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Research Article

Assessing karst landscape degradation based on the void development of karst aquifers in Gunungsewu, Indonesia

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Abstract

Compared to other landforms, karst areas are among those emerging from the dissolution process that have a higher risk of land degradation. The likelihood of karst landforms being harmed is increased by urbanization and other human activities like extensive agriculture. Subsurface streams' water quality gets worse when surface pollutants infiltrate through developed karst features like sinkholes and karst ponors. There is a greater risk of land degradation as more karst features, in this case void size, develop. The purpose of this research is to assess how void development, or the degree of karstification, relates to the potential for karst spring pollution in the event that land degradation occurs on the surface of the Karst Drainage System (KDS). This research was conducted at the KDS of Beton and Gremeng Spring in the Gunungsewu karst area, Indonesia. In addition, this study also provides recommendations related to environmental management on the basis of the level of development of voids at both sites. The degree of karstification represents the phase at which a hydrogeological system has been developing, and this information was later considered in formulating strategies for protecting karst groundwater from contamination. The results show that Beton and Gremeng had a complex discharge regime with degrees of karstification at 8 and 5.5, respectively. Based on flood hydrograph components, it was further confirmed that both areas were in the mature phase. The higher the degree of karstification, the higher the vulnerability to pollution.

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Introduction

There are abundant water resources and unique features in karst landscapes (Peng et al., 2021). However, karst landscapes are highly susceptible to land degradation, which may result in karst aquifer contamination (Pisano et al., 2022). Karst landscape degradation has escalated due to a variety of human activities, including extensive agricultural land use. Chemical-containing fertilizers and pesticides are used; rainwater leaches these substances and flows through sinkholes and ponors into subsurface river systems (Yu et al., 2022). The karst aquifer system's development naturally controls the occurrence of sinkholes and ponors.

Karst aquifers are known to have a high degree of heterogeneity congruent with voids development (Kaufmann, 2012). A more developed sub-surface void indicates an older karst or, in other words, a higher degree of karstification. When karst shows patterns of increasing voids development, this has implications for karst aquifers' dynamics, properties, and potential degradation, including sensitivity to pollutants in karst areas (Brinkmann and Parise, 2012).

Karst topography comprises highly soluble carbonate rocks that, due to dissolution, turn into a variety of matrix systems, including diffuse (small-size void), fissure (medium), and conduit (large) (Ford and Williams, 2007). Frequently, some conditions point out a positive linear correlation between the degrees of void developments and the sensitivity of a karst aquifer to pollution. When more conduits are formed, they provide more ways for contaminants to enter the aquifer's saturated zone (Vias et al., 2010). However, this linearity is not necessarily identical for every Karst Drainage System (KDS).

Consequently, karst hydrological management and protection from pollution require specific and comprehensive approaches (Ravbar et al., 2023). Several recommendations for karst hydrological management have been implemented. Some instances are proposed by Klimchouk (2015) and Goldscheider (2019), which consider ecological, hydrogeological, geomorphological, and land-use characteristics in formulating strategies to protect karst groundwater from contamination. This approach is, however, not specific enough to assess the aquifer's sensitivity to pollution. More particularly, the characteristics of water release from karst aquifers as one of the determining factors of sensitivity are not well-represented. Malik and Votjkova (2012) designed a method to calculate the degree of karstification (i.e., karst aquifer development) by analysing and generating a master recession curve from the flow hydrograph of karst springs and underground rivers. This approach is more specific because it can identify one or more flow sub-regimes by dividing flow hydrographs into several individual recession curves. Relying on the release characteristics of karst aquifers, it is expected better to describe the actual conditions of aquifer development in nature. This information can later be used to formulate recommendations for KDS management that are comprehensive and target-specific. Gunungsewu karst is a tropical karst landscape where springs emerge and allogenic rivers flow. There are five zones of the hydrogeological sub-system: (1) Panggang, (2) Wonosari-Seropan-Bribin, (3) Ponjong, (4) Pracimantoro-Giritontro, and (5) Donorejo-Pringkuku. This research focused on the KDS of Beton and Gremeng, which are parts of the Ponjong Sub-system and have allogenic recharge, i.e., a surface river outside the karst area that replenishes an underground river system through a ponor (Cahyadi et al., 2019). It also proposes several suitable recommendations for KDS management based on the development stage of aquifers in a tropical cockpit karst influenced by allogenic recharge, which has never been conducted before.

Karst aquifers with allogenic recharge can be more inherently susceptible to pollution than the ones receiving autogenic recharge (Riyanto et al., 2020). The latter seeps into and undergoes filtration by soil or rock pores, whereas the former directly enters karst underground river systems through ponors, bringing in contaminants from the surface without filtration. Therefore, any measures and initiatives to manage and protect Karst Drainage Systems with allogenic recharge must be implemented immediately.

Furthermore, the local community uses the recharge areas in both research locations for rainfed and dry farming, along with fertilizer and pesticide use, which naturally increases the risk of pollution. In light of this urgency, the research was intended to investigate the development of voids in karst aquifers in two locations: Beton Spring and Gremeng Allogenic River (Figure 1).

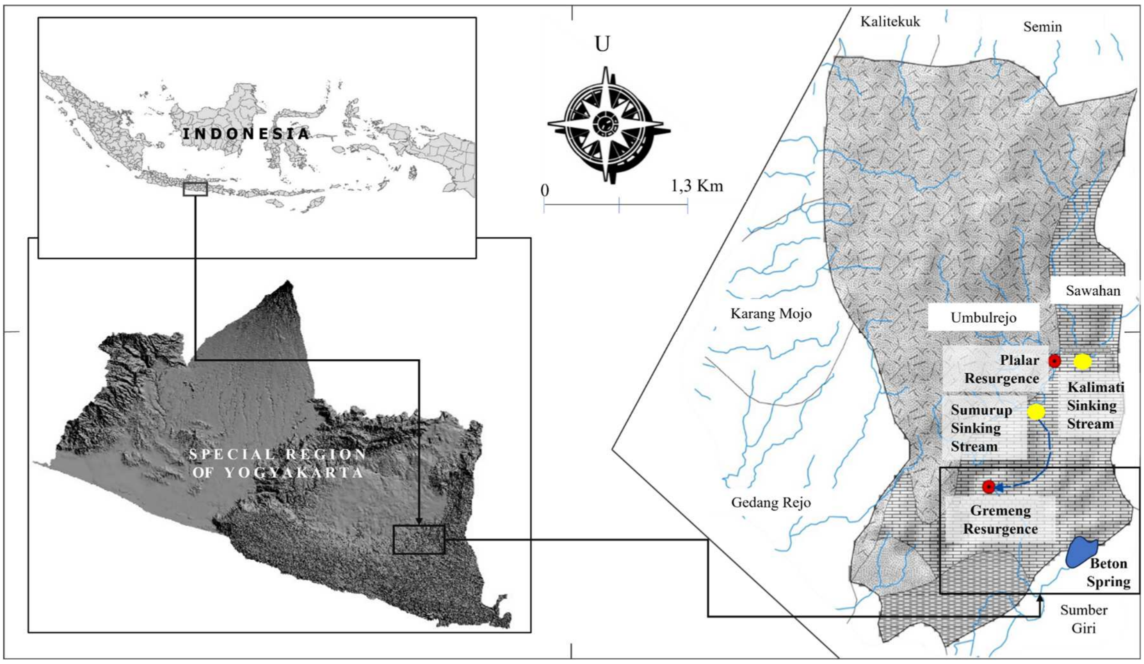


Figure 1. Positions of the two study areas, Beton Spring and Gremeng Allogenic River.

The objective was to ascertain whether the two study sites' differing pollution potentials could be indicators of karst aquifer system degradation. Thus, information for developing management and protection plans can be derived from the research's findings.

Methods

Water levels were recorded at 60-minute intervals using a HOBO U-30 automatic water level data logger. Also, flow discharge was measured directly to create rating curves together with the recorded water stage and to generate a flood hydrograph against a time measurement unit. Furthermore, regression analysis is applied to define the stage-discharge rating curve of Beton Spring and Gremeng Allogenic River, as presented in Figure 2. The resulting equation is close to number 1, meaning the relationship between water level (X-axis) and discharge (Y-axis) is increasingly directly proportional. The equation is then used to calculate the Beton Spring and Gremeng Allogenic River discharge during a year with the water-level recording time interval. According to the discharge hydrograph at Beton Spring's and Gremeng Allogenic River, flood events are selected to fit the requirements of its recession curve. Several individual recession segments of the hydrograph were selected to develop a master recession curve, from which the degree of karstification was determined, and the flow properties were analysed to support the karstification analysis results. In the software RC 4.0 program (Gregor and Malik, 2010), the MRC was constructed semi-automatically from a collection of recession curves selected. Then, the MRC produced was used to determine the characteristics of every flow sub-regime. A master recession curve (MRC) was created using two recession equations: simple exponential for laminar or diffuse flows (Equation 1) and linear turbulent for turbulent or conduit flows (Equation 2). In Equation 2, the β coefficient was calculated using Drogue's formula (1972) (Equation 3).

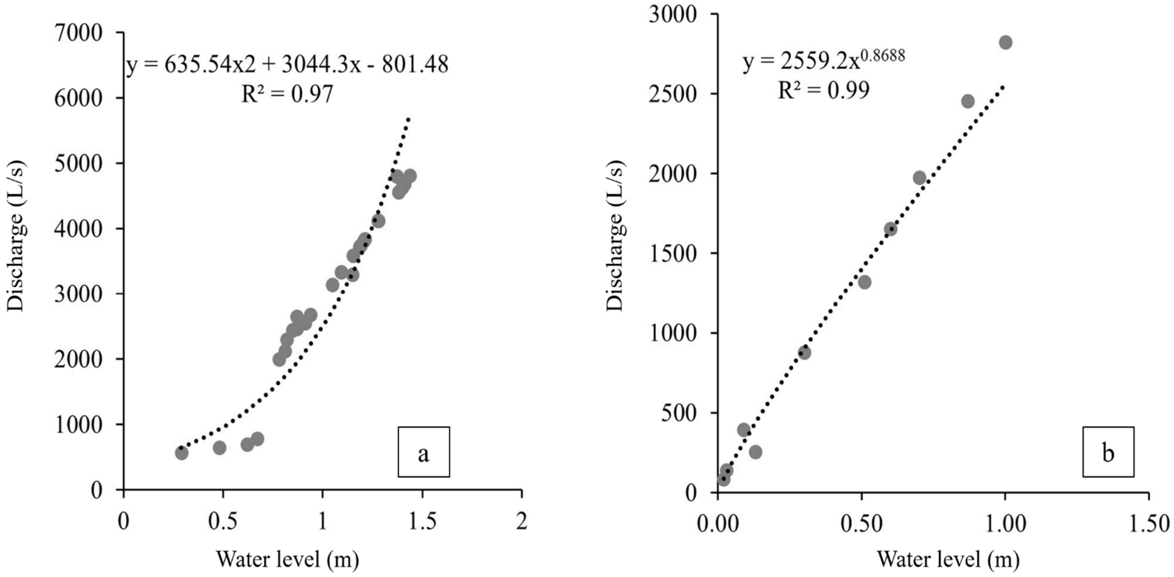


Figure 2. Stage-discharge rating curves of (a) Beton Spring and (b) Gremeng Allogenic River.

According to Malik and Vojtkova (2010), one flood event can consist of several laminar and turbulent flows (Figure 3). Therefore, any laminar or turbulent flows during recessions should be used to determine the degree of karstification (Malik, 2007), which has ten classes, from 1 for the least to 10 for the most developed karst.

$$Q_t = Q_0 e^{-\alpha t} \tag{1}$$

$$Q_t = Q_0 (1 - \beta t) \tag{2}$$

$$\beta = \alpha \left(Q_0^{-1/n}\right) \tag{3}$$

Flood hydrograph components were analysed to help characterise karst aquifer development accurately. They can reflect the condition of a drainage basin, water storage size, and water release characteristics (Adji et al., 2017). Accordingly, T_{lag} (length of time between peak rainfall and peak discharge), Q_p (flood peak discharge), and T_b (length of time between Q_p and baseflow) were calculated for each flood event at Beton and Gremeng (Figure 4).

Flood hydrograph components and MRC describe flow characteristics and aquifer development (Fatchurohman et al., 2018). This information was used to put together karst aquifer management strategies for the two research areas using a matrix that factored in flow characteristics with the Karst Drainage System as the unit of analysis. The Karst Drainage Systems of Beton and Gremeng have been determined previously by Cahyadi et al. (2019).

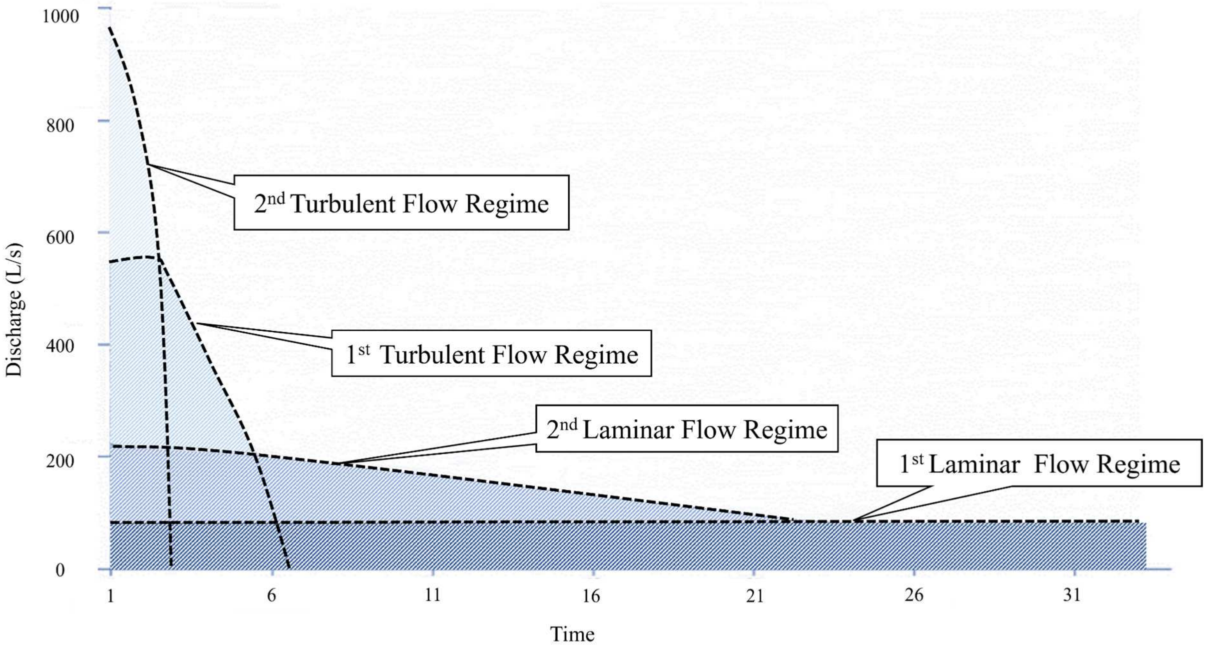


Figure 3. Illustration of a master recession curve (MRC) with two types of flows: exponential and linear.

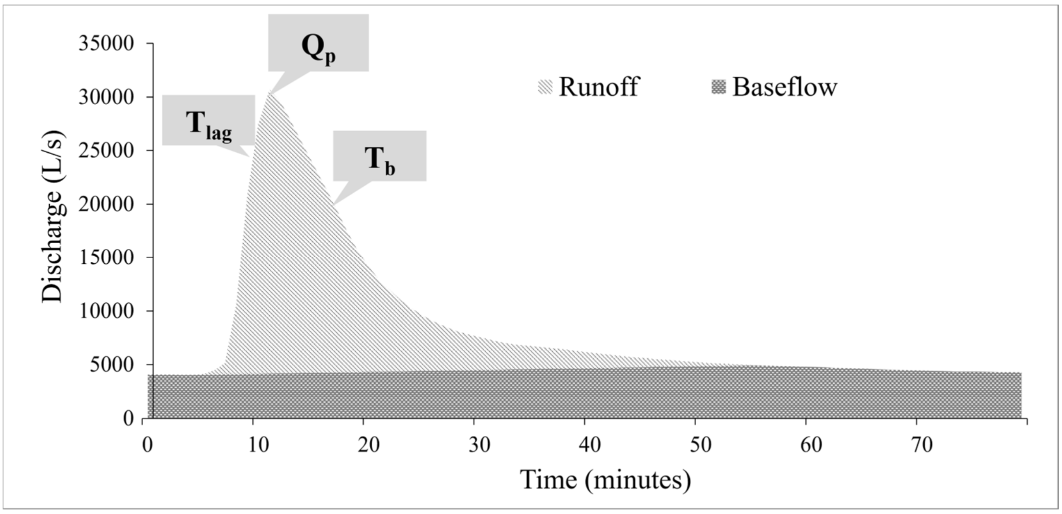


Figure 4. Illustration of a flood hydrograph.

Results and Discussion

Nine individual recession segments for the Beton Spring and sixteen recession segments for the Gremeng Allogenic River were analysed to create a master recession curve. After automatically processing and combining these curves, the generated MRC showed that the Beton Spring flow components found two turbulent flows and one laminar flow, while the Gremeng Allogenic River flow component found two laminar flows and one turbulent flow (Table 1). The MRC of Beton Spring and Gremeng Allogenic River produced the equation as shown in Table 2. Based on this equation, it can be converted according to Malik and Vojtkova (2012) classification of void development and hydrogeological characteristics. In addition, it was discovered that the Beton Spring's aquifer system development had reached 8 on the 10-scale of karstification degree, and the Gremeng Allogenic River had reached 5.5 (Figure 5). This conclusion was strengthened by the spring's rapid response (90 minutes) to the artificial tracer injected into the recharge zone (Cahyadi et al., 2020). On the contrary, Gremeng Allogenic River responded more slowly to the injected artificial tracer, more than 100 minutes (Cahyadi et al., 2021). Considering this condition, the river's Karst Drainage System had a lower karstification degree (5.5) or was at an earlier development stage than Beton Spring's.

Table 1. The recession coefficient and degree of karstification from the MRC analysis.

Springs	**α_1**	**α_2**	**β_1**	**β_2**	**Karstification degree (Dk)**
Beton	0.0008	-	0.086	0.04	8.0
Gremeng	0.0006	0.04	0.1	-	5.5

α shows the laminar flow type; β shows the turbulent flow type.

Table 2. Karstification degrees of Ponjong and Panggang Sub-systems in Gunungsewu karst area.

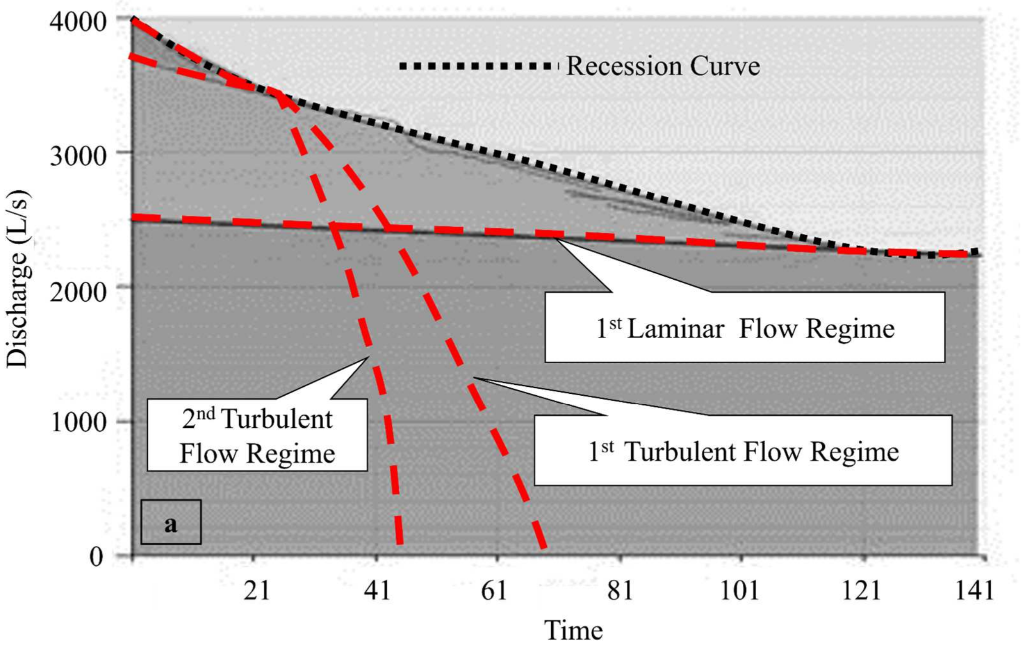
Location	**Total recession segments**	**Karstification degree (Dk)**	**Final discharge equation (Qt)**	**Void development and hydrogeological characteristics (Malik and Vojtkova, 2012)**
Ponjong Sub-system				
Beton Spring	9	8.0	$Qt = 2500e^{-0,0008t} + 1200(1-0.086t) + 255(1 – 0.04t)$	Extensive disruption and disintegration of the lithological environment with prevailing open, medium-size, karstified, and non-karstified fissures in the phreatic zone of the karst aquifer (according to α_1) and with the smaller influence of connected conduits (groundwater of large karstic channels, according to β_1)
Gremeng Allogenic River	16	5.5	$Qt = 20501e^{-0,0006t} + 500e^{-0,04t} + 1650(1-0.1t)$	Aquifers show highly developed karstification formed by large open conduits (karst channels). The presence of open, active small fissures and micro-fissures is reduced. Substantial components of groundwater are mainly circulated through preferred pathways of channel systems. There is no phreatic zone, or its role is insignificant.
Panggang Sub-system				
Petoyan Spring (Adji et al., 2019)	10	3.7	$Qt = 0.031^{0.0025t} + 0.032^{0.030t} + 0.034^{0.027t}$	Aquifers show an irregularly developed fissure network, with prevailing open macro-fissures and the possible presence of karst conduits to a limited extent. In extreme cases, even short-term turbulent flows might occur in this lithological environment.
Guntur Spring (Naufal et al., 2019)	8	5	$Qt = 0.35e^{-0.002t} + 0.07(1 – 0.02t)$	Aquifers show a probable disintegrated water-bearing zone (e.g., fault zone) or a dense network of open small fissures in combination with a simple, partly (or occasionally) phreatic conduit system of a limited extent (e.g., with an open karstified fault in the vadose zone).

Further, according to the void development and hydrogeological characteristics explained by Malik and Vojtkova (2012), the two research areas are recharged predominantly by an open allogenic river system, allowing the entry of carbon dioxide from the atmosphere, resulting in water that is often more aggressive in dissolving limestone than autogenic recharge (Palmer 2001). This condition plays a major role in controlling the void development (Palmer, 2007) of the Karst Drainage Systems of Beton and Gremeng in the Ponjong Sub-system. It is unlike the resurgence flows of the Panggang Sub-system with prevailing autogenic recharge. Petoyan and Guntur Springs have lower degrees of karstification than the two research areas (Table 1). Autogenic recharge is less aggressive than allogenic recharge in dissolving limestone because it tends to flow in a closed system and is solely sourced from rain falling in karst regions. There was a significant difference between the smallest and highest discharges of Beton Spring, 5,200 L/s, while a less substantial difference of 3,700 L/s was observed in Gremeng River (Table 3).

Based on the hydrographs, Beton experienced a more widely fluctuating discharge than Gremeng

(Figure 6). Generally, each spring shows a recession period during the dry season, and experiences flood events that vary during the rainy season. A seasonal recession begins when recharge processes decrease due to rainfall decrease, especially for the Gremeng Allogenic River. This condition differs from the Beton Spring, which fluctuates during the dry season. This condition is further evidence that the development of the Beton Spring aquifer system is more developed than the Gremeng Allogenic River.

The lag time or the length of time needed to reach peak discharge (T_{lag}) at Beton Spring was between 1 and 4 hours, with an average of approximately 2 hours. These results mean that its aquifer system responds fairly fast to a period of rainfall (Table 4); when it rains, the spring will likely reach its peak discharge in about two hours. The timebase or the length of time to reach the baseflow (T_b) was 33 hours or around 1.5 days. On the contrary, the Gremeng Allogenic River had a T_{lag} of 2-6 hours, with an average of 3 hours. While this was one hour slower than Beton Spring, the time range still indicated a fast response to rain. On average, the T_b was 21.4 h or less than a day, suggesting that Gremeng reached the baseflow or released water faster than Beton. A longer T_b means that the aquifer discharges water storages through matrices (diffuse) rather than conduits, which represents a conduit system that is still developing. The flood hydrograph component analysis further confirmed the derived karstification degree, showing Beton Spring had more voids developed than Gremeng Allogenic River.



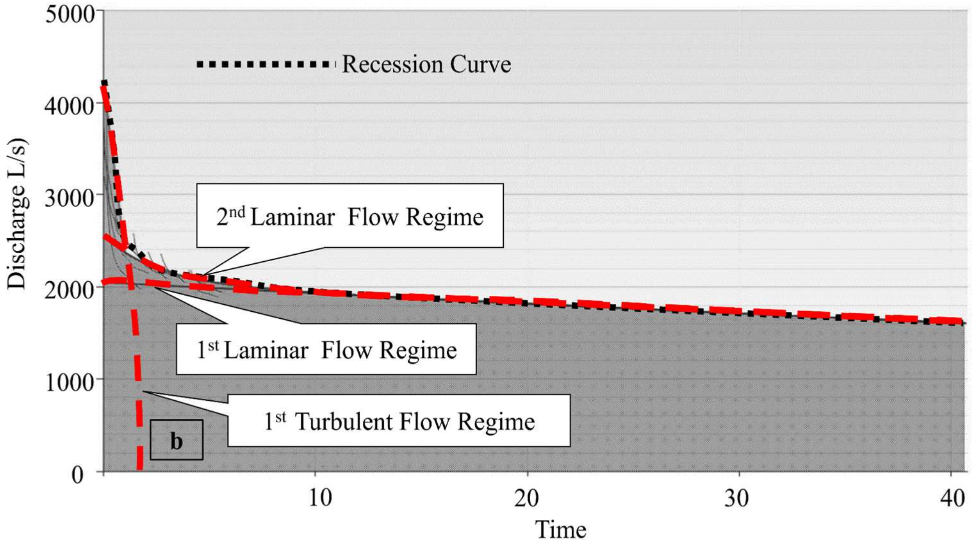


Figure 5. Modified illustration from automatic MRC of (a) Beton Spring and (b) Gremeng Allogenic River showing different combinations of flow sub-regimes.

Table 3. Minimum, maximum, and mean discharges of Beton Spring and Gremeng Allogenic River.

Location	**Karst Type**	**Hydrogeology Zone**	**Discharge-Q (L/s)**		
			Q min	**Q max**	**Q mean**
Beton Spring	Residual Cone	Ponjong Sub-system	635.4	5,896.6	1,572.5
Gremeng Allogenic River	Residual Cone	Ponjong Sub-system	405.6	4,194.6	1,146.7

Table 4. Flood hydrograph components.

Location	**Total Flood Hydrograph Analysed**	**Component**		
		Q_p (L/s)	**T_{lag} (h)**	**T_b (h)**
Beton Spring	7	3,343.5	2.2	33.6
Gremeng Allogenic River	8	3,485.5	3.0	21.4

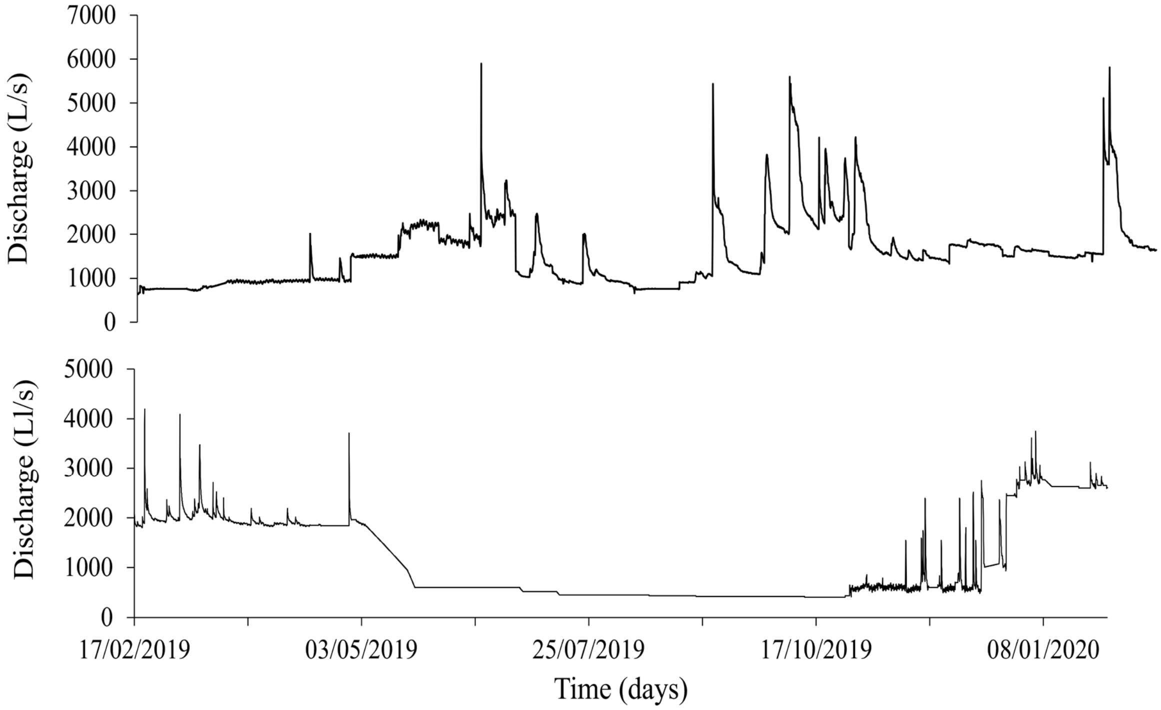


Figure 6. Flow hydrographs of Beton Spring (top) and Gremeng Allogenic River (bottom).

As seen from T_b, diffuse flows had the most significant influence on the Beton Spring's aquifer, even though its fissure and conduit systems were more developed than Gremeng. The relatively vast drainage basins are responsible for their complex flow characteristics and numerous branches of void networks (Cahyadi et al., 2020). Moreover, the recharge zones were mainly used for dry-cultivated lands and rainfed rice fields. Excessive use of fertilisers and pesticides can contaminate runoff or surface water flowing into the underground systems, increasing the possibility of pollution.

From these findings, it can be inferred that the two research areas are highly vulnerable to pollution, and target-specific preventive interventions should thus be implemented immediately (Table 5).

Conclusion

Beton Spring and Gremeng Allogenic River have complex discharge regimes with degrees of karstification at 8 and 5.5, respectively. Flow hydrograph components also confirm that both are in the mature phase of karst voids development. Together with dry-cultivated and rainfed rice fields that dominate land utilisation in the recharge zones, this condition makes them highly vulnerable to pollution. Excessive use of fertilisers and pesticides can be transported by runoff directly to the hydrogeological systems of Beton and Gremeng, contaminating underground rivers and indicating surface land degradation. It is suggested that the karst groundwater management and protection focus on preventive measures and initiatives.

Table 5. Potential degradation and recommended KDS management for Beton Spring and Gremeng Allogenic River based on voids development.

Causes Degradation	Impact (effect)	Actual Condition	Recommended Management
Direct emission of pollutants into the groundwater system through the network of karst conduits	• Deterioration of water quality • Contamination of the ecosystem	Conduit flows dominate the KDSs of Beton Spring* aquifer systems and Gremeng Allogenic River**.	Create drainage channels and protective layers on connected parts of the conduit system, especially in Beton's KDS, which covers a larger area and has a higher degree of karstification than Gremeng's. Educate the public and farmers, especially landowners in the KDSs, about karst area protection and management.
Use of pesticides and chemical products in agriculture	• Deterioration of water quality • Contamination of the ecosystem • Extinction of rare animal species		
Percolation of runoff from agricultural land	• Deterioration of water quality • Changes in morphology and hydrology of karst landscape • Contamination of the ecosystem extinction of rare animal species		
Deforestation	• Changes in morphology and hydrology of karst landscape		
		Recharge areas of both KDSs are at the top of the hills and have an open flow system (allogenic river).	Forbid land utilisation that produces waste in recharge areas and plants more vegetation to increase groundwater recharge.
		KDSs of Beton and Gremeng consist of karstic features like ponors and underground rivers.	Educate the public and farmers, especially landowners in the KDSs, about karst area protection and management. Create drainage channels around ponors and underground rivers to prevent contaminants from flowing directly to the underground systems. Plant more vegetation to prolong the time needed for runoff and pollutants it carries to seep into the soil. Solidify and enforce regulations that restrict or prohibit activities generating pollutants (liquid and solid waste) that surface flows can transport and directly enter the groundwater system through ponors.
		Diffuse flows also influence the two aquifer systems, although less significantly than conduit flows.	Plant multi-layered vegetation in the diffuse zone.
		Underground rivers in the Karst Drainage System of Beton and Gremeng flow, from the northeast to the south and southwest.	Remove any planned waste-producing activities to areas other than those in the direction of the flow. Remove any planned waste-producing activities to areas with lower elevations than springs and resurgences of allogenic rivers.

*Beton Spring, recharge area: 35.16 km^2, Karstification degree: 8.0.
**Gremeng Allogenic River, recharge area: 13.25 km^2, Karstification degree: 5.5.

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