the inputted parameters are the same, the equation constants and the measurement units of the calculation product are different. Both equations are expressed in Equations 2 and 3

$$D_{m\,(allogenic)} = \frac{12.6\,(T - T_A)}{A\,.\,Q} \qquad \text{(2)}$$

$$D_{m\,(allogenic)} = \frac{3.15\,(T - T_A)}{A\,.\,Q} \qquad \text{(3)}$$

Where D_m is the degree of karst dissolution (Eq. 2 = m^3/km^2/year, Eq. 3 = tone/km^2/year), 12.6 and 3.15 are constants calculated from the density of carbonate rocks, T is $CaCO_3$ concentration of groundwater at the resurgence point (mg/l), T_A is the $CaCO_3$ concentration in water from the allogenic or autogenic system (mg/l), Q is the average annual discharge at the resurgence point (m^3/s), and A is the karst area (km^2).

Cavity development can be quantitatively determined using the mean rate of solutional wall retreat [29], which can be estimated from hydrogeochemical characteristics. This analysis can be conducted at a resurgence point (an opening where underground rivers emerge) or a spring. This research calculated the wall retreat using Equation 4 [13].

$$S = \frac{31.56\,k\,(1 - \frac{C}{Cs})^n}{\rho} \qquad \text{(4)}$$

Where S is the mean rate of solutional wall retreat (cm/year), k is the coefficient of reaction, C/Cs is the saturation ratio, n is the order of response, and ρ is rock density (g/cm^3, which is usually given as 2.7 g/cm^3 for limestones).

4. Results and Discussion

Beton Spring released discharged water at a rate of 1,221 to 5,731 l/s, with an average of 2,465 l/s. The usual rainy season starts in October [30], but it started much later at the end of November during the research [31]. Climatic conditions significantly affect the storage of water resources in aquifers [32] [33] [34]. In the dry season, the flow hydrograph was sloping and was followed by a continuous decrease in discharge before becoming a study (Figure 4).

The rainy season starts at the end of November. The start of the rainy season did not immediately increase water flow as it first filled up empty spaces in the soil and rocks, and thus not immediately causing an increase in the flow discharge. In early December 2019, when they were saturated, the subsequent rainwater became surface flows and caused widely fluctuating discharges in the spring.

Baseflow separation analysis in Figure 5 shows that baseflow (blue) was dominant during the dry season, without additional supplies from rainwater (red). These results indicate the substantial role of groundwater in feeding Beton Spring. It was estimated that baseflow accounted for 71 to 100% of freshwater supply throughout the year, suggesting an aquifer with a large storage capacity and potential as water resources.

Beton KDB did not receive water from allogenic rivers during the dry season, meaning the relatively large discharge was entirely from the karst aquifer. Also, the diffuse flow had a large storage capacity and release characteristics that contributed to water resource availability in the region. This corresponds to Naufal [35], who stated that although Beton KDB was relatively well-developed with a karstification degree of 5, diffuse flows appeared to dominate the aquifer, with some influence of conduit flow began to show. Furthermore, using master recession curves (MRC) to analyze the flow hydrograph, he revealed that Beton Spring had one laminar and one turbulent flow.

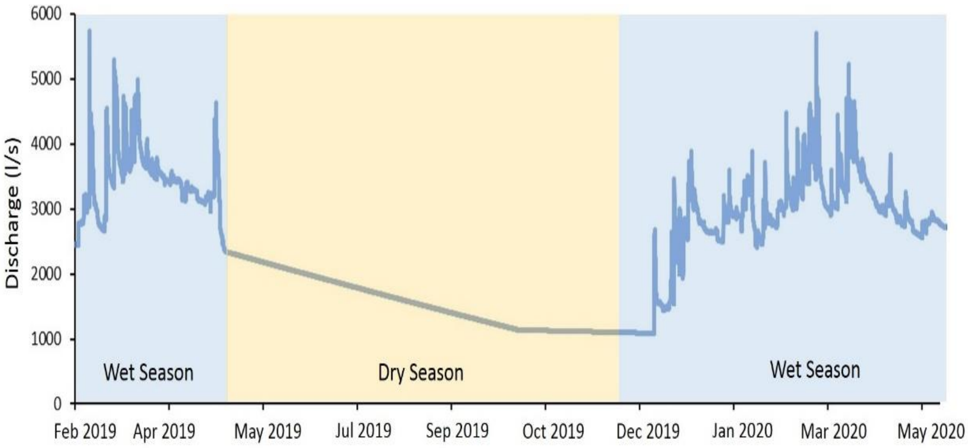

Figure 4: Flow discharge variations at the Beton Spring

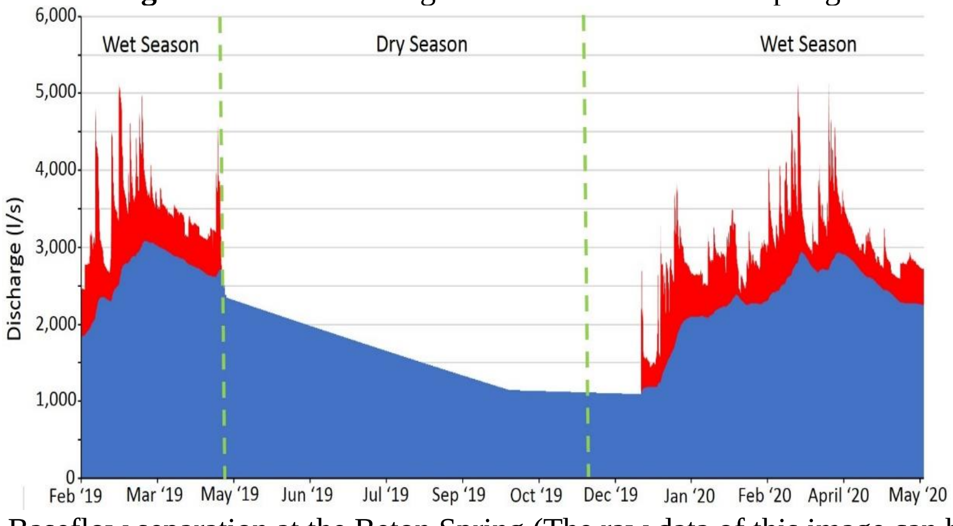

Figure 5: Baseflow separation at the Beton Spring (The raw data of this image can be accessed at the following link: https://doi.org/10.13140/RG.2.2.10733.15844)

Additionally, the groundwater at the beginning of the rainy season was undersaturated with calcium carbonate (CaCO3), likely to dissolve limestones (Figure 6). However, it became saturated by the end of the rainy season, meaning the water-rock interaction didn't lead to further dissolution. These patterns were likely influenced by the piston effect, i.e., when rainwater seeps and fills pores or voids in soil and rocks, it enters underground river systems or springs as aggressive water rich in carbon dioxide. There is no piston effect when pores in soils and rocks are filled with water, such as during the rainy season [27]. The groundwater was saturated with $CaCO_3$ during the dry season. Little to no rainwater means a low runoff contribution to the spring discharge (see Figure 5), suggesting that allogenic recharge does not significantly affect water aggressiveness during this season. This condition is, however, slightly better than Guntur Spring, where groundwater is saturated throughout the year and undersaturated only after rainfall [23]. The same flow characteristics were observed at Petoyan Spring. Guntur and Petoyan are epikarst springs in the Gunungsewu Karst Area that do not have allogenic recharges.

Beton KDB covers 35.04 km², 31.05% of which is karst landscape, and the rest is non-karst regions with tertiary volcanic rocks. The water in the allogenic river and at Beton Spring contained CaCO3, with higher amounts in the spring due to limestone dissolution in its karst aquifer. $CaCO_3$ was found at a concentration of 265.68 mg/l in the allogenic rivers and 383.22 mg/l at the Beton Spring. The dissolution of limestones in the karst aquifer was responsible for the high $CaCO_3$ content of the spring water; in contrast atmospheric carbon dioxide and volcanic rocks containing plagioclase calcium were the sources of $CaCO_3$ in the allogenic rivers.

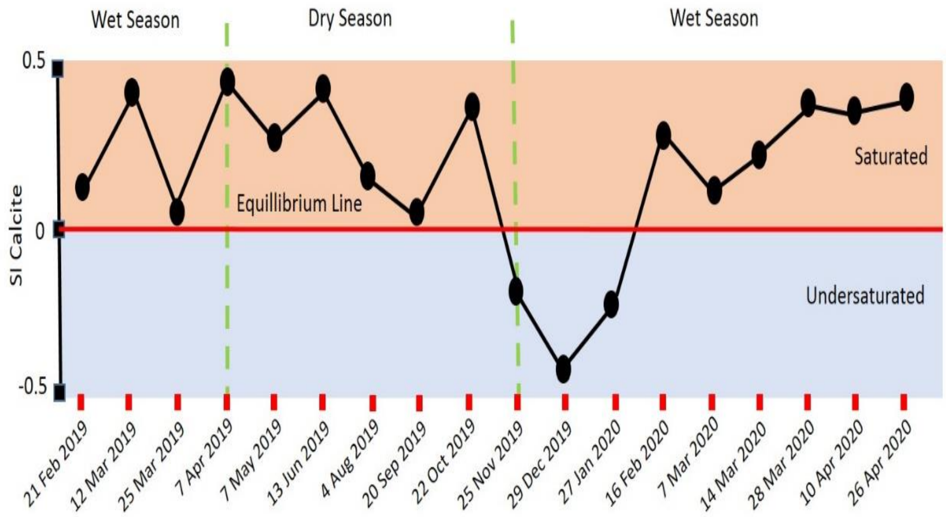

Figure 6: Calcium carbonate ($CaCO_3$) saturation index at the Beton Spring.

As Figure 7 shows, the dissolution in the study area occurred at a rate of 33.60 m^3/km^2/year, equivalent to 8.40 tonnes/km^2/year or 33.60 mm/ka. It was slightly faster than the dissolution rate at Guntur Spring, 32.93 m^3/km^2/year. These figures demonstrate that KDBs influenced by allogenic recharges have a more rapid dissolution rate than those receiving only autogenic recharges. On the contrary, 33.60 m^3/km^2/year was considered much slower than the estimate given by White [14]. It ranks below the dissolution rates of karst areas in temperate, arctic, or alpine regions. This is possible because even though dissolution occurs intensively due to high rainfall, the warm temperature in the tropics can decrease water's ability to dissolve calcium [2].

The average temperature of the research location was 25°C, and the mean P_{CO2} calculated using the data obtained from the laboratory analysis was 0.0148. The order of reaction (n) was

1.656 (based on P_{CO2}), the k value was 0.029 (based on temperature and P_{CO2}), and the C/Cs ratio was 0.8. From these values, the mean rate of solutional wall retreat in Beton KDB was 0.02359 cm/year, equivalent to 23.59 cm/ka, faster than the average wall retreat estimated by Palmer [29], which was 0.01 cm/year.

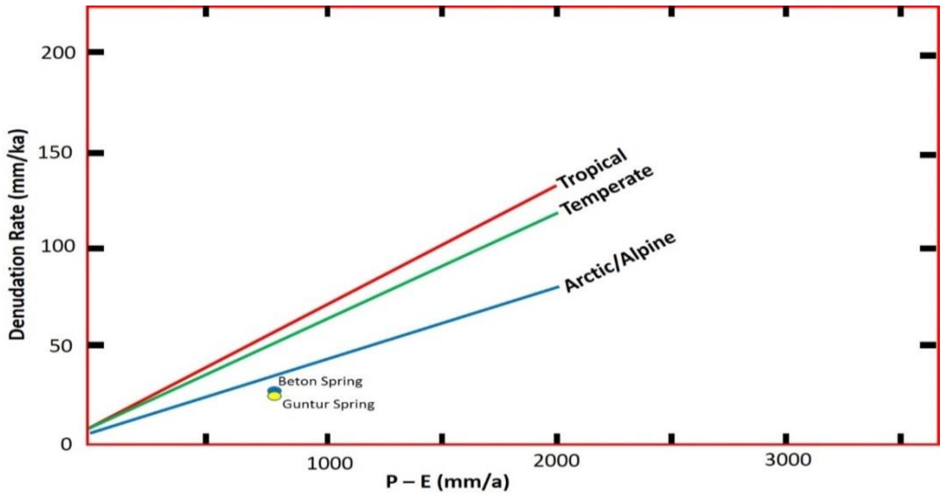

Figure 7: Dissolution rates at Beton Spring, Guntur Spring, and tropical and temperate regions (adapted from White [14])

5. Conclusions

Seasonal changes affect the water characteristics of tropical karst systems Beton KDB. At the start of the rainy season, water flows can erode the surrounding rock due to a piston effect. But by the end, and during the dry season, the water becomes less eroding as it's saturated with a mineral called $CaCO_3$. The underground rivers develop at a dissolution rate of 33.60 m^3/km^2/year with a mean rate of wall retreat at 0.02 cm/year. These characteristics are closely related to the influence of allogenic recharges in Beton KDB. Further, in the Gunungsewu Karst Area, the dissolution rate of springs fed by allogenic flows is generally higher than that of epikarst springs that only receive autogenic supplies. The rate of wall retreats is also faster than the global average, around 0.01 cm/year.

The allogenic rivers play a significant role in supplying water to the karst aquifer in the Beton KDB they should be managed not only on the karst aquifer but also include allogenic watersheds in this KDB. On the other hand, although the karst area in the study site is not very large, it has considerable potential for groundwater storage, so it has a role in water supply, especially during the dry season. Karst areas in this KDB should be prioritized as protected areas to preserve water resources.

Intensive conduit formation and direct connection with surface rivers outside the karst area cause the Beton KDB to have a high groundwater vulnerability to pollution. Protecting allogenic rivers, ponors and sinkholes is essential to prevent pollutants from entering underground rivers. In addition, the high dynamics of the conduits will result in several water quality problems mainly related to high alkalinity and hardness. Therefore, regular monitoring and water treatment to achieve a specific water quality according to the designation needs to be carried out.

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5. Disclosure and Conflict of Interest

The authors declare that they have no conflicts of interest.

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