Analysis of Master Recession Curve (MRC) and flood hydrograph components for karstification degree estimation in Kiskendo Cave, Jonggrangan Karst System, Indonesia

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Abstract. Karst that has triple porosity makes the characterization of the aquifer becomes challenging to conduct. Hydrograph analysis is a standard method that commonly used for the characterization. It is considered capable of reflecting the natural characteristics of karst aquifer. This research was conducted in Kiskendo Cave which is part of Jonggrangan Karst, Kulonprogo Regency, Java, Indonesia. Kiskendo Cave is a tourist area that continues to be developed. On the other hands, this location has underground rivers that are utilized by the community to meet their domestic needs. Therefore, karst aquifer characterization is essential to do to support karst water management efforts in its catchment area. This study aims to apply the Master Recession Curve (MRC) to know the degree of karstification in the catchment area of Kiskendo. MRC was developed to calculate the degree of karstification and the analysis of hydrograph flow components was carried out to support the calculation. The data used in this study is the underground river discharge recorded every 30 minutes at the time interval between 23 October 2017 and 16 May 2018. The results show that the karst aquifer in the catchment area of Kiskendo Cave has a complex discharge regime with the degree of karstification 5.5. The complexity is confirmed by the type of conduit, fissure, and diffuse flows, which visible on the MRC calculations. Meanwhile, the analysis of the hydrograph component of flood strengthens the result of calculation of karstification degree, i.e., the time to peak (Tₚ) is relatively fast(2.5 hours) compared to Petoyan Spring (6 hours) which is recharged by diffuse type karst aquifer. This value shows the existence of conduit flow that fills the underground river during rainfall. Time to the baseflow calculation (Tₜ) both manually (flood hydrograph analysis) and automatic (MRC) has 40 hours in average which reflects that karst aquifer. This value shows that the channel is still useful in storing diffuse groundwater. Overall, karst aquifers in the catchment area of Kiskendo Cave are still dominated by diffuse-type voids, although it also has sufficiently developed conduit-type voids.

1. Introduction
The karstic aquifer has the characteristic of triple-porosity which causes several methods to characterize its aquifer properties, such as Darcy's methods, to be inaccurate [1]. A standard method used to perform karst aquifer characterization is the flow hydrograph analysis at karst system outlets or springs [2]. According to [3], this analysis may reflect the characteristics of the karst aquifer in releasing its flow and indirectly being able to identify its void development rate (conduit, fissure, diffuse). A review of several methods for flow hydrograph analysis of a karst spring has been performed by [4] which includes calculation of recessionary constants, time series analysis, and flow duration curve analysis.
Previously, the use of recession constants in the field of hydrology has been much improved. The calculation of the recession constant manually using the graph is first performed by [5], which separates the flow hydrograph recession curve into three runoff components, i.e., overland flow, interflow, and baseflow. The concept is further used by [6-10] to calculate the conduit flow recession constant, fissure, and diffuse in karstic aquifers. The studies used the concept of a single recession curve with a simple exponential form (1) as described by [11]. Some research suggests that simple exponential form equations oversimplify the actual conditions. [12] conveys some equations for calculating recession curves. Then, simple exponential form and linear turbulent models or combinations are the most commonly used methods.

The use of a single recession curve has the common problem of recession variation in each different flood event. Therefore, the making of Master Recession Curve (MRC) which is a combination of several single recession curves is done to overcome the problem. In general, MRC can be made by matching strip method [13] or correlation method [14]. [15] conducted a study showing that the matching strip method was more accurate than the correlation method. [16] making MRC automatically with digital computation showing computational calculation results having a 74% confidence level. Meanwhile, research by [17] shows that a single recession curve and MRC are equally accurate when used to identify the flow type in a flood hydrograph.

One of the MRC applications on karst characterization aquifers is to know its karstification degree. [18] first made a classification of the karst degree of a karstic aquifer. Furthermore, [19] modified the classification to analyze the sensitivity of groundwater to the pollutant karst. [20] calculated the degree of karstic aquifer karstification to analyze the catchment area of two adjacent springs. In Indonesia, the application of calculation of the degree of karstification is conducted by [21, 22] in Gunungsewu karst, Gunungkidul Regency and [23] in South of Karst Rengel, Tuban Regency (both on Java Island).

This research was conducted in Kiskendo Cave which is included in karst Jonggrangan area, Kulonprogro Regency, Java Island. Kiskendo Cave is used as a tourist attraction characterized by the presence of managers and tourism facilities [24]. Naturally, the Kiskendo Cave has an underground river which subsequently comes out as a river of resurgence on the Sumitro Cave [25-27]. Water that comes out in Sumitro Cave is used by the community to fulfill their daily domestic needs. This study aims to apply the Master Recession Curve (MRC) to know the degree of karstification in the catchment area of Kiskendo Cave. As there has been no study of karst aquifer characterization in this area, hydrograph monitoring of underground river basins and the determination of karstification degree is an essential preliminary study to be done concerning karst aquifer management in the Kiskendo Catchment Area.

2. Site Description
The Kiskendo Cave is part of the Karst Jonggrangan area which is physiographically located in the Kulonprogro Mountains (Figure 1) [28]. A complicated process forms the Kulonprogro Mountains, namely volcanism, drowning, and the most recent being up-doming [29]. Jonggrangan Formation is composed of the conglomerate, marl, tuff, and sandy sandstone with lignite inserts on the bottom. Limestone reef composes the top of this formation. According to [30], limestones in Jonggrangan Formation are deposited in the phase of sea shrinkage in the tidal zone environment to the open ocean. The limestone deposition occurs above the Old Andesite Formation.

Research by [27] shows that the karst system Kiskendo-Soemitro has upstream in the western part of the Kiskendo Cave entrance and flows towards the Soemitro Cave (Figure 1). Several sinkholes with a depth of 10 - 40 meters recharge this system. Furthermore, the underground river from the Kiskendo Cave exits on the Soemitro Cave which is the final outlet of this karst system. The total length of the karst system Kiskendo - Soemitro is 1.94 km.

3. The Methods
The water level data on the underground river of Kiskendo Cave is recorded from 23 October 2017 to 16 May 2018 with a time interval of 30 minutes, using the Automatic Water Level Logger (Hobo U-30) instrument. Discharge measurements for the stage-discharge rating curve and flow hydrograph were performed eight times with the velocity-area method. Furthermore, the analysis of the flood
hydrograph component and the calculation of MRC to determine the degree of karstification was performed on the flow hydrograph during the recording period. A description of MRC and flood hydrograph components is presented in the following sub-chapters.

Figure 1. Geological setting and Kiskendo-Soemitro Karst System (after [26, 27])
3.1. Master Recession Curve (MRC) and Karstification Degrees of Kiskendo Cave

The development of digital computing in today’s era calculates MRC can be conducted automatically. [31] have implemented the visual basic program to calculate MRC by matching strip method automatically. This study calculated MRC by matching strip method using RC 4.0 software [32]. This software is classified as user-friendly and can calculate MRC in full-automatic or semi-automatic (matching strip method).

In this study, MRC was constructed using two recession equations, which are simple exponential (1) for laminar flow type (diffuse flow) and turbulent linear (2) for turbulent flow type. According to [20], flood events can consist of several laminar and turbulent flows as presented in Figure 2. Furthermore, the existence of laminar or turbulent flow types on the recession curve is used to determine the degree of karstification. The degree of karstification consists of ten classes that show the most developed karst [19].

\[
Q_t = Q_0 e^{-\alpha t} \quad (1)
\]
\[
Q_t = Q_0 (1 - \beta t) \quad (2)
\]

Figure 2. Example of MRC which contains 2 flow type of exponential and linear[20,21]

Figure 3. Example of flood hydrograph [34]
3.2. Flood Hydrograph Characteristics

Flood hydrograph is shaped like a right-leaning bell and consists of several components, time lag \((T_{\text{lag}})\), peak discharge \((Q_p)\), and time to baseflow \((T_b)\) (Figure 3). Flood hydrograph can be used as an indicator in karst aquifer characterization because its shape or component reflects the condition of its catchment area, the size of the water storage in the aquifer, and it is release properties when filling the springs [33]. For example, [34] using a flood hydrograph analysis to perform aquifer characterization in the Pindul Cave Karst System (in Gunungsewu Karst). This research will calculate \(T_{\text{lag}}, Q_p,\) and \(T_b\) on every flood incident occurring in Kiskendo Cave. \(T_{\text{lag}}\) is the duration between the peak of the rainfall to peak discharge \((Q_p)\), \(Q_p\) is the peak discharge of flood events, and \(T_b\) is the duration from \(Q_p\) to baseflow.

4. Result and Discussion

4.1. Hydrograph and Flood Characteristics of Kiskendo Cave

The relationship between the discharge and the water level leads to a stage-discharge rating curve as shown in Figure 4. The rating curve has the formula (3) with \(R^2\) being 0.89. Furthermore, hydrographs during the period of 23 October 2017 to 16 May 2018 are presented in Figure 5. The rainy season is characterized by the presence of flood hydrographs occurring from October 2017 to March 2018, while the dry season began in April. Meanwhile, the discharge in the dry season ranges from 500 liters/second which has increased to about 1000 liters/second in the rainy season. The flood that occurred on 27 November 2017 was an extreme event caused by Cempaka Tropical Cyclone. Therefore, the incidence was not used in the analysis of this study. The peak discharge on the occurrence of tropical cyclone Cempaka reaches about 8000 liters/second.

\[
Q = 2174.8H - 950.3
\]  

(3)

![Figure 4. Stage-discharge rating curve of Kiskendo Cave](image-url)
Analysis of the flood hydrograph component was carried out on six flood events. Not all flood events can be computed since the analysis can only be performed on a single-peak flood hydrograph. Table 1 presents the results of calculations $T_p$, $Q_p$, and $T_b$ in Kiskendo Cave, with average $T_p=2.5$ hours; $Q_p=1,649$ liters/second; and $T_b=40$ hours.

Comparison of the calculations of the flood hydrograph components with other locations (Pindul Cave, Gilap Cave, and Petoyan Spring) is presented in Table 2. Pindul Cave is an outlet of a developing karst system characterized by inputs originating from sinking streams and cave systems [34]. Gilap Cave is upstream of the Bribin karst system that dominates fissure voids [7]. Meanwhile, Petoyan is a karst spring that is still dominated by diffuse voids [9]. The Kiskendo cave is classified as having a large $Q_p$ and a fast $T_p$ which is almost identical to the characteristics of Pindul Cave. This condition reflects the development of the type of conduit voids in karst systems that recharge the Kiskendo Cave. Meanwhile, the value of $T_b$ in Gua Kiskendo has a relatively slow value (40 hours) which is almost the same as Petoyan Spring though with a much larger $Q_p$. This slow $T_b$ characterizes the karst aquifer which recharges the Kiskendo Cave is still good at storing diffuse groundwater.

Table 1. Characteristics of flood hydrograph component in Kiskendo Cave

| Date    | Time  | $T_p$ (hour) | $Q_p$ (liter/second) | $T_b$ (hour) |
|---------|-------|--------------|----------------------|--------------|
| 1/18/2018 | 18:30 | 2            | 1332                 | -            |
| 1/28/2018 | 22:30 | 2.5          | 1795                 | -            |
| 2/3/2018  | 14:30 | 2            | 1700                 | 37           |
| 2/5/2018  | 10:00 | 2.5          | 1707                 | 39           |
| 2/15/2018 | 22:30 | 2.5          | 1667                 | 46           |
| 2/24/2018 | 23:00 | 2.5          | 1694                 | 39           |
| Minimum  |       | 2            | 1332                 | 37           |
| Maximum  |       | 2.5          | 1795                 | 46           |
| Average  |       | 2.5          | 1649                 | 40           |

Table 2. Flood hydrograph component comparisons at Kiskendo Cave, Pindul Cave, Gilap Cave, and Petoyan Spring

| Characteristics | Kiskendo | Pindul | Gilap | Petoyan |
|----------------|---------|--------|-------|---------|
| $T_p$ (hour)    | 2.5     | 2      | 3     | 6       |
| $Q_p$ (liter/second) | 1,649 | 12,232 | 172   | 59      |
| $T_b$ (hour)    | 40      | 13.4   | 36    | 42      |
4.2. Master Recession Curve (MRC) of Kiskendo Cave

MRC at Kiskendo Cave is formed from seventeen single recession curves (RC). Figure 6 shows that the Kiskendo Cave has two types of linear reservoir recession and one type of exponential recession. The type of exponential recession characterizes the type of conduit flow released by the karstic aquifer of Kiskendo Cave while the first linear recession indicates the start of the diffusion flow. Meanwhile, a second linear recession can be identified with the initial release of fissure flow. According to [35], some karstic aquifers have a fissure flow type that flows through an intermediate-sized void.

MRC that formed from several RC will reflect the characteristics of the karst aquifer to release its water stores. Based on the concept, Kiskendo Cave has a duration of conduit flow discharge from 0 to 15 hours; fissure flow release duration of 15 - 40 hours, and time to baseflow (T_b) about 40 hours (equal to T_b calculation on flood hydrograph component). The T_b calculation on this MRC confirms the T_b calculations manually using the flood hydrograph as described above.
Figure 7. Water-level recorder installation (upper-left), Sanyar Sinkhole (upper-right), drip flow in Kiskendo Cave System (bottom-left), underground river (bottom-right) (after [27])

4.3. Karstification Degree of Kiskendo Cave

Underground river in Kiskendo Cave has MRC as presented in equation (4). The equation consists of two simple exponential (linear reservoir recession type) and one simple linear turbulent equation (turbulent flow recession type). Based on the classification [19], the Kiskendo Cave has a complex discharge regime with the characteristic of "extensive disruption and disintegration of rock environment, with the majority of open, medium size, both not karstified and karstified in the phreatic zone of the fissure karst aquifer and with the influence of connected conduits".

\[ Q_t = 1500e^{-0.007t} + 500e^{-0.04t} + 470(1 - 0.038t) \]  

The existence of complex discharge regime in Kiskendo Cave is proved by the type of conduit flow, fissure, and diffuse that appear on the MRC graph (Figure 6). The development of conduit void type is evidenced by the existence of underground rivers and sinkholes that recharge Kiskendo underground river (Figure 7). Besides, the time to peak (T_{p}) recorded in the Kiskendo Cave is relatively fast (2.5 hours), which also reflects the flow of conduits during rainfall events (Table 2).

Meanwhile, the dominance of the diffuse flow in Kiskendo Cave reflects the karst aquifer which recharges the total discharge is still useful in storing the groundwater and releasing it slowly. This sufficient storage and slowly releasing are indicated by the time to baseflow (T_{b}) which is relatively slow (40 hours) as shown in Table 2.

5. Conclusion

Kiskendo Cave has a discharge of about 500 liters/second in the dry season and about 1000 liters/second in the rainy season. The calculation of the degree of karstification indicates that Kiskendo Cave has a complex discharge regime (degree of karstification 5.5). The complex is confirmed by the type of conduit flow (duration of release of 0 - 15 h), fissure (release duration 15-40 h), and diffuse (release time of about 40 h), which visible from the graphic on MRC calculations. Furthermore, the analysis of the hydrograph component of the flood strengthens the result of calculation of karstification degree in Kiskendo Cave. Time to peak (T_{p}) is relatively fast (2.5 hours) shows the existence of a flow conduit during rain events. Meanwhile, calculating the time to baseflow (T_{b}) manually using flood hydrograph results in value almost equal to the MRC calculation, which is about 40 hours. This fact shows that karst aquifer which recharges underground river in Kiskendo Cave is still able to store rainwater in diffuse voids and release it slowly.

6. Acknowledgment

Authors gratefully acknowledge the research funding and support from Hibah Penelitian Dosen, entitled “Time-series analysis hubungan debit dan hujan untuk karakterisasi akuifer karst di kawasan
Kast Jonggrangan DIY-Jateng,” which was funded by BPPTN-BH 2018. Authors would also like to thank all parties involved in the research preparation, field survey, and evaluation.

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