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Assessment of aquifer karstification degree in some karst sites on Java Island, Indonesia

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Abstract This research was conducted on several springs and underground rivers in two different karst areas: the Gunung Sewu karst in the southern part of Java Island and the Rengel karst in northern Java. The objective was to determine the spatial degree of karstification in springs and underground rivers in these areas using available data on hydrograph recession. Hydrograph recession curves from eight water-level gauges in springs and underground rivers were analyzed and classified for each location based on quantitative parameters to express individual groundwater flow sub-regimes. Discharge was used to generate recessional equations, and these were related to karstification degree on a qualitative scale varying from 1 to 10. The karstification degree calculated using selected data on flood recession ranged from a low value of 3.7 in the Petoyan spring to a high value of 7.7 in the Bribin river. The value of 3.7 (low) indicates that the aquifer is dominated by a network of uniform small-sized voids (diffuse and fissure), the majority of which are open with minimal macro-fissure karst channels. Meanwhile, the value of 7.7 (high) indicates highly developed karstification of the aquifer, which is formed by large open conduits (karst channels). Furthermore, the general degree of karstification in Gunung Sewu is more developed than in the karst region of Rengel, except in the Petoyan spring, located in the western part of the Gunung Sewu karst region. Interestingly, the degree of karstification in Gunung Sewu varied. This may be due to differences in variable surface geomorphology, which is controlled by the differing solubility and thickness of the limestone beds. This study also indicates that there is a fairly strong positive relationship between the degree of karstification and the extent of the catchment area of springs.

Keywords Karst aquifers · Karstification degree · Turbulent flow · Laminar flow

Introduction

Java, the most populous island in Indonesia, has widespread karst (Balazs 1968) of the tropical variety (Sweeting 1972). As tropical, the karst surfaces on Java are well developed due to warm temperatures, high rainfall intensity, and dense vegetation, which result in large discharge of a high CO_2 groundwater (Lehmann 1936; Verstappen 1969; Balazs 1971; Nguyet 2006). Furthermore, White (1988) points out that lithology, tectonic setting, relief, temperature, carbonate rock thickness, and the partial pressure of CO_2 are important factors that should be considered in assessing the degree of karstification in an area. Due to the differing geologic and hydrologic environments, some research also reveals that morphology in tropical karst varies considerably (Jennings 1972; Sweeting 1980; Trudgill 1985; Ford and Williams 1992). Cockpit, Kegel, and Mogotes karst are spectacular types of tropical karst, formed under conditions of intense karstification, which are found in Java as well as Maros (Indonesia), China, Vietnam, Cuba, Jamaica, and Puerto Rico (Zhu et al. 2013).

In Indonesia, particularly in the northern part of Java, tectonic processes and the erosion of limestone still occurred until the end of the tertiary period (Susilohadi 1995); this resulted in karst features that are normally shallow, rounded, and gentle. Here, the karst processes did

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not have time to form spectacular karstic features on the surface, but they still created complex hydrogeological characteristics, as with other karst aquifers. One of the karst areas in the northern part of Java is the Rengel karst, which has been uplifted since the late Pleistocene. The Rengel karst is dominated by Plio-Pleistocene reef limestone of the Paciran formation (Noya et al. 1992; Haryono et al. 2001; Haryono 2008). Bemmelen (1949) identifies the limestones in Rengel as Karren Limestone. Conversely, the karst in the southern part of Java shows the spectacular morphology known as Kegel Karst (Danes 1910; Lehmann 1936), which is characterized by the development of thousands of positive formations of blunt, residual, conical hills (Flathe and Pfeiffer 1965; Verstappen 1969; Waltham et al. 1983). The most famous karst area in the southern part of Java is Gunung Sewu, which is dominated by the Miocene limestone of the Wonosari Formation, which consists of massive coral reef limestones in the south and bedded chalky limestones in the north (Surono et al. 1992). In short, the karst in the southern part of Java is older and more developed than the karst areas in northern Java, so it can be hypothesized that these karst regions have different levels of aquifer development.

In the last few decades, the emergence of karst springs has been regarded as the key to understanding the development of karstification in karst aquifers. Some research on karst springs has been conducted to discover more about karst aquifer development, such as hydrochemograph analysis (Shuster and White 1971), kernel functions analysis (Dreiss 1989), ratio of heterogeneity (Karami and Younger 2002), recession constant analysis (Ford and Williams 1992), and aquifer flashiness (Delleur 1999). More specifically, Bonacci (1993), White (2002), Kresic and Bonacci (2010), and Mohammadi and Shoja (2014) explain that spring hydrograph analysis reveals the characteristics, internal conditions, and the flow system of a karst aquifer. This opinion is strengthened by Quinlan et al. (1989, 1991), who also confirm that spring hydrograph analysis could provide representative data that reflect the natural characteristics of the aquifer.

Recession-curve analysis is a basic method for hydrologic studies. In karst areas, the use of recession-curve analysis is still progressing and expanding (Kovács et al. 2005). Rashed (2012) applies this method to determine the karstification degree by analyzing almost all of the flood hydrograph components. In addition, recession-curve analysis is also applied to determine the karstification degree of a karst aquifer based on the sub-regime recession coefficient of discharge (Malik 2007; Malik and Vojtkova 2010, 2012). From these two studies, it seems that an aquifer's karstification degree will greatly affect the characteristics of groundwater recharge, storage capacity, and

the discharge of an aquifer, as reflected in a karst spring flood hydrograph.

The objective of this study is to assess aquifer karstification degree by applying the recession-curve characteristic approach to some springs in the Rengel and Gunung Sewu karst areas. The karstification degree aquifer assessment conducted in these two regions is becoming increasingly interesting because Gunung Sewu karst in southern Java is older and more developed than the Rengel karst areas in northern Java. Another reason for carrying out this study is based on the research conducted by Haryono and Day (2004), which reveals that, based on the thickness, solubility, and porosity of the limestone, Gunung Sewu karst may be classified into three distinct landscape subsets (referred to as labyrinth-cone karst, polygonal karst, and residual-cone karst), so it is estimated that the aquifer has different degrees of karstification.

The study area

This research was conducted in two areas that have different karst rock formations, geological ages, and development of karst topography, namely (1) the Gunung Sewu karst region in the southern part of Java and (2) the Rengel karst region in the northern part of Java (Fig. 1).

Physiographically, the southern part of Java is characterized by block faulting and uplift forming plateaus separated by plains. In contrast, the northern part of Java, including part of the Rembang Anticline, is formed by strike-slip faulting basement (Pannekoek 1949; Bemmelen 1970). The Gunung Sewu karst, composed of Miocene reef limestones, was uplifted onto the mainland around the end of the Pliocene to early Pleistocene (Rahardjo et al. 1977; Surono et al. 1992), while the Rengel karst, composed of reef limestones, was in place by around the end of the Pliocene to the Holocene (Premonowati 2005) and has been exposed since the late Pleistocene.

In general, the geological structure in Gunung Sewu is a homocline sloping to the south with a slope angle of between 5° and 15°. Kusumayudha (2005) describes that the structural fabric in Gunung Sewu, consisting of thick cracks, faults, and fractures, which show a general structural direction from northwest to southeast and from northeast to southwest. Meanwhile, the limestone in Rengel is included in the Paciran Formation, which comprises wackstone and boundstone microfacies. Rengel Karst and surroundings is an anticline that has been eroded in an east–west direction and has a slope of approximately 15° (Haryono et al. 2001; Haryono 2008). Haryono (2008) also explains that the limestone in the Rengel karst contains more magnesium than the limestone in Gunung Sewu karst.
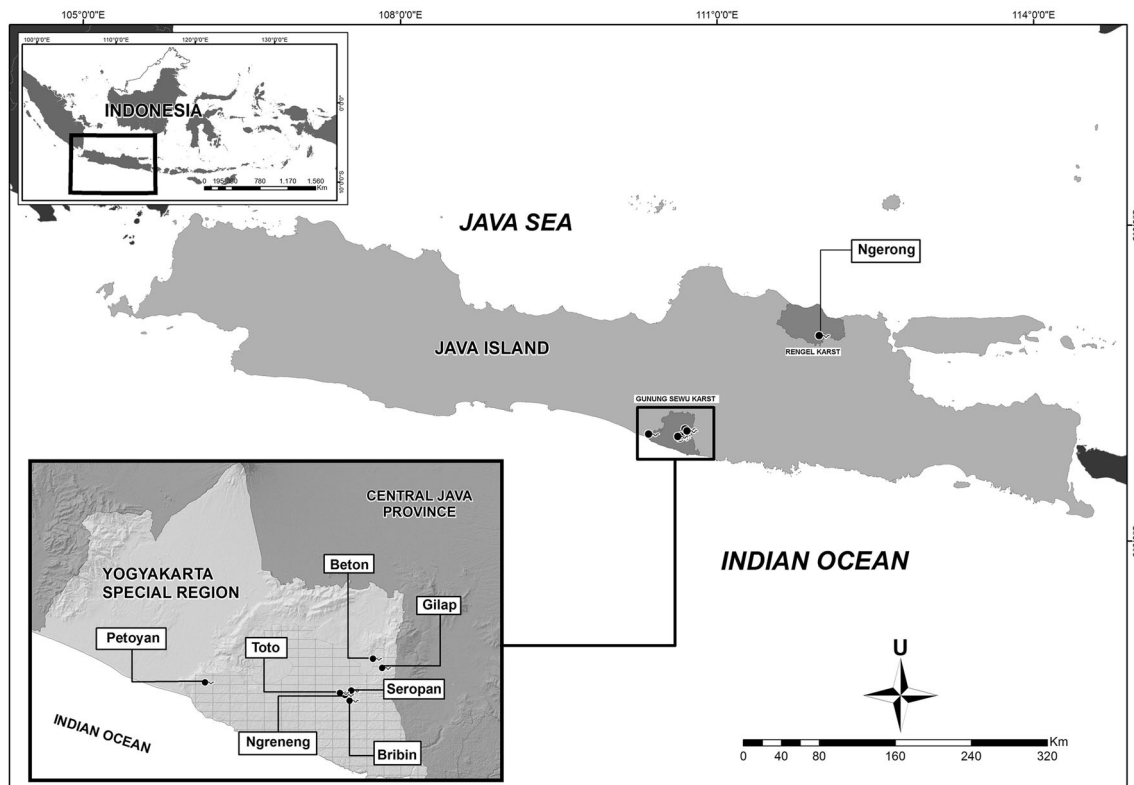
Fig. 1 The study areas of Gunung Sewu karst and Rengel karst in Java

In more detail, Haryono and Day (2004) divide the development of karst in Gunung Sewu into three types based on thickness, solubility, and the porosity of the limestone. This detailed study distinguishes three Gunung Sewu karst subtypes: labyrinth-cone, polygonal, and residual-cone karst. The labyrinth-cone subtype occurs in the central Gunung Sewu karst where hard, thick limestones have undergone intensive deformation. Polygonal karst has developed in the western perimeter on insoluble, but thinner, limestone beds, whereas the residual-cone subtype occurs in the soluble and more porous limestones (wackstones or chalks), despite considerable bed thickness.

In the Gunung Sewu karst, the monthly rainfall intensity mostly increases from December to February, with the highest monthly intensity (272 mm) falling in December, and decreasing from March to September (Adji et al. 2015). Furthermore, the average annual rainfall in this area, recorded in 12 rain gauge stations in the period 1947–2001, ranges from 1439 to 2699 mm/year, and the monthly average temperature ranges from 22 to 28 °C. In the Rengel karst, the average annual rainfall is 1480 mm/year and approximately 70% of the annual rainfall is concentrated in the rainy season from December to April. Based on the data from three rain gauges that were installed in 2013–2014, the rainfall intensity of this area reached

160 mm/hour during the peak rainfall, and the temperatures ranging from 26 to 27 °C.

Many springs and underground rivers, which are generally perennial, commonly occur in the Gunung Sewu karst. Some of them already have recording devices for water-level fluctuations, such as:

1. Petoyan spring, an epikarst cave located in the western part of the Gunung Sewu karst, which has an average discharge of 7.6 l/s, a minimum discharge of 5.5 l/s and a maximum discharge of 48.4 l/s (Adji and Bahtiar 2016). The populations around this spring experience water shortages during the dry season, and many of the residents in this region rely heavily on the sustainability of this karst spring.

2. Beton spring, located on the north side of the Gunung Sewu karst, is a perennial spring with an average discharge of 720 l/s and a minimum discharge of 505.9 l/s. This spring has an important function to locally supply domestic water, and water for irrigation and fisheries.

3. Gilap underground river is located in the upper catchment of Bribin river. McDonald (1984) mentions that the discharge at the Gilap cave is perennial (Haryono et al. 2016) and has a minimum discharge of about 6 l/s and a maximum discharge of 380 l/s. The

water from this cave has not been utilized by the community.

4. Ngreneng spring is an emergence of an underground river that is believed to be a leak from the Bribin river, which was found as the result of a tracer test conducted by McDonald (1984). The spring's discharge during the rainy season can be very high due to the entrance of the Ngreneng cave also serving as a sinkhole for runoff from the basin around this cave.

5. The underground river in Seropan cave is located at an altitude of 203 m asl. and has an average discharge of 875.7 l/s and a maximum discharge of 1184.5 l/s. The water resources in this cave have been used by the people in the surrounding villages for various purposes.

6. The underground river in Toto cave is located at an altitude of 164 m asl.; it discharges an average of 153.5 l/s and has a minimum discharge of 124.5 l/s and a maximum discharge of 943.5 l/s. Unfortunately, the water resource potential in this cave is still untapped by the surrounding community.

7. The underground river in Bribin cave is downstream of the Bribin river and is believed to be the last appearance of the Bribin river before it finally emerges as a submarine vent in the Indian Ocean. The average discharge measured in this cave is about 1700 l/s. The Bribin river was first described by McDonald (1984). This begins at the surface as the Pentung river and then disappears into the Sawahombo sinkholes. The river comes out in Luweng Jomblangan, emerges again in Gilap cave, Luweng Jomblang Banyu, and Luweng Jurangjero, and at last appears in Bribin cave. In the section between Luweng Jurang Jero and Bribin cave, it outflows into the Ngreneng spring, which also then flows into the Indian Ocean (Adji 2012).

Meanwhile, the karst area in Rengel also has some appearance of karst springs; Ngerong spring represents the largest discharge in this area and also has the highest fluctuations between the dry and wet seasons. This perennial spring is located in the foothills of the southern part of the Rengel karst, at the point of contact between carbonate rock and the alluvial plain. The minimum discharge is 450 l/s, whereas during flood events the discharge may increase up to 7500 l/s. The discharge characteristics during the study period for each of the springs and underground rivers are shown in Table 1.

Methods

HOBO U20L-02 water-level data loggers were installed in every spring, and discharge measurements were taken to obtain the discharge hydrograph. The stage discharge rating curves that were used are based on some discharge measurements within the peak, average, and low spring water levels. Some flood hydrographs were then selected to be used in the karstification degree calculation.

The determination of the aquifer karstification degree of the spring was carried out using recession-curve analysis, which is based on the formula and classification proposed by Malik and Votjkova (2012), who demonstrated that the recession-curve has several sub-regimes of flow, which are expressed as a laminar flow and a turbulent flow. The main difference between this method and other methods is with respect to the number of sub-regimes of flow. In this method, a recession curve could have only one or more sub-regimes of flow (Fiorillo 2014). Laminar and turbulent flows were distinguished using the Reynolds number. Through this number, it is identified that the laminar flow has a value of $N_{Re} < 2000$, while the value for turbulent flow is $N_{Re} \geq 2000$, with a maximum value of $N_{Re} = 10{,}000$ (Dreybrodt 1988; Ford and Williams 1992). Then, the sub-regime coefficient of laminar flow was calculated using Maillet's (1905) formula (Formula 1), while the characteristics of

Table 1 Springs and underground rivers discharge in the study area

Location	Karst type	Discharge-Q (l/s)		
		Q min	Q max	Q mean
Petoyan spring	Gunung Sewu (polygonal)	5.50	48.49	7.62
Beton spring	Gunung Sewu (residual-cone)	505.90	11,111.70	1555.70
Gilap cave (upstream of Bribin river)	Gunung Sewu (residual-cone)	6.00	380.00	47.31
Ngreneng spring (leakage of Bribin river)	Gunung Sewu (labyrinth-cone)	60.00	1905.30	180.04
Seropan cave (underground river)	Gunung Sewu (labyrinth-cone)	812.40	1184.50	875.70
Toto (underground river)	Gunung Sewu (labyrinth-cone)	124.50	943.50	153.50
Bribin cave (downstream of Bribin river)	Gunung Sewu (labyrinth-cone)	1630.00	2520.00	1771.11
Ngerong spring	Rengel (younger karst)	580.20	6407.90	968.50

turbulent flow were calculated using Kullman's (1983) formula, as expressed in Formula 2.

$$Q_t = Q_0 \times e^{-\alpha t} \qquad (1)$$

where Q_t is the discharge at t, Q_0 is the discharge at the previous t, e is a constant, α is a recession constant, and t is time (h).

$$Q_t = Q_0(1 - \beta t) \qquad (2)$$

The β coefficient in Formula 2 is calculated using Drogue's (1972 cited in Fiorillo 2014) formula, which is expressed in Formula 3.

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

Next, based on the linear value and recession coefficient of the sub-regime of flow, Malik (2007) creates an index called the karstification degree. It is divided into ten classes of karstification degree. Class 1 for the lowest degree, with discharge recession only, consists of a laminar flow. Class 10 is the highest degree, and it consists of three or more turbulent flows. The overview of possible recessional types with the presence of different flow sub-regimes described by typical recessional equations, values of recession-curve parameters, and a brief description of assumed karstic groundwater circulation is presented in Table 2.

Results and discussion

Hydrograph parameters and base flow separation

After taking discharge measurements for the springs and underground rivers within the peak, average, and low spring water levels, the pairs of data between the discharge and water level were analyzed to obtain the rating-curve constants for each of the springs and underground rivers (Table 3).

Furthermore, some significant flood hydrographs with significant discharge and a long recession limb were selected (Schulz 1976). The selected flood hydrographs and the base flow separation in every spring and underground river are presented in Fig. 2. The base flow separations (straight-line method) generate points on the recession curve that separate the base flow recession and quick flow recession (separation point), which were then used as a reference to calculate the time to base flow (T_b) and time event, as presented in Table 4.

Gilap cave has the most rapid response to rainfall ($T_p = 3$ h) because it is located on the upstream side of Bribin river. Next is Petoyan spring, as an epikarst spring, which has $T_p = 3.6$ h (the catchment is small < 3.0 km^2), and this is followed by Ngreneng spring ($T_p = 4.5$ h). On the other hand, Gilap cave has the capacity to release water for a much longer period ($T_b = 36.0$ h) than those found in Petoyan spring ($T_b = 9.3$ h) and Ngreneng spring ($T_b = 16.8$ h). Bribin cave, which is located downstream of the Bribin river, has had a rapid response to rainfall ($T_p = 5.5$ h) because the catchment area is big so it has more points of recharge and shaft flow, with a fairly long T_b (36 h). Ngerong spring, one of the largest karst springs in the Rengel karst, shows a fairly fast response to rainfall events ($T_p = 10.25$ h), and the capacity to release water appears to be faster ($T_b = 20.54$ h) than that found in Bribin cave. This condition is different from the characteristics that were found in the Seropan cave, Toto cave and Beton springs, which have a longer response to rainfall (T_p), namely 83.6, 14.4, and 12.9 h, respectively.

The highest base flow percentage (during flood events) is found in Bribin cave (87–97%), while the lowest base flow percentage is found in Petoyan spring, which has a percentage of about 27% at the peak of the rainy season. Ngerong spring (located in the Rengel karst) has a base flow percentage in the region of 50%. This value is still smaller than that found in Gilap cave (50–70%), Seropan cave (60–70%), and Toto cave (65–75%), and is almost the same as the base flow percentage in Beton spring.

The spatial distribution of the karstification degree

In general, the results of the karstification degree calculation show different values in each spring and underground river, either locally or regionally. In the local Gunung Sewu karst, the degree of karstification is distinguished on the basis of the position of the site on the upstream and downstream of the river Bribin, and is also differentiated for each type of karst development proposed by Haryono and Day (2004). On a broader scope, the degree of karstification is distinguished between the Gunung Sewu karst (in the southern part of Java) and the Rengel karst (in the northern part of Java). The summary of the karstification degree at each location is presented in Table 5, and the recession hydrograph for each location is shown in Fig. 3.

The upstream part of the catchment area of the Bribin river in the Gunung Sewu karst is represented by the Gilap cave and Beton spring, which are included in the residual-cone karst morphology. Bribin cave and Ngreneng spring, which are located on the downstream of Bribin river, are included in the labyrinth-cone karst morphology; Toto cave and Seropan cave are also found in the labyrinth-cone karst morphology, but have separate catchment systems within Bribin river. In the western part of the Gunung Sewu karst, the polygonal karst is represented by Petoyan spring. However, in the northern part of Java, Ngreneng spring, which is the largest spring in the Rengel karst region, is the

Table 2 Karstification degree in recharge areas of springs according to recession-curve parameters (after Kullman 2000; Malik 2007; Malik and Vojtkova 2012)

Karstification degree	Groundwater flow sub-regime type	Characteristic recession-curve equation	Recession-curve parameters	Characteristics of karstification degree
0.5	Single laminar sub-regime, lower values of α_1	$Q_t = Q_{o1} e^{-\alpha 1 t}$	$\alpha_1 < 0.001$	Usually tectonic faults and shear zones filled with crushed material, with high buffering capability in relation to discharge. Mainly deeper groundwater circulation
1.0			$\alpha_1 = 0.001$–0.0025	
2.0	Single laminar sub-regime, higher values of α_1		$\alpha_1 = 0.0025$–0.007	Tectonic faults filled with crushed material with higher permeability and lower buffering capability in relation to discharge. In some cases deeper groundwater circulation
2.3			$\alpha_1 > 0.007$	
2.5	Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, lower values of α_1 and α_2	$Q_t = Q_{o1} e^{-\alpha 1 t} + Q_{o2} e^{-\alpha 2 t}$	$\alpha_1 < 0.0024$ and $\alpha_2 < 0.033$ $\alpha_1 < 0.0024$, or $\alpha_2 < 0.033$	Aquifer with dense, prevailingly regular fissure network, with majority of micro-fissures and small fissures. Increase in values α_1 and α_1 accompanies increasing permeability and also higher heterogeneity of fissured rock environment
2.7			$\alpha_1 = 0.0024$–0.0045	
3.0			$\alpha_2 < 0.033$–0.067	
3.5	Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, higher values of α_1 and α_2		$\alpha_1 < 0.0024$–0.0043 and $\alpha2 = 0.060$–0.16	Aquifer with irregularly developed fissure network, with majority of open macro-fissures, also with possible presence of karst conduits of limited extent. In extreme cases, even short-term turbulent flow might occur in this type of rock environment
3.7			$\alpha1 > 0.0043$ and $\alpha2 < 0.060$	
4.0			$\alpha1 = 0.0041$–0.018 and $\alpha2 = 0.055$–0.16	
4.3	Discharge hydrogram is composed of a sub-regime with turbulent flow and a sub-regime with laminar flow. Substantial role in groundwater discharge plays the sub-regime with laminar flow	$Q_t = Q_{o1} e^{-\alpha 1 t} + Q_{o4} (1 - \beta 1 t)$	$\alpha_1 > 0.018$ or $\alpha_2 > 0.16$	Aquifer with anticipated existence of crushed water-bearing zone (e.g., fault zone) or by dense network of open small fissures in combination with simple, partly (or occasionally) phreatic conduit system of considerable extent (e.g., with open karstified fault in the vadose zone)
4.7			$\alpha_1 > 0.018$ and $\alpha_2 > 0.16$	
5.0			α and β low values	
5.5	Complex discharge regime, a combination of one sub-regime with turbulent flow and two sub-regimes with laminar groundwater flow. Discharge sub-regime with turbulent flow is of short-term influence in comparison with overall groundwater discharge	$Q_t = Q_{o1} e^{-\alpha 1 t} + Q_{o2} e^{-\alpha 2 t} + Q_{o4}$ $(1 - \beta 1 t)$	$\alpha_1 > 0$ and $\alpha_2 > 0$ and $\beta_1 > 0$	Extensive disruption and disintegration of rock environment, with majority of open, medium size, both not karstified and karstified fissures in the phreatic zone of the fissure karst aquifer (according to α_1) and with smaller influence of connected conduits (groundwater of large karstic channels, according to β_1)
6.0	Very complex discharge regime, a combination of two sub-regimes with turbulent flow and two sub-regimes with laminar groundwater flow. Discharge sub-regimes with turbulent flow are of short-term influence in comparison with overall groundwater discharge	$Q_t = Q_{o1} e^{-\alpha 1 t} + Q_{o2} e^{-\alpha 2 t} + Q_{o4}$ $(1 - \beta 1 t) + Q_{o5} (1 - \beta 2 t)$	β_2, β_1 and α_2, α_1 high values	Extensive disruption and disintegration of rock environment, with majority of open, medium size, both not karstified and karstified fissures in the phreatic zone of the fissure karst aquifer (according to a1) and with smaller influence of connected conduits (groundwater of large karstic channels, according to β_1 and β_1)

Table 2 continued

Karstification degree	Groundwater flow sub-regime type	Characteristic recession-curve equation	Recession-curve parameters	Characteristics of karstification degree
7.0	Discharge regime is a combination of one sub-regime with laminar flow with two to three sub-regimes with turbulent flow. Substantial role in groundwater discharge plays the sub-regime with laminar flow.	$Q_t = Q_{o1}e^{-\alpha 1t} + Q_{o4}(1 - \beta 1t) + Q_{o5} + Q_{o6}(1 - \beta 3t)$	$\beta_3, \beta_2, \beta_1$ and α high values, $\beta_1 > \beta_2$	Developed karstification of the aquifer, formed by large open tectonic faults and karstic channels, as well as by significant portion of karstified and non-karstified fissures and micro-fissures in rock blocks, generating phreatic zone with karstic groundwater table
8.0	Discharge regime is a combination of a sub-regime with laminar flow with two to three sub-regimes with turbulent flow. Substantial role in groundwater discharge is played by sub-regimes with turbulent flow. Sub-regime with laminar flow is less significant		$\beta_3, \beta_2, \beta_1$ and α high values	Highly developed karstification of the aquifer, formed by large open conduits (karst channels). The presence of open active small fissures and micro-fissures is reduced. Circulation of substantial part of groundwater is mainly via preferred pathways of channel systems. Phreatic zone is missing, or its role is insignificant
8.5	Groundwater flow regime is represented merely by turbulent flow, with only one turbulent flow sub-regime present, which represents turbulent circulation in channel systems (conduits) without hydraulic connection to the groundwater in adjacent rock blocks. Groundwater circulation is mostly connected to vadose zone	$Q_t = Q_{o4}(1 - \beta 1t)$	$\alpha_1; \alpha_2 = 0$ and $\beta_1 > 0$	Karstic aquifer with well-developed conduit system, without any significant connection to open phreatic fissure systems in adjacent rock blocks. Extensively developed conduit system can ensure permanent groundwater replenishment
9.0	Groundwater flow regime is represented merely by turbulent flow, consisting of two turbulent flow sub-regimes. These represent turbulent circulation in channel systems (conduits) without hydraulic connection to the groundwater in adjacent rock blocks Groundwater circulation is mostly connected to vadose zone	$Q_t = Q_{o4}(1 - \beta 1t) + Q_{o5}(1 - \beta 2t)$	$\beta_1; \beta_2$ low values	Karstic aquifer with well-developed conduit systems of karstic groundwater pathways, without any significant connection to open phreatic fissure systems in adjacent rock blocks. Replenishment of groundwater resources can still be ensured by extensively developed conduit system
10.0	Complex turbulent flow regime of groundwater discharge, consisting of three different turbulent flow sub-regimes. Probability of a very complex groundwater circulation by occasional flows in the vadose zone. Documented only in perennial flows	$Q_t = Q_{o4}(1 - \beta 1t) + Q_{o5} + Q_{o6}(1 - \beta 3t)$	$\beta_1; \beta_2; \beta_2$ high values	Karstic aquifer with extensive conduit system, without any significant connection to open phreatic fissure systems in adjacent rock blocks. In its spatial extent, the conduit system is bound only to the vadose zone, without enabling permanent groundwater replenishment

Table 3 The stage discharge rating curves of springs and underground rivers

Location	Number of discharge measurement	Stage discharge rating curve
Petoyan spring	12	$y = 94.591(x) + 0.6292$[a]
Beton spring	17	$y = 4449.6x^{2,3324}$
Gilap cave (upstream of Bribin river)	9	$y = 7,9129e^{2,7173x}$
Ngreneng spring (leakage of Bribin river)	9	$y = 49,164e^{1.343x}$
Seropan cave (underground river)	7	$y = 1418.9Ln(x) + 557,22$
Toto (underground river)	9	$y = 5500.3x2 - 3007.9x + 536.37$
Bribin cave (downstream of Bribin river)	15	$y = 1204.5\ x^{1,0103}$
Ngerong spring	20	$y = 5.0196(x) - 2.0501$

[a] y is the discharge (l/s), and x is the water level (meters)

only spring outlet that flows southward from the underground river systems of this region.

In the upper part of the Bribin river catchment (Gilap cave and Beton spring), the degree of karstification (D_k) is in the range of 6–7, which means the aquifer has already formed an open channel (conduit); this is particularly the case in Beton spring ($D_k = 6.6$), which has frequent occurrences of floods with a big discharge (> 10,000 l/s). The D_k value for Beton spring means that the aquifer has a combination of one sub-regime with laminar flow, and two or three sub-regimes with turbulent flow. However, the regional groundwater storage is still controlled by sub-regimes with laminar flow. Gilap cave ($D_k = 5.8$), which is located higher than Beton spring, has a combination of one sub-regime with turbulent flow and two sub-regimes with laminar groundwater flow. As for the visual evidence, Gilap cave has not shown the conduit development that is found in Beton spring. Here, the discharge sub-regime with turbulent flow is of a short-term influence in comparison with overall groundwater discharge (maximum discharge = 380 l/s). In addition, both Gilap cave and Beton spring are included in the geomorphology of the residual-cone karst, which occurs in the weaker and more porous limestones.

On the downstream of Bribin river (Bribin cave), which is classified as the labyrinth-cone karst, aquifers display the highest degree of karstification ($D_k = 7.7$). The aquifer shows highly developed karstification, fashioned by large, open conduits (karst channels) and the occurrence of open, active, small fissures and micro-fissures is reduced. Here, the circulation of substantial amounts of groundwater is mainly by means of preferred pathways of the channel systems, and the phreatic zone is missing, or its role is insignificant. In the field, this fact is easily recognizable by the large size of the underground river corridor in Bribin with a discharge during flood events of more than 2000 l/s. The development of voids in the aquifer of Bribin cave is consistent with the theory expressed by Adji (2012), which

states that the majority of the cracks in the aquifer catchment of Bribin cave are open channels allowing conduit flows to recharge quickly during the rainfall period. Adji (2012) also reveals that, in terms of the recession flow type, the role of the diffuse flow during flood events has been greatly reduced, while turbulent flow dominates.

Furthermore, in the central part of labyrinth-cone karst the Bribin catchment area, Ngreneng spring, Seropan cave and Toto cave (which are expected to be tributaries of Bribin river; Adji and Misqi 2010) show a low degree of karstification with values of 6.0, 5.2, and 5.0, respectively. These values exclude the young stage up to the adult stage of karstification. The degree of karstification in Ngreneng spring indicates that the aquifer is still aggressive enough to dissolve the carbonate rocks, with the voids beginning to be developed into open, medium-sized fissures; both of these are experienced by rocks that are easy or difficult to dissolve in the phreatic zone. The flow properties are slightly affected by the open channels (conduits) that are interconnected. Meanwhile, the flow properties of recession have a very complex input, which is a combination of two types of turbulent flow plus laminar flow (diffuse flow). Here, the nature of the turbulent flow during floods is only demonstrated within a very short time period. In Seropan cave and Toto cave, the level of classification is lower than that calculated for Ngreneng spring, with flow properties that supply the underground river when the flood event occurs consisting of a sub-regime with a turbulent flow and sub-regimes with laminar flow. The role of diffuse (laminar) flow dominates the turbulent flow. From the degree of karstification, which has a value of 5.0–5.2, it is understood that the karst aquifer has a growing network of small-sized channels (diffuse fissures), which are still growing quite rapidly, and some of which already have a phreatic water system.

The polygonal karst in this study is represented by Petoyan spring in the western part of the Gunung Sewu karst. The smallest aquifer storage capacity and the base
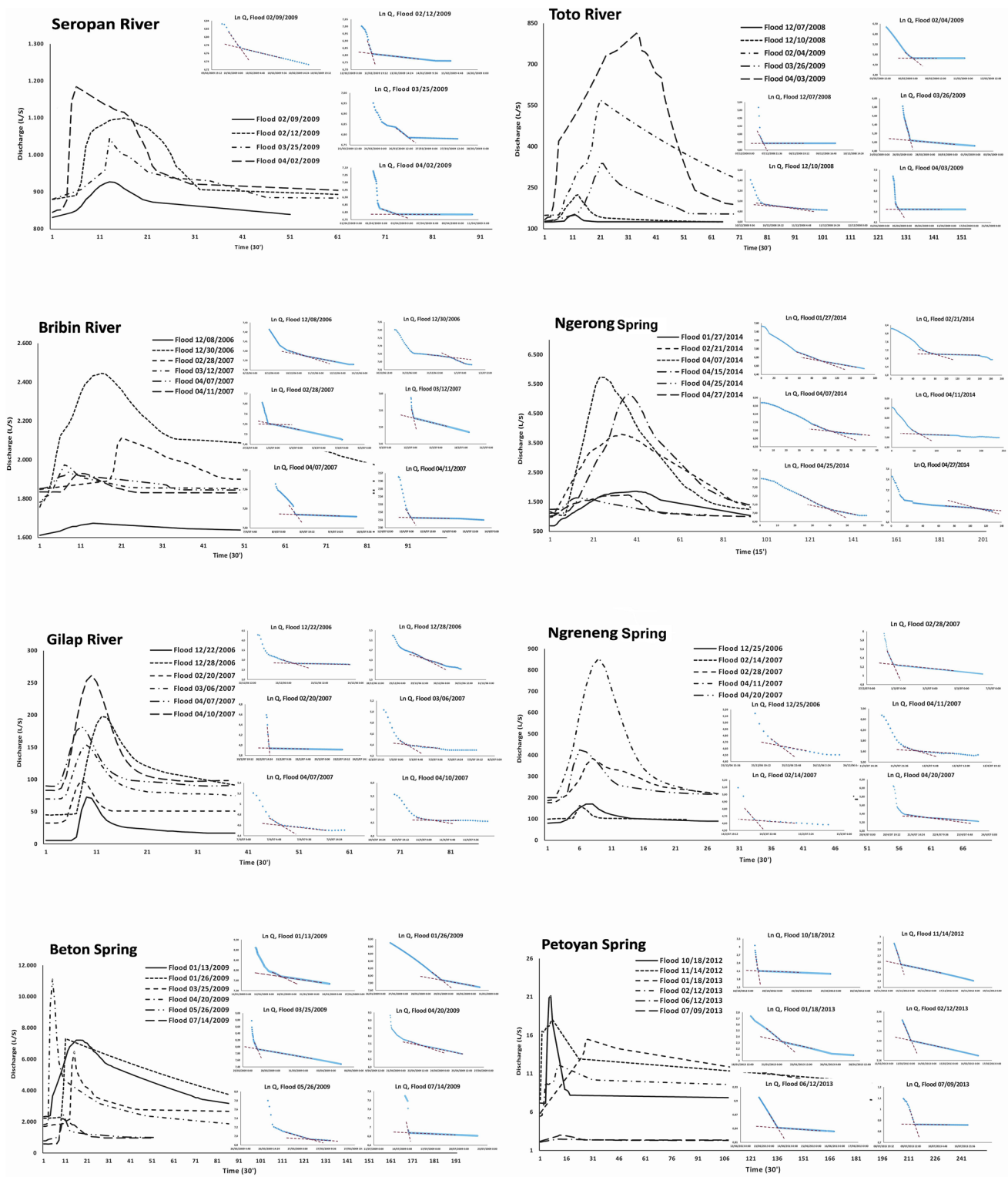
Fig. 2 Selected flood hydrographs for every spring and underground river

flow percentage illustrate that it has a small catchment area (Ramdhani 2014). In this epikarst spring, the degree of karstification exhibits a value of 3.7, which indicates the aquifer is dominated by a network of uniform, small-sized voids (diffuse and fissure), the majority of which are open and have minimal macro-fissure karst channels. During flood events, there may be a turbulent flow in the short term. In addition, this spring is supplied by a combination

Table 4 Flood hydrograph parameters and base flow percentages

Location	Number of flood hydrograph analyzed	Time (hour)			% of base flow		
		T_p	T_b	T_{event}	Early wet season	Mid-wet season	End wet season
Petoyan spring	10	3.6	9.3	12.9	40.36	22.67	39.56
Beton spring	23	12.9	193.4	154	48.22	51.77	46.94
Gilap cave (upstream of Bribin river)	16	3.0	36	37.56	52.78	55.68	72.12
Ngreneng spring (leakage of Bribin river)	8	4.5	16.8	56.12	45.10	48.75	–
Seropan cave (underground river)	7	83.6	619.2	702.85	–	70.47	67.09
Toto (underground river)	7	14.4	910	924.28	73.09	66.64	72.65
Bribin cave (downstream of Bribin river)	12	5.5	36	41.45	88.79	87.13	97.27
Ngerong spring	13	10.25	20.54	30.77	50.46	57.26	48.14

%base flow ratio of the base flow to the total flow

T_p time to peak, T_b time to base flow, T_{event} $T_p + T_b$

of two or more sub-laminar flow regimes characterized by a different discharge coefficient for each flow.

In the Rengel karst (northern Java), Ngerong spring demonstrates a low degree of karstification (with a value of 4.8) that is generally lower than all of the locations in the Gunung Sewu karst (except Petoyan spring). The karstification in Ngerong spring is a little more developed than Petoyan spring, which is characterized by the development of a dense network of small channels (diffuse-fissure), some of which have begun to develop into an open system and already have a phreatic water system. The type of flow that supplies Ngerong spring is a combination of a sub-

turbulent flow regime and a sub-laminar flow regime with a predominance of laminar flow.

The degree of karstification and the catchment area

For the study region, the catchment area of the springs or underground streams varies depending on the discharge, and its position in the developed system or network. From the simple water balance calculations conducted by Adji and Misqi (2010), Ramdhani (2014), and Mujib (2015), the extents of catchment areas for the springs or underground streams vary between 2.7 and 150.4 km² (Table 6). From

Table 5 Spatial distribution of karstification degree

| Location	Number of recession discharges analyzed	Karstification degree from recession curves (D_k)	Final discharge equation	Karst type
Petoyan spring	10	3.7	$Qt = 0.031^{0.0025t} + 0.032^{0.030t} + 0.034^{0.027t}$	Gunung Sewu (polygonal-cone)
Beton spring (upper of Bribin catchment)	23	6.6	$Qt = 2.757^{-0.009t} + 3.372(1{-}006t) + 6.478(1 - 0.0005t)$	Gunung Sewu (residual-cone)
Gilap cave (upstream of Bribin river)	16	5.8	$Qt = 0.103^{-0.0256t} + 0.183(1 - 0.145t)$	Gunung Sewu (residual-cone)
Ngreneng spring (leakage of Bribin river)	8	6.0	$Qt = 0.191^{0.0019t} + 0.260(1 - 0.851t) + 0.385(1 - 0.099t)$	Gunung Sewu (labyrinth-cone)
Seropan cave (underground river)	7	5.2	$Qt = 0.218^{0.0045t} + 0.244^{0.0186t} + 0.424(1 - 0.0365t)$	Gunung Sewu (labyrinth-cone)
Toto (underground river)	7	5.0	$Qt = 1.447^{-0.009t} + 1.639(1 - 0.000019t)$	Gunung Sewu (labyrinth-cone)
Bribin cave (downstream of Bribin river)	12	7.7	$Qt = 1.847^{-0.0007t} + 1.911(1 - 0007t) + 1.936(1 - 0.0028t)$	Gunung Sewu (labyrinth-cone)
Ngerong spring	13	4.8	$Qt = 1.447^{-0.009t} + 1.639(1 - 0.000019t)$	Rengel (younger karst)
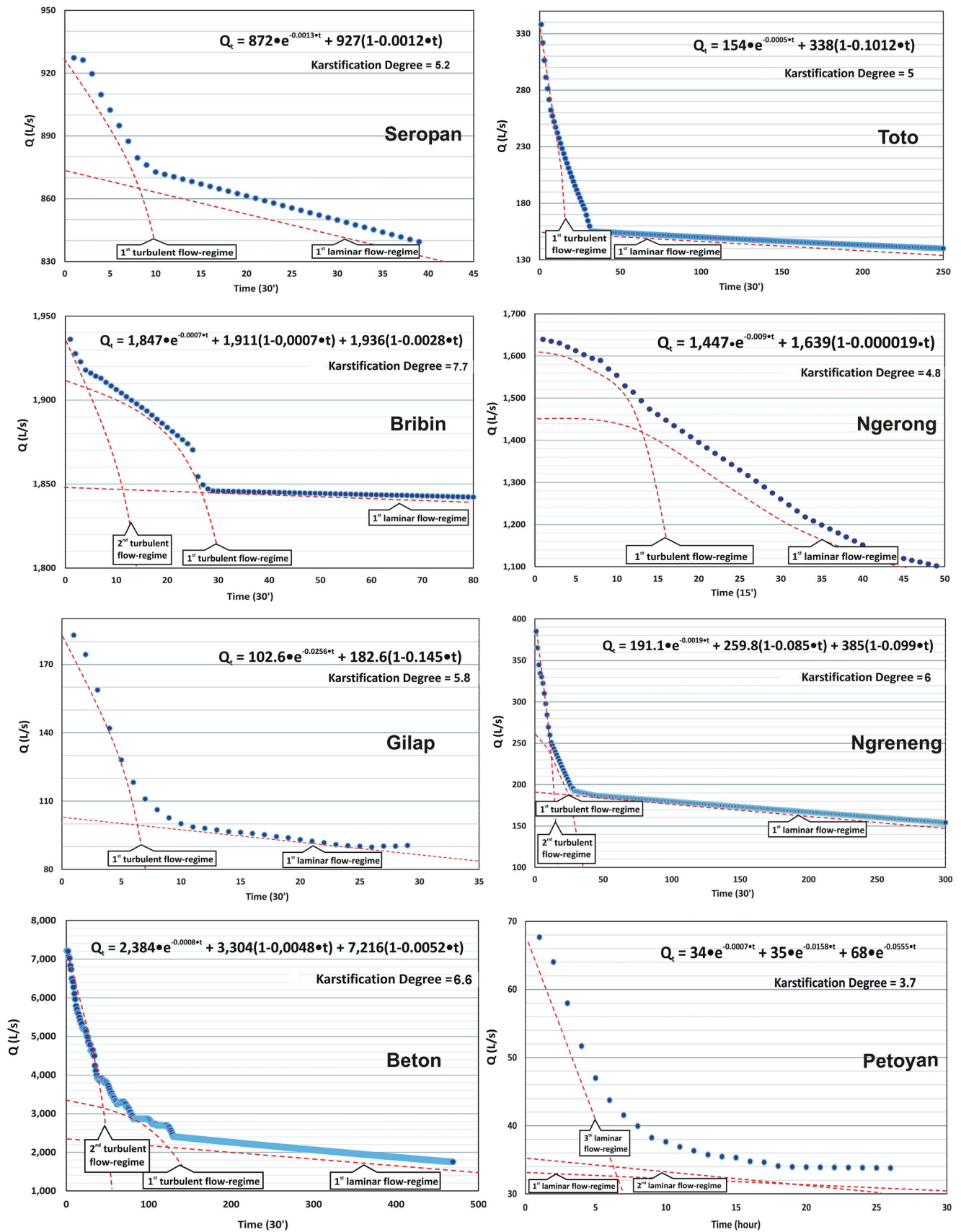
Fig. 3 The recession hydrograph for each location showing the different combinations of sub-regime types

Table 6 Spatial distribution of karstification degree

| Location	Catchment area (km^2)	Q mean (l/s)	Karstification degree from recession curves (D_k)	Karst type
Petoyan spring	3.0	7.62	3.7	Gunung Sewu (polygonal-cone)
Beton spring (upper of Bribin catchment)	97.7	1555.70	6.6	Gunung Sewu (residual-cone)
Gilap cave (upstream of Bribin river)	2.7	47.31	5.8	Gunung Sewu (residual-cone)
Ngreneng spring (leakage of Bribin river)	14.9	180.04	6.0	Gunung Sewu (labyrinth-cone)
Seropan cave (underground river)	73.2	875.70	5.2	Gunung Sewu (labyrinth-cone)
Toto (underground river)	13.5	153.50	5.0	Gunung Sewu (labyrinth-cone)
Bribin cave (downstream of Bribin river)	150.4	1771.11	7.7	Gunung Sewu (labyrinth-cone)
Ngerong spring	20.1	968.50	4.8	Rengel (younger karst)
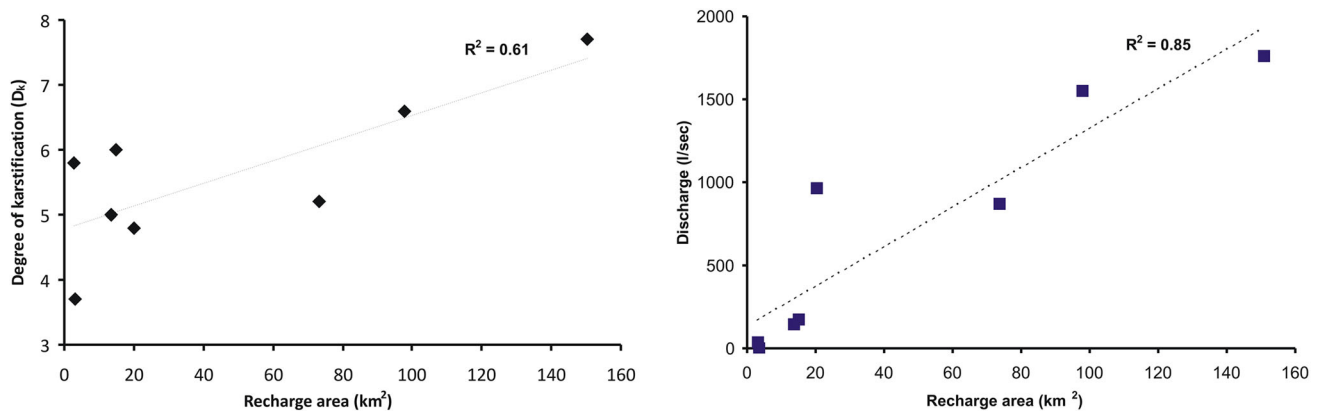
Fig. 4 The relationship between recharge area and D_k (left), and recharge area and discharge (right)

Fig. 4, it appears that there is a strong relationship between the extent of the catchment area and the spring or underground river discharge, with $R^2 = 0.844$.

Furthermore, the correlation between the karstification degree (D_k) and the extent of the catchment also displays a positive relationship, albeit with more scatter ($R^2 = 0.605$). This correlation value means that the more extensive the catchment area, the higher the degree of karstification. Nonetheless, this study has not been able to conclude that the extent of the catchment area will have positive implications on the value of D_k, since only a few samples (karst sites) were examined in this study. In other words, the results of this study can be considered to be a preliminary result.

In terms of the spatial distribution of the karstification degree in the study area, it appears that, in general, there are relatively high variations, with the values ranging from 3.7 to 7.7. Compared to the Gunung Sewu karst, the degree of karstification in the Rengel karst (Ngerong spring) is still at a younger stage with a low degree of karstification value ($D_k = 4.8$). The explanation of this is quite simple; it is because the geological age of the limestone in the Rengel karst is younger and contains more magnesium. In addition, the surface has less developed karstic geomorphology

compared to that found in the Gunung Sewu karst (Haryono 2008).

In this study, an interesting thing is evident in the spatial distribution of the karstification degree in the Gunung Sewu karst. In this karst region, the variation in the degree of karstification is high. In the northeast of the study area, known to be of the residual-cone karst type (Haryono and Day 2004), the karstification degree shows values between 5.8 (Gilap cave) and 6.6 (Beton spring). The value of 5.8 in Gilap cave indicates that the aquifer already has a combination of two sub-regimes with turbulent flow and two sub-regimes with laminar karst flow, whereas the value of 6.6 in Beton spring indicates that the aquifer has already developed and formed large, open karstic channels. The difference in degree of the karstification between Gilap cave and Beton spring (both located in the residual-cone karst) is probably caused by the location of the Gilap cave, which is more upstream, meaning that the catchment area is small and has a high slope, and, as a consequence, results in the least time for the karst water to reside in the zone of water–rock interaction (Adji 2013). In Beton spring, which is located more downstream, the dissolution process is more intensive on the type of residual-cone karst. (The limestone is more soluble with high porosities, but has relatively thick beds.)

In the central part of the Gunung Sewu karst, where the limestones are insoluble and thicker (labyrinth-cone karst), the degree of karstification values range from 5.0 to 7.7. Almost all locations in the labyrinth-cone karst indicate a karstification degree value smaller than 6.0, except for that found in Bribin cave (7.7). This low value for the degree of karstification shows that the development of voids is still at the young stage because the limestones are relatively less soluble than in the residual-cone karst. Meanwhile, the high value for the karstification degree in Bribin cave is more due to its position (as it is located mostly downstream), its large discharge, and the extensive catchment area (150.4 km^2—the largest in this study). Also, hydrogeochemically, the water of Bribin river during wet season is dominated by conduit flow, which causes decreasing values of calcium and bicarbonate while the CO_2 content increases. This condition illustrates that the karst system is open and developed (Adji 2012).

Furthermore, in the western part of the Gunung Sewu karst, where most limestones are characterized as polygonal karst (less soluble with thinner limestone beds), the values for degree of karstification, as represented by Petoyan spring, have a low value (3.7). With this small value, the level of void development in the karst aquifers is still considered to be at a young level, which is indicated by the presence of several sub-laminar flow regimes (derived from the non-uniform diffuse flow development), and the lack of any turbulent flow contribution. According to McDonald (1984), the western part of the Gunung Sewu karst does indeed encompass many perennial springs that are epikarstic with small discharge (> 5.0 l/s). These data reinforce the assumption that, in the polygonal karst, the development of voids in karst aquifers has not been as intensive as that found in the labyrinth-cone and residual-cone karst.

Conclusion

The results of the karstification degree calculation using selected flood recession data give a range from a low value of 3.7 (Petoyan spring) to a high value of 7.7 (Bribin cave). The value of 3.7 indicates the flow type to be a combination of two or more sub-regime laminar flows, which are distinguished by a different discharge coefficient for each type of flow they supply, with turbulent flow occurring in the short term during flood events. Meanwhile, the value of 7.7 indicates that the aquifer is experiencing a later stage of the karstification process, and has a predominance of open channel (conduit) flow. In general, the degree of karstification in the Gunung Sewu karst is at a level that is more developed than in the Rengel karst. The exception is Petoyan spring, which is located in the western part of this karst region. Here, the aquifer has a karstification degree

indicating it is at a young stage and has an undeveloped type of turbulent flow. In the Gunung Sewu karst, the value of the karstification degree demonstrates a high level of variation as a result of the differences in surface geomorphology type, which is controlled by the different solubility and thickness of the limestone beds. In addition, there is a fairly strong positive relationship between the degree of karstification and the extensive catchment area of the springs.

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