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Karst Aquifer Characterization by Means of Its Karstification Degree and Time Series Analysis (Case: Ngerong Spring in Rengel Karst, East Java, Indonesia)

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Abstract - The purpose of this study is to define the characteristics of the karst aquifer, which is approximated by the parameters of (1) degree of karstification (Dk) and (2) time series analysis (cross-correlation and auto-correlation). This research focuses on the Ngerong Spring, the largest spring in Rengel Karst, East Java, Indonesia. Pendant rain gauge RG-3M and HOBO U20L-02 water-level data loggers were installed over one year with a recording interval of 15 minutes. Furthermore, after one year of time-series discharge data was obtained, the discharge recession coefficient was applied to make the recession formula. It was then used to estimate the karstification degree scale from 1 to 10. The aquifer memory system and the spring response to rainfall events were analyzed by auto-correlation and cross-correlation. The results of this study indicate that the karstification degree (Dk) of the Ngerong Spring system is 4.8-5.0, with one laminar and one turbulent flow subregime type. The aquifer system comprises a subregime with turbulent and laminar flow, where the substantial role in groundwater discharge plays the subregime with laminar flow. Meanwhile, time series analysis shows that the capacity of aquifer storage in the Ngerong Spring is large enough. It has a memory effect for 26.41 days, followed by a rapid response to rainfall events within 8 hours. Compared with several other karst sites in Java, the Ngerong Spring aquifer has the youngest development level with the best storage and the slowest release.

Keywords: karst aquifer, karstification degree, time series analysis, Rengel karst

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Introduction

Background

The karst aquifer condition is often difficult to characterize, because karst aquifers are usually composed of two types of release discharge from their storage, namely those controlled by slow-flow and quick-flow dominance (Kiraly, 2002). This duality of discharge reflects the complex development of the karst aquifer system, in which the developed aquifer is dominated by conduit-sized voids that discharge to the springs more rapidly. This is what differentiates aquifer investigation methods in karst areas from those used in porous media areas (Suhendar *et al*., 2020; Putranto *et al*., 2020; Mahdid *et al*. 2022). A karst spring is a transition point from groundwater storage in an aquifer to surface water, reflecting the karst aquifer natural characteristics (Quinlan, 1989; Kresic and Stevanovic, 2010). The spring hydrograph analysis can describe the aquifer characteristics, internal conditions, and flow system (Bonacci, 1993; Padilla and Pulido-Bosch, 1995; White, 2002; Kresic and Bonacci, 2010; Mohammadi and Shoja, 2014). Quinlan (1989) and Quinlan *et al*. (1991) also confirmed that the spring could provide representative data that reflect the aquifer natural characteristics.

One of the quantitative parameters used in the last decade to determine the development of voids in karst aquifers is the degree of karstification (Dk) obtained by processing the recession curve parameters in the hydrograph of karst springs. The recession-curve analysis is the basic method of hydrological studies. However, this method is still progressing and expanding, especially for research in the karst area (Kovács *et al.*, 2005; Malík and Vojtková, 2012; Fiorillo, 2014; Malík *et al.*, 2021). In the last few years, the recession-curve analysis was also applied to determine the karstification degree (Dk) of the karst aquifer based on the subregime recession coefficient of discharge (Malik, 2007; Malík and Vojtková, 2010, 2012) and the analysis of all the hydrograph components (Rashed, 2012). Here, the aquifer karstification degree will significantly affect groundwater recharge characteristics (dispersed or concentrated), storage capacity, and water discharge of an aquifer (Smart and Hobbes, 1986).

In addition to applying recession curves, time-series statistical analysis using rainfall and discharge data can also explain aquifer characteristics in a particular geographical area. Time series analysis, according to Larocque *et al.* (1998), was a straightforward approach to be implemented, and was used to describe the karst aquifer characteristics. The application of time series analysis in the karst aquifer was firstly applied by Mangin (1984a, 1984b). It was based on the single variable analysis characterized by the univariate spectral and the cross-correlation function without analyzing or going deeply into the other functions of the cross-spectral analysis. Furthermore, Mangin (1984b) used correlation and spectral analysis to classify the karstification degree of the karst aquifer. In Indonesia, this time series analysis application has also been carried out, such as in the Pindul Cave karst system (Gunungsewu Karst) (Nurkholis *et al.*, 2019) and three springs of the Jonggrangan Karst area, Central Java (Kurniawan *et al.*, 2019).

Today, several studies using time series analysis in the karst aquifer have been applied (Padilla and Pulido-Bosch, 1995; Eisenlohr *et al.*, 1997; Larocque *et al.*, 1998; Rahnemaei *et al.*, 2005; Panagopoulos and Lambrakis, 2006; Valdes *et al.*, 2006; Fiorillo and Doglioni, 2010; Liu *et al.*, 2011; and Zhang *et al.*, 2013). One of them is auto-correlation and cross-correlation analysis. Auto-correlation analysis is a normalized measure of the linear dependence among successive data series values (Larocque *et al.*, 1998). The linear relationship of each data variable will reflect the memory effect of the aquifer system. The shape of the correlogram gives information on the karstification and the groundwater flow reserves of the karst aquifer (Mangin, 1984b, Padilla and Pulido-Bosch, 1995).

In tropical regions, the development of karst landforms is good. It is influenced by several factors, such as warm temperatures, high intensity of rainfall, and dense vegetation, resulting in a high concentration of CO_2 and large groundwater flows (Nguyet and Goldscheider, 2006). The types of karst landforms frequently found in tropical climates are cockpit, kegel, and mogotes in Java, Maros, Jamaica, and Puerto Rico. These occur in relatively soft, porous Cenozoic carbonates, mainly Paleocene to Miocene thick-bedded limestone and limy dolomite. These landforms are ordinarily shallow, rounded, and gentle. It is a typical 'young' karst (Zhu *et al.*, 2013).

Indonesia tectonic processes and limestone uplift are still ongoing (Susilohadi, 1995). Thus, there may still be many younger karst areas that do not have time to form karstic topographical features on the surface, but they still have complex hydrogeological characteristics as other karst aquifers. The Rengel Karst is one example of karst areas in the northern part of Java Island that has been uplifted since Late Pleistocene. It is part of the Paciran Formation lithologically comprising reef limestones (Noya *et al.*, 1992; Haryono *et al.*, 2001; Haryono, 2008) or called *karren limestone* by Bemmelen (1949). The Rengel Karst is younger than Gunungsewu Karst in the southern part of Java, deposited in Middle Miocene.

This study aims to assess the karstification degree of the aquifer by applying the recession-curve approach. Furthermore, to understand the characteristics and the nature of the aquifer flow, an analysis of time series in the form of auto-correlation and cross-correlation is performed to describe the flow properties, the aquifer memory system, and spring response to rain events. Based on the discharge and rainfall variation approach in two rainy season periods, the research is expected to be the basis for understanding the aquifer characteristics in the merokarst area in the tropical region. The karstification degree calculation in the Ngerong Spring has been conducted by Adji *et al.*(2019), but only used a single flood in its calculations. This study tries to average out several single floods, and is supplemented by using the master recession curve (MRC) approach to reduce bias in calculations. Moreover, this study also includes the use of time series analysis (in this case, cross-correlation and auto-correlation) to obtain the most significant probability of time lag to reach the peak of flooding and the length of time to release storage aquifers through small voids (diffuse flow).

Geological Settings

Ngerong Spring (49 M 611269; 9219516) is located in Rengel District, about 30 km south of Tuban City, East Jawa Province, Indonesia. This area is derived from shallow marine reef units in the Northeast Java Basin (Premonowati *et al.*, 2004). Rengel Karst area is characterized by a Plio-Pleistocene reefal limestone that overlies Middle Miocene Formations called Rembang Zone Anticlinorium. This zone consists of some roughly east-west trending anticlinoria, alternating with alluvial plains (Susilohadi, 1995), where Rengel Karst is part of this zone. Geologically, the Rengel Karst is made up of Paciran Formation, overlain by Early to Middle Miocene reef limestones, formed and built up later Pleistocene (Bemmelen, 1949). The Paciran Formation is a shallow sea sediments with coral reefs hermatypic as the dominant framework built together with algae, molluscs (gastropods, pelecypods, Scaphopoda), benthic foraminifers, bryozoan, echinoderms, porifers, and ostracods (Premonowati *et al.*, 2004). Paciran Formation comprises wackestone and boundstone microfacies, and it is surrounded by an eroded anticline in the East-West direction with an apparent slope of 15° (Haryono *et al.*, 2001; Haryono, 2008). This pure limestone lithology is also shown by the dominant hydrogeochemical facies of Ca-HCO_3 (Mujib *et al.*, 2020). Rengel Karst is part of the Tuban Karst region. Haryono *et al.*(2001) referred to the merokarst region and, in some places, is classified as a nonkarst carbonate rock area. Haryono (2008) also pointed out that the major and minor karst features did not develop. Here, the karst hill slopes range between 28 and 33%, while the doline is not found in this region.

Ngerong Spring performs the highest discharge in the Rengel Karst, and shows the highest discharge fluctuations between normal and storm conditions. This perennial spring is located in the foothills of the southern part of the Rengel Karst, at the contact between carbonate rock and alluvium plain of Bengawan Solo River (Figure 1). Based on the water balance analysis (Mujib, 2015), the recharge area of Ngerong Spring is approximately 1,922 ha. The system combines autogenic (direct recharge from limestone) and allogenic (derived from sandstone and quartz sandstone). The autogenic recharge comes from limestone of Paciran Formation, while the allogenic recharge comes from the quartz sandstone of Ngrayong Formation and marl limestone of Mundu Formation.

During dry season, the average spring discharge is 0.69 m^3/s, and the minimum discharge is 0.45 m^3/s. During flood events, the discharge may increase up to 7.5 m^3/s. The variation of the discharge coefficient is low at 0.6, indicating that

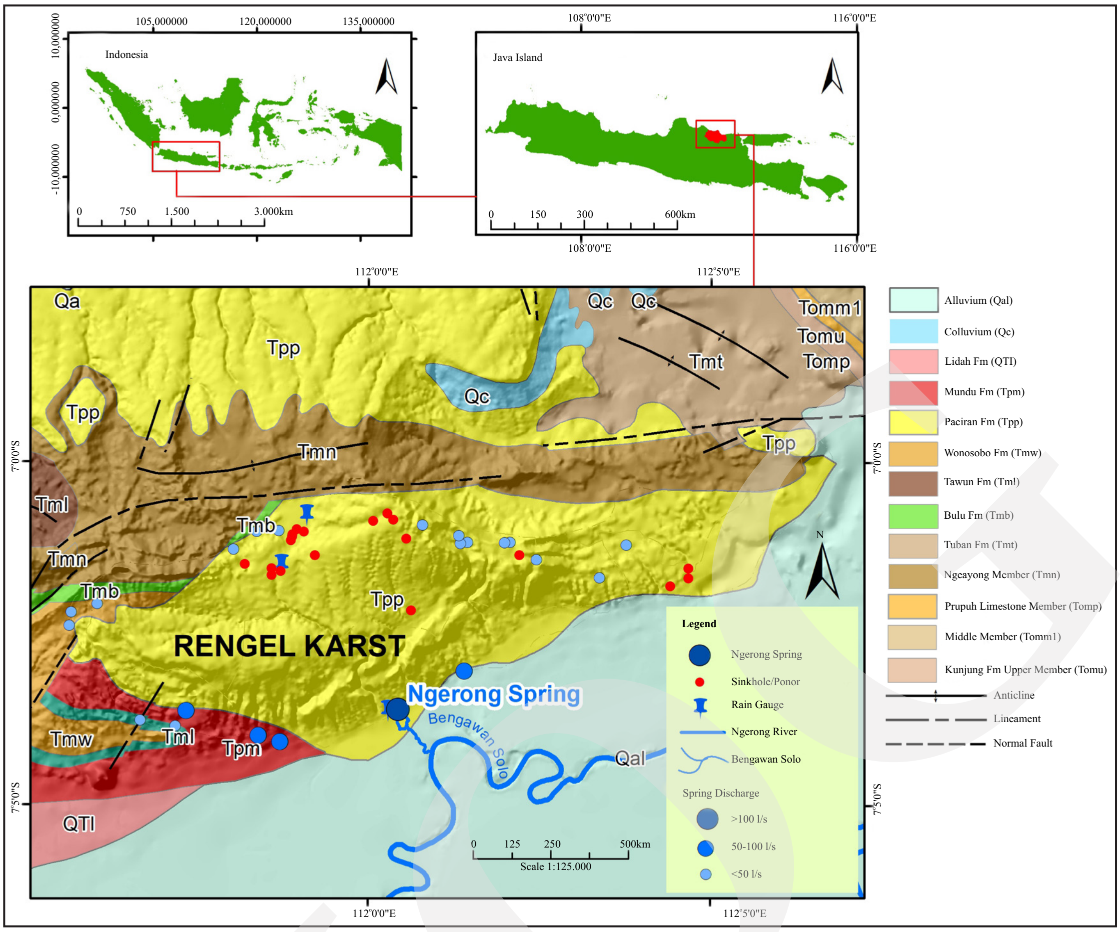

Figure 1. Recharge area of The Ngerong Spring system in Rengel Karst, East Java

the minimum and maximum discharge range is not so significant as the average discharge of 0.911 m^3/s. The statistics of Ngerong Spring discharge are shown in Table 1.

The recharge area of Ngerong Spring is dominated by subsurface drainage. Stratigraphically, the studied area is formed from Early Miocene to Pleistocene Epoch. Limestone of Tawun Formation (Tml) was formed during Early Miocene to Middle Miocene, which consists of sandy marl interspersed with bioclastic limestones in a marine depositional environment. Quartz sandstone unit of the Ngrayong Formation (Tmn) formed during Middle Miocene intersperse with bioclastic limestones and claystone. Late Middle Miocene limestone of Bulu Formation (Tmb) deposited in the form of sandy limestone with sandy marl insertions.

Furthermore, at the beginning of Late Miocene, Wonocolo Formation (Tmw) was deposited, consisting of sandy marl interspersed with sandy limestone. During Late Miocene, Ledok Formation comprising glauconite sandstone units with sandy limestone intercalations was deposited. In Pliocene, marl unit of Mundu Formation (Tpm)

Table 1. Statistics of Ngerong Spring Discharge

Spring discharge of Ngerong Spring	
Q_{min} (m^3/s)	0.457
Q_{max} (m^3/s)	7.535
Ø (m^3/s)	1.018
σ (m^3/s)	0.621
C_v (-)	0.600
Q_{10}	1.359
Q_{50}	0.911
Q_{90}	0.592

Notes: Ø mean; σ standard deviation; C_v coefficient of variation; Q_{10} 10^{th} Percentile; Q_{50} 50^{th} Percentile; Q_{90} 90^{th} Percentile.

was deposited in the form of marl, silty claystone, and marly limestone. Pliocene to Pleistocene, Paciran Formation (Tpp) was deposited as a reef limestone. Furthermore, in Late Pleistocene, this area as a whole was raised to land.

The primary recharge input in this aquifer is rainwater, with an annual rainfall of 1,480 mm/year. Meanwhile, the temperatures range from 26-27°C. Approximately 70% of the annual rainfall is concentrated in the rainy season from December to April. Based on the data from three rain gauges, which were installed upstream (hills near Ponor), the middle and downstream (near Ngerong Spring) of the recharge area, the rainfall intensity of this area reached 160 mm/hour during the peak rainfall (Mujib, 2015).

Materials and Methods

Karstification Degree

The data used in this study were gained from: (1) Spring water level recorded continuously at intervals of 15 minutes using Hobo water-level data logger; (2) Spring discharge measured temporally using velocity and slope area methods in some variations of discharge, which was validated using discharge measurement by Cipolleti weirs, and; (3) Rainfall data of the recharge area recorded continuously in every 15 minutes using three automatic tipping bucket rain gauges. During these measurement period, twenty pairs of discharge and water level data were obtained, which were then used to determine the stage-discharge rating curve, resulting in a linear determination (R^2)= 0.99. Furthermore, the baseflow separation is carried out using an automated recursive digital filter approach developed by Eckhardt (2005).

The aquifer karstification degree determination is conducted using recession-curve analysis based on the formula and classification proposed by Malík and Vojtková (2012). Both experts described that the recession curve had several subregime of flow, expressed as laminar and turbulent flows. In this method, a recession curve could have one or more subregime of flow (Fiorillo, 2014).

Laminar and turbulent flows were distinguished using the Reynolds number, as formulated in Formula 1:

$$Re = \rho\, v\, d / \mu \quad \text{...............} (1)$$

where:,
ρ = fluid density,
μ = fluid viscosity,
d = segment length, and
v = fluid velocity.

By this Reynolds number method, it is known that laminar flow has a value of N_{Re} <2000, whereas the value of turbulent flow is $N_{Re} \geq 2000$ with a maximum value of N_{Re} = 10000 (Dreybrodt, 1988; Ford and Williams, 2007). Then, the subregime coefficient of laminar flow was calculated using Maillet Formula (1905) as shown as Formula 2, while the turbulent flow characteristic was calculated using Kullman Formula (1983) as formulated in Formula 3.

$$Q_t = Q_0 \text{ x } e^{-at} \quad \text{...............} (2)$$

where:
Q_t is the discharge at t (m^3/s);
Q_0 is the discharge at the previous t (m^3/s);
e is a constant;
α is a recession constant, and
t is time (h).

$$Q_t = Q_0\,(1\text{-}\beta t) \quad \text{...............} (3)$$

The β coefficient in Formula 3 is calculated using Drogue Formula (1972) in Fiorillo (2014), which is formulated as Formula 4.

$$\beta = \alpha(Q_0^{\,-1/n}) \quad \text{...............} (4)$$

Based on the linear value and recession coefficient of the subregime of flow, Malik (2007) and Malík and Vojtková (2012) made a Karstification Degree Index. It was divided into ten classes of karstification degrees. Class 1 for the lowest degree, discharge recession only consists of laminar flow. Meanwhile, class 10 is the highest degree composed of turbulent flow. Furthermore, the karstification degree is determined based on the high and low values of α (laminar/diffuse flow recession coefficient) and β (turbulent/conduit flow recession coefficient). The karstification degree is then obtained in two ways. The first uses the Formulas 2, 3, and 4 on each single recession curve at fourteen flood events, which were then averaged. Secondly, considering the application of a single recession curve has the disadvantage of varying recession curves in every flood event, a Master Recession Curve (MRC), which is a combination of several single recession curves, then can be done. More specifically, MRC construction can be carried out more accurately through the strip-matching method approach (Rahmawati *et al.*, 2020). In this research, the MRC construction was aided by RC 4.0 software (Gregor and Malik, 2012).

Time Series Analysis

Furthermore, auto-correlation and cross-correlation were used to analyze the time series response of spring discharge to rainfall. The auto-correlation analysis was applied to determine the memory system, and was an indicator of the aquifer storage capacity. Auto-correlation was formulated in Formulas 5 and 6,

$$r(k) = \frac{c(k)}{c(0)} \quad (5)$$

$$C(k) = \frac{1}{n}\sum_{t=1}^{n-k} X_t - \bar{X}) \quad (6)$$

where:
k is the time interval (hours);
n is the time length of the time series;
r(k) is the auto-correlation function;
x_t is discharge at t (m^3/s);
x is the average occurrences (m^3/s).

The high intensity of rainfall in the karst aquifer dominantly has a linear relationship to the increasing spring discharge. This relationship was analyzed using cross-correlation. Rainfall at a certain time is referred to x_t, while discharge at a certain time is referred as y_t. This function is not symmetrical [$r_{xy}(k) \neq r_{yx}(k)$]. If the lag time of rainfall and discharge is longer than 0 (k> 0), then the correlation function is calculated by Formulae 7 and 8:

$$r_{xy}(k) = \frac{C_{xy(k)}}{\sigma_x \sigma_y} \quad (7)$$

$$C_{xy}(k) = \frac{1}{n}\sum_{t=1}^{n-k} (X_t - \bar{x})(Y_{t+k} - \bar{y}) \quad (8)$$

where:
k is the time interval;
n is the time length of series data (number of samples);
$r_{xy}(k)$ is the cross-correlation function;
C_{xy} (k) is the cross-correlogram;
x_t and y_t are the input and output of time series variables; and
σ_x and σ_y are the standard deviations of the time series.

Results and Discussion

Recession Curve and Karstification Degree of Ngerong Spring

Ngerong Spring is a horizontal cave with a width and height of cave mouth of about 7 and 4 m, respectively. It is about 1.8 km in length. The stream of Ngerong Spring is ended at a small lake as an inlet sump. The temporal variation of Ngerong Spring discharge and rainfall is presented in Figure 2.

Water level data recorded for one year (January to December 2014) showed that Ngerong Spring had high discharge fluctuation in the wet periods (January to May 2014), while discharge fluctuations tended to be stable from June to December 2014. The flood period occurred from January 5th to May 16th 2014. During that period, it was recorded twenty-one flood events where (1) lower floods were thirteen events, (2) medium floods were four events, and (3) higher floods were four

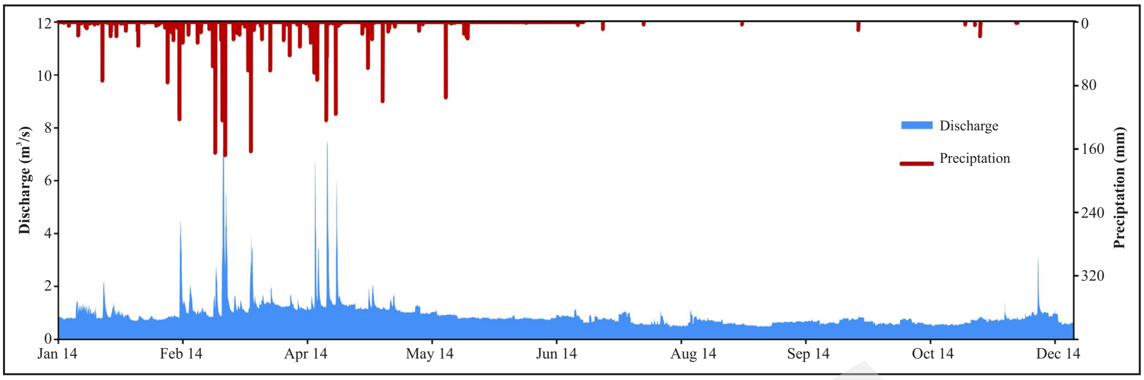

Figure 2. Temporal variation of rainfall and spring discharge.

events. Flood events in a higher discharge did not always have a prolonged recession, because the sequel flood often followed three days after the previous flood. There were only fourteen flood events that had a long period of recession to be analyzed. Those selected flood events represent the lower, medium, and higher floods.

Furthermore, every flood event had different characteristics and shapes of recession- curves. The separation of the subregime coefficient of laminar flow (α) of Formula 1 and the turbulent flow coefficient (β) of Formula 2 is shown in Figure 3. In this study, almost all of the flood recessions had one subregime of laminar flow and one subregime of turbulent flow. Nevertheless, some flood events had different characteristics; there were floods on February 21st, March 9th, March 30th, and April 27th, 2014. They had two subregime of laminar flow and one subregime of turbulent flow. The recession coefficients of laminar flow (α) were shown in Figure 3, ranging from 0.001 to 0.018, while the recession coefficient of turbulent flow (β) ranged from 0.010 to 0.033. The lowest karstification degree is 4.0, characterized by two subregimes of laminar flow, which occurred in a flood recession on March 14th 2014 (the peak discharge of 1.48 m^3/s). The aquifer characteristics at this degree were fissure networks developed irregularly, dominated by open macrofissures, and conduit development could be possible to a certain extent. At certain conditions, turbulent flow occurred in a relatively short time. This mechanism also involves other non-karst rocks, such as a concentrated recharge system with surface runoff from non-karst rock entering through the ponor during the rainy season, as well as a diffused recharge system that drains water from beneath the stratigraphy of Paciran Formation, namely the Mundu and Ngrayong Formations, and flows it into base flow during the dry season. Turbulent flow occurs in a short time, because the response of the springs to rain events is also quite fast, namely 8 hours.

The dominant karstification degrees were 4.3, 4.7, and 5.0, consisting of one laminar and one turbulent flow. Laminar flow was dominantly in groundwater discharge. The aquifer had a network of small open fissures combined with a partly conduit channel system in the phreatic zone. The groundwater recharge at the Ngerong Springs characterizes karst rocks and non-karst; this can be seen from its hydrochemical characteristics. The intensity of the dissolution of carbonate rocks can be reflected through the Mg^{2+}/Ca^{2+} ratio (Setiawan *et al.* 2020). The Mg^{2+}/Ca^{2+} ratio of water samples in the studied area was mainly in the range of 0.06-0.43 (average=0.27), and most of them were below 0.5, indicating that silicate dissolution was also involved in the dissolution of the dominant carbonate rock.

The highest degree of karstification occurred in flood events on February 21st, March 9th, March 30th, and April 27th, 2014, at the value of 5.5, consisting of one turbulent flow and two laminar flows. The effect of the turbulent flow had to be short of the overall groundwater discharge. The aquifer characteristics at this degree were a fis-

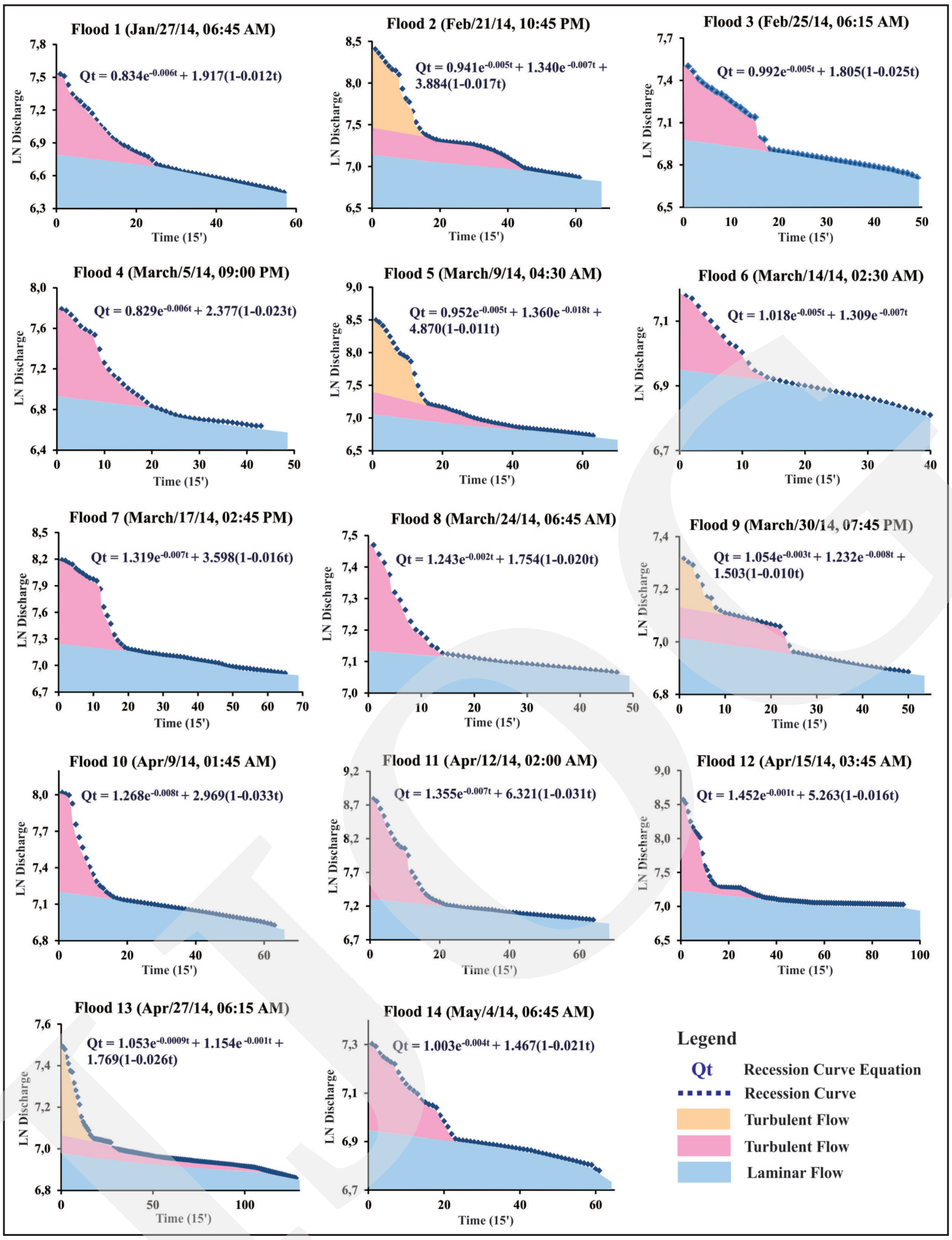

Figure 3. Recession-curve of the selected flood events in Ngerong Spring.

sure in medium sized, and opened in the vadose zone (characterized by the values of α_1) influenced by a conduit channel in the phreatic zone (characterized by the value of β_1). The separation of the laminar flow coefficient (α) and turbulent flow coefficient (β) is shown in Figure 3. They produced a formula for the recession coefficient described in Table 2 to determine the aquifer karstification degree.

Based on the results of the recession formula shown in Table 2, it can be concluded that the aquifer of the Ngerong Spring system has a karstification degree of 4.7, which was characterized by one subregime of laminar flow ($\alpha = 0.005$) and one turbulent flow (β= 0.020). To this degree, it can be described that the aquifer has dense open small fissures in a combination of phreatic conduit system. There are cavities/holes in the vadose zone.

Table 2. Recession-curve Formula and Karstification Degree of Every Flood Recession in Ngerong Spring

No	Flood Events		Recession Curve Equation	Karstification Degree (Dk)
	Date	Time		
1	Jan 27th, 2014	06.45	$Q_t = 0.834e^{-0.006t} + 1.917(1-0.012t)$	4.7
2	Feb 21st, 2014	22.45	$Q_t = 0.941e^{-0.005t} + 1.340e^{-0.007t} + 3.884(1-0.017t)$	5.5
3	Feb 25th, 2014	06.15	$Q_t = 0.992e^{-0.005t} + 1.805(1-0.025t)$	4.7
4	March 5th, 2014	21.00	$Q_t = 0.829e^{-0.006t} + 2.377(1-0.023t)$	4.7
5	March 9th, 2014	04.30	$Q_t = 0.952e^{-0.005t} + 1.360e^{-0.018t} + 4.870(1-0.011t)$	5.5
6	March 14th, 2014	02.30	$Q_t = 1.018e^{-0.005t} + 1.309e^{-0.007t}$	4.0
7	March 17th, 2014	14.45	$Q_t = 1.319e^{-0.007t} + 3.598(1-0.016t)$	5.0
8	March 24th, 2014	06.45	$Q_t = 1.243e^{-0.002t} + 1.754(1-0.020t)$	4.3
9	March 30th, 2014	19.45	$Q_t = 1.054e^{-0.003t} + 1.232e^{-0.008t} + 1.503(1-0.010t)$	5.5
10	April9th, 2014	01.45	$Q_t = 1.268e^{-0.008t} + 2.969(1-0.033t)$	5.0
11	April 12th, 2014	02.00	$Q_t = 1.355e^{-0.007t} + 6.321(1-0.031t)$	5.0
12	April 15th, 2014	03.45	$Q_t = 1.452e^{-0.001t} + 5.263(1-0.016t)$	4.3
13	April 27th, 2014	06.15	$Q_t = 1.053e^{-0.0009t} + 1.154e^{-0.001t} + 1.769(1-0.026t)$	5.5
14	May 4th, 2014	06.45	$Q_t = 1.003e^{-0.004t} + 1.467(1-0.021t)$	4.7
	Average		$\mathbf{Q_t = 1.143e^{-0.005t} + 2.915(1-0.020t)}$	**4.7**

When rain with a high intensity happens, it will be a point recharge where runoff sinks and enters the underground river. The laminar flow dominates the groundwater flow, whereas the turbulent flow occurs only in flood events. The laminar flow comes not only from a thin epikarst zone but also from non-karst rocks that are stratigraphically below it, namely the Ngrayong and Mundu Formations.

Based on the field survey, the karstified aquifer is located in the upper part of the catchment area. A few point recharge dolines characterize it with ponor as the inlet of the underground river network. The upper part of the catchment area is dominated by internal runoff, and there is also allogenic recharge from the outside of carbonate formation, while the lower part is dominated by diffuse system type through cracks or fissures of rocks. This lower part is also fed by quartz sandstone of the Ngrayong Formation, which provides groundwater input with slow movement through soil pores and rock fissures.

Next, the MRC analysis of the Ngerong Spring shows the duality reservoir of releasing its groundwater storage, as presented in Table 3. The equation of Ngerong Spring MRCs consists of one type of linear/laminar reservoir and one type of turbulent flow recession. Figure 4 also shows reservoir modelling results in releasing its storage, which shows that the karst aquifer in the Ngerong Spring has one laminar and one turbulent flow. These results show that the value of Dk= 5 is similar to the calculations using the single recession method (Dk = 4,8).

Hydrologically, at the beginning of the rainy season, the rainwater infiltrated first fills the aquifer storage capacity in soil moisture and the relatively thin epikarst zone, which is about 4-6 m when viewed from the resistivity value (Bappeda, 2003). That water is called new water; it would slowly push the stored water in the aquifer (old water) to the fracture and conduit networks. This condition affected the flood discharge. In this stage, a high flood discharge rarely happens, because the infiltrated rainwater can not fill a total flow of flood. Conversely, in the middle of rainy season, high intensity of rainfall within a certain period would expedite the process of flushing water in aquifers. The old water would quickly push out with new

Table 3. Duality of Flow Regime in Ngerong Spring

Spring	Sub-regime 1	Q_0*	K**	Sub-regime 2	Q_0	k	Dk
Ngerong	Laminar reservoir	2200	0.0081	Turbulent flow model	4350	0.019	5.0

*Initial discharge ** Recession constant

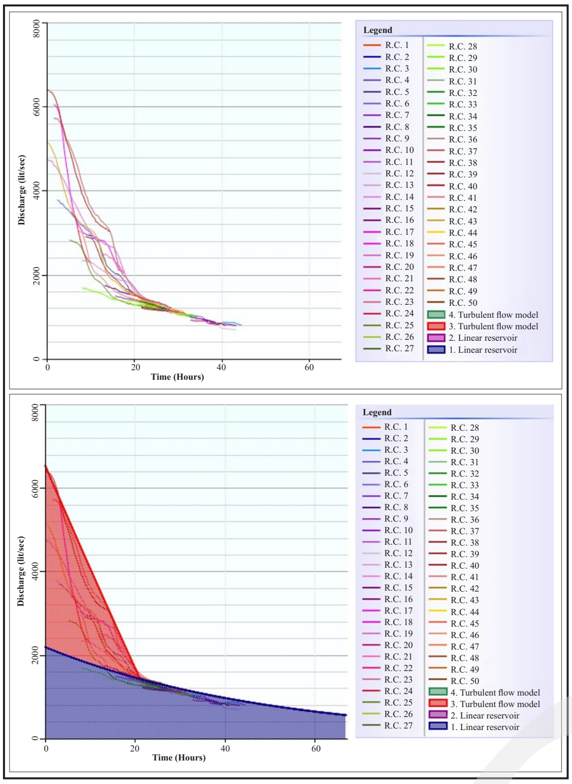

Figure 4. (a) Recession curve during the measurement period, and (b) Reservoir modeling results at the Ngerong Spring.

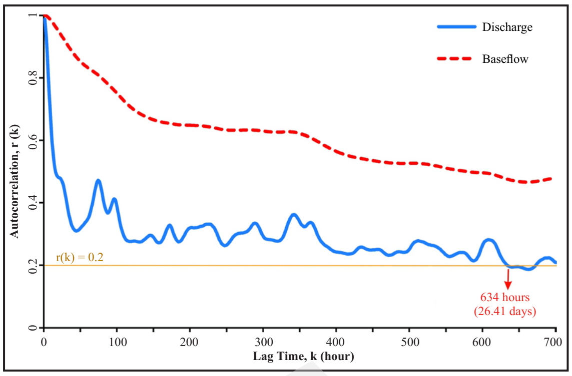

Figure 5. Auto-correlation graph of discharge and base flow of Ngerong Spring.

water (piston effect). This diffuse recharge system would not cause a high discharge of flood if it was not supported by the recharge from doline and ponor/sinkholes in the catchment area.

Time Series (Auto-correlation and Cross-correlation) Analysis

The auto-correlation result of Ngerong Spring shown in Figure 5 was a decreased graph that was unstable, and two parts could be distinguished. The first part of the graph downed rapidly within two days, then the second part decreased and slowly fluctuated until it reached the $r_x(k)= 0.2$ after 634 hours or 26.41 days. Two characters from this auto-correlation function indicated the duality of karst aquifers. The first part was much influenced by a quick flow that flowed rapidly through the conduit network. While the second part resulted from a smaller conduit shaft and fractured as a result of the flow system in the long term.

The form of the correlogram of Ngerong Spring fluctuated and was unstable. The high frequency of rain events was heavily influenced by diffuse-type (slow flow) recharge ratio and internal runoff. In this period, the higher frequency of flood events also resulted in a steeper decline in the correlogram graph. (Grasso and Jeannin 1994 in Kresic and Stevanovic, 2010; Eisenlohr *et al.*, 1997). The frequency of rain events in the Ngerong Spring system recharge area was very high in the wet-month period, adding to the nature of recharge, which was dominant when the flood events were dominated by internal runoff through ponor/sinkholes. Several hours after the high-intensity rainfall, the internal runoff ratio is greater than the diffuse ratio. Thus, this condition affected correlogram graph fluctuations up and down and still unstable.

This discharge correlogram differed from the baseflow correlogram, which decreased slowly and gradually. The decline lasted for a long time (more than three months). This fact showed that the aquifer system would take out the baseflow throughout the year, even in prolonged drought conditions. The auto-correlation function of discharge and baseflow reflected the memory system of the karst aquifer. The longer rx(k) value indicated the greater capacity of the aquifer. Mangin (2013) classified the memory system of a karst aquifer in southern Europe into four degrees, the smallest memory systems (<5 days); the small memory systems (10-15 days); the large memory systems (50-60 days); and the largest memory systems (70 days). Based on the classification, it was known that the aquifer memory system of

Ngerong Spring recharge area was categorized as the extensive memory system for 26.41 days.

The cross-correlation function demonstrated the r_{xy} (k) positive value, indicating that the rainfall events affected the spring discharge. The value of r_{xy} (k) was small, namely, 0.34, which characterized that the average rainfall event which occurred in the recharge area was significantly reduced when entering the aquifer system. It took a long time to reach the groundwater level when it was infiltrated through the unsaturated zone. This condition indicated that the degree of karstification was medium, and the aquifer storage capacity was large. On the other hand, the aquifer system of Ngerong Spring has a quick response to rainfall events; it was illustrated by the graph, which highly increased (Figure 6). The spring discharge responses to the rainfall events were 8 hours. During that time, the infiltration of rainwater into the rock mass through primary and secondary porosity, while pressure pulse rapidly flowed through the conduit void with the recharge characteristics as internal runoff through the ponor/sinkholes in the upper part of Ngerong Spring recharge area.

The rainfall heavily influences flood events in Ngerong Spring in the previous periods. It could be seen from the second peak of the correlogram that the value of r_{xy} (k) is 0.12 within 83 hours (3.45 days). The examples of the flood on February 21st, 2014, with an average rainfall of 105 mm/hour (peak flood discharge of 4.4 m^3/s), influenced the next flood on February 24th, 2014, which had a rainfall intensity of only about 11.4 mm/hour (discharge peak 2 m^3/s). Flood on April 11th, 2014, with an average rainfall of 150 mm/hour (peak discharge of 3.4 m^3/s), also affected the flood on April 14th, with 83 mm/hour rainfall intensity (discharge peak of 7.5 m^3/s). In general, it became a figure that rainfall, infiltrated into the aquifer, had a quick response within 8 hours, and contributed to the flood events within 3 to 6 days.

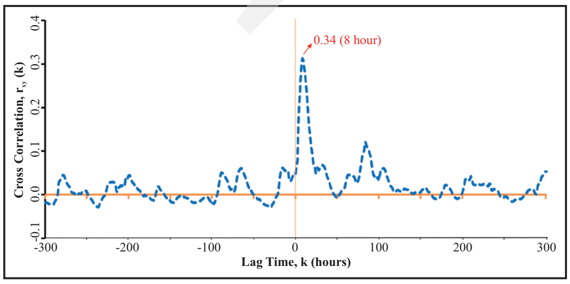

Figure 6. Cross-correlation graph of discharge and rainfall events in the Ngerong Spring.

The rainfall in the upper part of the recharge area had significant contributions compared with the rainfall which occurred downstream. In the upstream recharge area, there appeared topography karst, and more prominently, there found many ponors and dolines. On the other hand, rainfall in the downstream catchment area has a low effect on the increasing Ngerong Spring discharge (indicated by a r_{xy}(k) value of 0.24). This phenomenon is because most rainwater will become an overland flow, with only a small portion inputting the conduit system. Field observations support this fact: when rainfall occurs in the downstream catchment area, the discharge increase is insignificant, and the water in the springs remains clear. The lithological conditions of the rocks in the upstream catchment area with the anticlinorium system can have an impact on the hydrogeologically of transfer mechanism between the aquifer and the underlying rocks in the Ngerong Spring catchment area, especially in the upstream part of Paciran Formation surface with karst topography in the form of ponor and doline receiving input in the form of point recharge from quartz sandstone (Ngrayong Formation) and affects increasing flood discharge. In contrast, at the bottom of the underground water system, the Ngrayong Formation moves diffusely through the soil pores with the laminar flow, which provides input to the stability of the Ngerong Spring during the dry season.

Comparison with Some Karst Sites in Java Island

To see the difference between the karst aquifer conditions of the Ngerong Springs (Rengel Karst) with other springs in Java, Table 4 shows a summary of the reservoir conditions, karstification

Table 4. Comparison of Karst Aquifer Characteristic Parameters at Several Karst Sites in Java Island

Karst site	Name of the springs	Karstification degree		Time series analysis	
		Reservoir condition	Dk	Time to peak-T_{lag} (hour)	Diffuse flow duration (hour)
Gunungsewu	Pindul*	1 laminar ; 2 turbulent	8.0	1.75	6.75
	Kakap**	1 laminar ; 2 turbulent	8.0	5.00	16.00
Gombong	Kalisirah***	1 laminar ; 2 turbulent	8.0	0.75	>125.00
Jonggrangan	Mudal****	1 laminar; 2 turbulent (low β values)	5.5	3.75	150.00
	Kiskendo****	1 laminar; 2 turbulent (low β values)	5.5	4.25	90.00
Rembang	Sumbersewu*****	2 laminar ; 1 turbulen	5.0	4.50	15.00
Rengel	Ngerong	1 laminar ; 1 turbulent	4.8-5.0	8.00	634.00

after: *Nurkholis *et al.* (2019), **Fatchurohman *et al.* (2018),***Rahmawati *et al.* (2020),****Kurniawan *et al.* (2019), *****Dewantara and Adji (2019).

degree, and the results of time series analysis (cross-correlation and auto-correlation) on several karst areas on the island of Java.

Table 4 shows that the Ngerong Spring has the lowest karstification degree value (4.8 - 5.0), with the groundwater released from its storage in the form of two laminar flows and one turbulent flow. The degree of karstification in the Ngerong Spring is slightly lower than that found in the Sumbersewu Spring in Rembang Karst (5.0). This fact shows that the two regions (Rengel and Rembang Karsts), located in the northern region of Java Island, also have similar karst development levels. Meanwhile, the Gombong and Gunungsewu Karst areas have a much more developed aquifer development level (Dk= 8, with two turbulent reservoirs). In contrast, Jonggrangan aquifer karst area is slightly more developed (Dk= 5.5, with two turbulent reservoirs) than Rengel Karst.

Additionally, in terms of time series analysis, as a spring located in young karst (Rengel Karst--low Dk), the Ngerong Spring shows T_{lag} (the interval between the onset of rain and the peak of flooding), which is the most prolonged (8 hours). The Ngerong Spring also had the longest baseflow discharge time (634 hours/26.42 days). These characteristics indicate that the aquifer in the Ngerong Spring has the best capacity for storing groundwater compared to other springs in the karst region of Java Island. Ngerong Spring catchment area has a thin epikarst layer, so the storage capacity in the catchment area apart from the epikarst is also from the underlying sediments, namely quartz sandstone of the Ngrayong Formation. This fact also indicates that although the aquifer in Ngerong Spring has developed conduit-sized voids, its dominance is still controlled by diffuse voids, which take a long time to store and are slow to release their groundwater storage.

Conclusions

The spring discharge hydrograph recession curve can be used as an initial parameter to determine the karst aquifer level of development by calculating the degree of karstification (Dk). The calculation of Dk with MRC construction shows that the karst aquifer recharging Ngerong Spring has a reservoir containing one laminar flow and one turbulent flow resulting in a value of Dk= 4.8. The aquifer in Ngerong Spring has anticipated the existence of a crushed water-bearing zone (*e.g.* fault zone) or a dense network of small open fissures in combination with a simple, partly (or occasionally) phreatic conduit system of considerable extent (*e.g.* with an open karstified fault in the vadose zone). In this case, the aquifer system in Ngerong Spring is classified as young karst and merokarsts with a rare eksokarst appearance, even though they already have similar hydrogeological conditions to other karst areas. Meanwhile, compared with the Dk value at several karst sites in Java, Rengel Karst aquifer development level is among the lowest. Hydrodynamic conditions, release properties from karst aquifer storage, and memory capacity can be identified with a time series approach. This approachment is statistically capable of characterizing duality properties in karst aquifers, including a slow flow discharge system (diffuse flow), which recharges a spring, and a quick flow discharge system (conduit flow) in a concentrated stream. Both types of flow release can quickly occur after rainfall with high concentrations (approached by cross-correlation) or slow flow that flows continuously throughout the year (approached by auto-correlation). The results of time series analysis (cross-correlation) show that the Ngerong Spring has a quick flow T-lag of about 8 hours (the slowest compared to other karst springs in Java). Meanwhile, auto-correlation analysis at the Ngerong Spring shows a slow flow release time (634 hours or 26.41 days), which indicates that the aquifer recharging this spring is dominated by small voids (diffuse). This condition is the best for storing groundwater when compared to that found in other karst sites on the island of Java. Here, due to the relatively rapid response of the springs to rainfall and a large amount of base flow and memory effects, the aquifer system in Ngerong Spring may be categorized as an intermediate karst system. In the future, the calculation results of this study need to be confirmed by a further research with a longer and spatially wider scale of recording flow and rain data (other than the Ngerong Spring only). Another point that needs to be emphasized is that the time series analysis is a statistical-based method. Consequently, the results may not reflect the actual physical function of the karst hydrological system of Ngerong Spring. Therefore, several other approaches still need to be conducted in Rengel Karst, such as speleological surveys, artificial tracer tests, and hydrogeochemical investigations.

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References

Adji, T.N., Haryono, E., Mujib, A., Fatchurohman, H., and Bahtiar, I.Y., 2019. Assessment of aquifer karstification degree in some karst sites on Java Island, Indonesia, *Carbonates and Evaporites*, 34, p.53-66. Springer Berlin Heidelberg, DOI:10.1007/s13146-017-0403-0

Bemmelen, R.W., 1949. *The Geology of Indonesia. General Geology of Indonesia and Adjacent Archipelagoes,* Government Printing Office, The Hague, 545-547-562.

Bappeda (Tuban Regency Regional Development Planning Agency and Geological Research and Development Centre). 2003. *Final report: Compilation of study and identification of water and groundwater vulnerable areas in Tuban District*. Bandung: Puslitbang Geologi

Bonacci, O., 1992. Karst springs hydrographs as indicators of karst aquifers. *Hydrological Sciences Journal*, 38, p.51-62. DOI: 10.1080/02626669309492639

Dewantara, B.P. and Adji, T.N., 2019. Pendekatan Respon Debit-Curah Hujan Untuk Karakterisasi Akuifer Karst di Mataair Sumbersewu, Rembang. *Jurnal Bumi Indonesia*, 8, p.1-11

Dreybrodt, W., 1988. *Processes in karst systems: physics, chemistry, and geology*, Springer, Berlin, p.140-182.

Eckhardt, K., 2004. How to construct recursive digital filters for baseflow separation. *Hydrological Processes,* 19, p.507-515. DOI: 10.1002/hyp.5675

Eisenlohr, L., Bouzelboudjen, M., Király, L., and Rossier, Y., 1997. Numerical versus statistical modelling of natural response of a karst hydrogeological system. *Journal of Hydrology*, 202 (1-4), p.244-262. DOI: 10.1016/S0022-1694(97)00069-3

Fatchurohman, H., Adji, T.N., Haryono, E.,and Wijayanti, P., 2018. Baseflow index assessment and master recession curve analysis for karst water management in Kakap Spring, Gunung Sewu. *IOP Conference Series: Earth and Environmental Science,* 148, 012029. DOI:10.1088/1755-1315/148/1/012029.

Fiorillo, F., 2014. The Recession of Spring Hydrographs, Focused on Karst Aquifers. *Water Resources Management*, 28. p.1781-1805. DOI: 10.1007/s11269-014-0597-z

Fiorillo, F. and Doglioni, A., 2010. The relation between karst spring discharge and rainfall by cross-correlation analysis (Campania, Southern Italy). *Hydrogeology Journal*, 18, p.1881-1895. DOI: 10.1007/s10040-010-0666-1

Ford, D. and Williams, P., 2007. *Karst Hydrogeology and Geomorphology*. Chicester, West Sussex: John Wiley & Sons Ltd. p.103-140.

Gregor, M. and Malik, P., 2012. *RC 4.0 User's manual : hydro office software for water science*. Bratislava, Slovakia.

Haryono, E., 2008. *Model perkembangan karst berdasarkan morfometri jaringan lembah di Karangbolong, Gunungsewu, Blambangan dan Rengel.* Disertasi, Program Pascasarjana Fakultas Geografi, Universitas Gadjah Mada (Unpublished)

Haryono, E., Suratman, W., Sriyono, and Soenarso, S., 2001. *Pemetaan zonasi kawasan karst di Jawa Timur bagian utara (Kabupaten Tuban)*, Yogyakarta.

Kiraly, L., 2002. Karstification and groundwater flow; Evolution of karst; from prekarst to cessation. *Proceedings of Evolution of karst; from prekarst to cessation, Postojna*.

Kovács, A., Perrochet, P., Király, L., and Jeannin, P.Y., 2005. A quantitative method for the characterization of karst aquifers based on spring hydrograph analysis. *Journal of Hydrology*, 303 (1-4), p.152-164. DOI: 10.1016/j.jhydrol.2004.08.023

Kresic, N. and Bonacci, O., 2010. Spring discharge hydrograph. *Groundwater Hydrology of Springs*, p.129-163. DOI: 10.1016/B978-1-85617-502-9.00004-9

Kresic, N. and Stevanovic, Z., 2010. *Groundwater Hydrology of Springs: engineering, theory, management, and sustainability*. Butterworth-Heinemann, Oxford.

Kullman, E., 1983. Rezˇim podzemny´ch voˆds turbulentny´m pru´denı´mv puklinovo-krasovom horninovom prostredı´. Groundwater regime with turbulent flow in fissure-karst rock environment (in Slovak)]. Geologicky´ u´stav Diony´za Sˇtura, Bratislava. *Geologicke´ pra´ce,* 79, p.237-262.

Kurniawan, I.A., Adji, T.N., Nurkholis, A., Haryono, E., Fatoni, H., Waskito, W.A., Cahyadi, A., and Agniy, R.F., 2019. Karst aquifer response by time series analysis applications in Jonggrangan Karst, Java Island, Indonesia. *Environmental Earth Sciences*, 78 (379). DOI: 10.1007/s12665-019-8386-x

Larocque, M., Mangin, A., Razack, M., and Banton, O., 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). *Journal of Hydrology*, 205 (3-4), p.217-231. DOI: 10.1016/S0022-1694(97)00155-8

Liu, L., Chen, X., Xu, G., and Shu, L., 2011. Use of hydrologic time-series data for identification of hydrodynamic function and behavior in a karstic water system in China. *Hydrogeology Journal*, 19, p.1577-1585. DOI: 10.1007/s10040-011-0774-6

Mahdid, S., Chabour, N., Debieche, T.H., Drouiche, A., and Pistre, S., 2022. Robustness of DRASTIC Method for Groundwater Vulnerability Case of Wadi Nil Aquifer in Jijel, NE Algeria. *Indonesian Journal on Geoscience,* 9 (2), p.229-246. DOI: 10.17014/ijog.9.2.229-246

Maillet, E., 1905. *Essais D'hydraulique Souterraine Et Fluviale.* Herman Paris.

Malik, P., 2007. Assessment of regional karstification degree and groundwater sensitivity to pollution using hydrograph analysis in the Velka Fatra Mountains, Slovakia. *Environmental Geology*, 51, p.707-711. DOI: 10.1007/s00254-006-0384-0

Malík, P., Švasta, J., Bajtoš, P., and Gregor, M., 2021. Discharge recession patterns of karstic springs as observed in Triassic carbonate aquifers of Slovakia. *Hydrogeology Journal*, 29, p.397-427. DOI: 10.1007/s10040-020-02276-x

Malík, P. and Vojtková, S., 2010. Use of combined recession curves analyses of neighbouring karstic springs to reveal karstification degree of groundwater springing routes. *Environmental Earth Sciences*, p.101-106. DOI: 10.1007/978-3-642-12486-0

Malík, P. and Vojtková, S., 2012. Use of recession-curve analysis for estimation of karstification degree and its application in assessing overflow/underflow conditions in closely spaced karstic springs. *Environmental Earth Sciences*, *65*, 2245-2257.

Mangin, A., 1984a. Pour une meilleure connaissance des systèmes hydrologiques à partir des analyses corrélatoire et spectrale. *Journal of Hydrology*, 67 (1-4), p.25-43. DOI: 10.1016/0022-1694(84)90230-0

Mangin, A., 1984b. The use of autocorrelation and spectral analyses to obtain a better understanding of hydrological systems. *Journal of Hydrology*, 67, p.25-43.

Mangin, A., 2013. Karst Hydrogeology. *Groundwater Ecology*, p.43-67.

Mohammadi, Z. and Shoja, A., 2014. Effect of annual rainfall amount on characteristics of karst spring hydrograph. *Carbonates and Evaporites*, 29, p.279-289. DOI: 10.1007/s13146-013-0175-0

Mujib, M.A., 2015. *Analisis Karakteristik dan Tingkat Karstifikasi Akuifer Karst di Sistem Mataair Ngerong, Kecamatan Rengel, Kabupaten Tuban,* Thesis Faculty of Geography, Universitas Gadjah Mada.

Mujib, M.A., Adji, T.N., Suma, N.N., Ikhsan, F.A., and Indartin, T.R.D., 2020. The quality and usability of spring water for irrigation (case study: Ngerong Spring, Rengel Karst, Tuban, East Java). *IOP Conference Series: Earth and Environmental Science*, 485 (012025). DOI: 10.1088/1755-1315/485/1/012025

Nguyet, V.T.M. and Goldscheider, N., 2006. Tracer tests, hydrochemical and microbiological investigations as a basis for groundwater protection in a remote tropical mountainous karst area, Vietnam. *Hydrogeology Journal*, 14, p.1147-1159. DOI: 10.1007/s10040-006-0038-z

Noya, Y., Suwarti, T., Suharsono, and Sarmili, L., 1992. *Geological map of The Mojokerto Quadrangle, Jawa*, scale 1: 100.000 Bandung, Indonesia.

Nurkholis, A., Adji, T.N., Haryono, E., Cahyadi, A., and Suprayogi, S., 2019. Time series analysis application for karst aquifer characterization in Pindul Cave Karst system, Indonesia. *Acta Carsologica*, 48, p.69-84. DOI: 10.3986/ac.v48i1.6745

Padilla, A. and Pulido-Bosch, A., 1995. Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. *Journal of Hydrology*, 168, p.73-89. DOI: 10.1016/0022-1694(94)02648-U

Panagopoulos, G. and Lambrakis, N., 2006. The contribution of time series analysis to the study of the hydrodynamic characteristics of the karst systems: Application on two typical karst aquifers of Greece (Trifilia, Almyros Crete). *Journal of Hydrology*, 329, p.368-376. DOI: 10.1016/j.jhydrol.2006.02.023

Premonowati, Koesoemadinata, R.P., and Pringgoprawiro, H., 2004. Stratigrafi Isotop Oksigen dan Karbon dari Formasi Paciran Jawa Timur. *Seminar Geologi Nuklir dan Sumberdaya Tambang*, Jakarta: Pusat Pengembangan Bahan Galian dan Geologi Nuklir-BATAN, p.208-219.

Putranto, T. T., Winarno, T., and Susanta, A.P.A., 2020. Risk Assessment of Groundwater Abstraction Vulnerability Using Spatial Analysis: Case Study at Salatiga Groundwater Basin, Indonesia. *Indonesian Journal on Geoscience*, 7 (2), p. 215-224. DOI: 10.17014/ijog.7.2.215-224

Quinlan, J.F., 1989. *Ground-Water Monitoring in karst terranes: Recommended Protocol and Implicit Assumptions*. EPA 600/X-, Las Vegas, Nevada: US. Environmetal Production Agency.

Quinlan, J.F., Smart, P.L., Schindel, G.M., JR., E.C.A., Edwards, A.J., and Smith, A.R., 1991. Recommended administrative/regulatory definitions of karst aquifer, Principles for classification of carbonate aquifers, Practical evaluation of vulnerability of karst aquifers and determination of optimum sampling frequency at springs. *Hydrology, Ecology, Monitoring and Management of Ground Water in Karst Terranes Conference, 3rd*, p.573-635.

Rahmawati, A.I., Priambada, A.P., Al-Ghozali, M.Q., Fauzi, D.R., Adji, T.N., Setyawan, A., Mahrizkhal, D.S., Agniy, R.F., Nurkholis, A., Cahyadi, A., Astuti, E.S., and Haryono, E., 2020. Master Recession Curve (MRC) analysis to characterize karst aquifers of several springs in the north side of the Karangbolong (Gombong) karst area. *E3S Web of Conferences*. DOI: 10.1051/e3sconf/202020204002.

Rahnemaei, M., Zare, M., Nematollahi, A.R., and Sedghi, H., 2005. Application of spectral analysis of daily water level and spring discharge hydrographs data for comparing physical characteristics of karstic aquifers. *Journal of Hydrology*, 311 (1-4), p.106-116. DOI: 10.1016/j.jhydrol.2005.01.011

Rashed, K.A., 2012. Assessing Degree of Karstification: a New Method of Classifying Karst Aquifers 1 Background. *Sixteenth International Water Technology Conference*, p.1-9.

Setiawan. T., Alam, BYCSS., Haryono, E., and Hendarmawan., 2020. Hydrochemical and Environmental Isotopes Analysis for Characterizing a Complex Karst Hydrogeological System of Watuputih Area, Rembang, Central Java, Indonesia. *Hydrogeology Journal,* 28, p.1635-1659. DOI: 10.1007/s10040-020-02128-8

Smart, P.L. and Hobbes, S.L., 1986. Characteristics of Carbonate Aquifers: A conceptual basis. *Proceedings, Environmental Problem in Karst Terrains and Their Solution*. Bowling Green, KY: National Well Water Association, p.1-4.

Suhendar, R., Hadian, M.S.D., Muljana, B., Setiawan, T., and Hendarmawan, H., 2020. Geochemical evolution and groundwater flow system in batujajar groundwater basin area, west java, Indonesia. *Indonesian Journal on Geoscience*, 7 (1). DOI: 10.17014/ijog.7.1.87-10

Susilohadi, 1995. *Late Tertiary and Quaternary Geology of the East Java Basin, Indonesia*, University of Wollongong.

Valdes, D., Dupont, J.P., Massei, N., Laignel, B.T, and Rodet, J., 2006. Investigation of karst hydrodynamics and organization using autocorrelations and T-ΔC curves. *Journal of Hydrology*, 329 (3-4), p.432-443. DOI: 10.1016/j.jhydrol.2006.02.030

White, W.B., 2002. Karst Hydrology: Recent Developments and Open Question. *Engineering Geology*, 65, p.85-105. DOI: 10.1016/S0013-7952(01)00116-8

Zhang, Z., Chen, X., Chen, X., and Shi, P., 2013. Quantifying time lag of epikarst-spring hydrograph response to rainfall using correlation and spectral analyses.*Hydrogeology Journal*, 21, p.1619-1631. DOI: 10.1007/s10040-013-1041-9

Zhu, X., Zhu, D., Zhang, Y., and Lynch, E.M., 2013. Tower Karst and Cone Karst, *Treatise on Geomorphology*, p.327-340. DOI: 10.1016/B978-0-12-374739-6.00141-X