Flood hydrograph parameters in the Pindul underground river, Gunungkidul, to characterise the release of stored water from karst aquifers

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Abstract. This research was conducted in the Pindul underground river, a cave tubing tourism site in Gunungsewu Karst, Indonesia. The purpose of this study is to identify flood hydrograph parameters that can be used to characterise how karst aquifer release groundwater storage. The recording of water level fluctuations was carried out with the installation of HOBO U20L-02 (November 2020-August 2021). The discharge measurement was carried out 20 times to create a stage-discharge rating curve. Furthermore, eleven flood events were selected to calculate the recession constant of diffuse (Kb), fissure (Kf), conduit (Kc), time to peak (Tp), and time to baseflow (Tb). The results of the calculation of the hydrograph parameters show the number Kb=0.996, which indicates the slow release of groundwater storage supported by the Tb value = 20.72 hours (long enough). Compared with Kb and Tb values in other karst springs in Java, the Pindul underground river has a slightly slower releasing of groundwater storage, although its Tb value is shorter than the average for other karst springs. Meanwhile, based on the Kc value (0.429), the Pindul underground river is faster in releasing its conduit flow which is strengthened by a reasonably short Tp data (3.1 hours).

1. Introduction

Karst is a landform formed due to the dissolution process [1], characterized by unique physical characteristics in surface and subsurface morphology [2]. Underground rivers are one of the subsurface karst formations resulting from the dissolution process [3]. Underground rivers formed in a karst landform cannot be separated from the formation of karst caves. These karst caves will be connected to form a cave system and, if filled with water, will become an underground river system [4].

Pindul Cave is one of the underground rivers as a cave-tubing tourist destination in Gunungkidul Regency, Yogyakarta Special Region [5]. Flood conditions heavily influence Cave-tubing activities in the Pindul underground river. Pretty significant flood conditions do not allow any activities carried out in Pindul Cave because the conditions are not safe for tourist activities. Therefore, it is necessary to define the characteristics of the karst aquifer in Pindul Cave to mitigate disasters that may occur.

The release of water storage components can define the characteristics of karst aquifers. The components of water release are analyzed (one of them) by looking at the recession curve of the hydrograph during a flood event. The recession curve is defined as the distribution of the flood
hydrograph after the absence of rain so that the karst aquifer releases its storage. The nature of this release corresponds to what is stored in voids of different sizes [6]. The concept of releasing the storage component from the aquifer media was put forward by [7], who assumed that the aquifer is a water storage medium after there is no rain, releasing the three storage components according to a function of time. The graph of the discharge decreasing during this recession is exponential and has a constant for each component of the aquifer flow released. Furthermore, [7] divides the recession constant in the flood hydrograph into three types, namely the recession channel (Kc); constant recession flow (Ki); and constant recession base flow (Kb). Meanwhile, [8] categorizes that flow components in karst aquifers are divided into diffuse, fissure, and conduit flows. This classification is then somewhat adapted to that proposed by [9] that the size of the voids in karst aquifers can be classified into four types: (a) inter-granular/diffuse (10^{-3}-10^{-1} mm); (b) fracture (10^{-1} - 10 mm); (c) fissure (10 - 10^{2} mm); and (d) conduit (10^{2} - 10^{4} mm). Therefore, conduit flow is considered channel flow, fissure flow is equivalent to interflow, and diffuse flow is considered base flow. The recession curve is the distribution of the flood hydrograph in karst springs after there is no rain so that the discharge is reduced. Figure 1 shows that the slope of the curve when releasing reservoirs from large cavities (channels) will be faster or sharper than when the aquifer releases flow components from smaller cavities (fissures, then diffuses).

![Recession Curve](image)

**Figure 1.** Diffuse, fissure and conduit flow separation in Petoyan Spring, Gunungsewu karst [10]

This study aims to analyse the nature of the aquifer in Pindul Cave in releasing its groundwater storage. This research is essential to do as a disaster mitigation effort in Pindul Cave tourist attractions. In addition, the water resources in this location are also widely used by the surrounding community for irrigating rice fields and other domestic water needs. This research is also expected to enrich the literature review, especially the development of karst aquifers and their comparison with karst hydrological conditions in other locations on the island of Java, Indonesia.

2. **Methodology**

This research was conducted by installing a water level data logger (HOBO U20L-02) in the Pindul underground river from November 2020 to August 2021, every 15 minutes. A stage-discharge rating curve was created with the measured discharge data to obtain a discharge hydrograph during the study period. The discharge measurement is carried out using the slope-area method and the velocity-area method. The discharge measurement was carried out 20 times, representing low, average, and high water levels to get a good rating curve accuracy. Furthermore, 11 flood events were selected based on several single floods that occurred during the study period and had reached base flow at the end of the recession period. Then, the recession constant of each component of conduit flow (Kc), fissure (Ki), and diffuse (Kb) is calculated by the following formula [11]:

\[
K = \frac{Q}{Q_0} 
\]
\[ Q(t) = Q(t_0)e^{-k(t-t_0)} \]

where \( k \) is the recession constant in the aquifer system, \( t \) is the release time at \( t \), and \( t_0 \) is the initial release time of the recession period. The formula is considered to be linear on a semi-log scale, so the formula becomes:

\[ \ln Q(t) = -k(t - t_0) + \ln Q(t_0) \]

\[ k = -\frac{1}{t - t_0} \ln (Q(t) - Q_0) \]

In addition, to obtain a more definite description of the differences in the release of deposits from the karst aquifer, time-to-peak (Tp) and time-to-baseflow (Tb) calculations were performed for each flood event. The results of the calculation of the recession constant are then compared with other areas on the island of Java, namely the karst areas of Gunungsewu (DIY), Jonggrangan (Central Java), Rembang (Central Java), Gombong (Central Java), and Rengel (East Java).

### 3. Result and Discussion

#### 3.1. Discharge Measurement and stage-discharge rating curve

The discharge measurement in Pindul Cave during the research period (November 2020 – August 2021) was carried out 20 times. Table 1 shows the results of discharge measurements in Pindul Cave.

| No | Date       | Time   | Water level (meter) | Q (liter/sec) |
|----|------------|--------|---------------------|--------------|
| 1  | 08/11/2020 | 11:07  | 0.47                | 1.930        |
| 2  | 22/11/2020 | 13:23  | 0.55                | 2.092        |
| 3  | 20/12/2020 | 10:50  | 0.67                | 2.333        |
| 4  | 03/01/2021 | 09:21  | 0.67                | 2.327        |
| 5  | 17/01/2021 | 08:01  | 0.66                | 2.319        |
| 6  | 27/01/2021 | 04:00  | 1.06                | 4.299        |
| 7  | 14/02/2021 | 11:05  | 0.77                | 2.543        |
| 8  | 24/02/2021 | 03:45  | 1.28                | 5.262        |
| 9  | 24/02/2021 | 04:45  | 1.12                | 4.601        |
| 10 | 14/03/2021 | 09:57  | 0.69                | 2.368        |
| 11 | 19/03/2021 | 03:45  | 0.93                | 3.972        |
| 12 | 28/03/2021 | 11:33  | 0.67                | 2.329        |
| 13 | 25/04/2021 | 10:10  | 0.60                | 2.199        |
| 14 | 23/05/2021 | 09:51  | 0.66                | 2.305        |
| 15 | 06/06/2021 | 15:20  | 0.65                | 2.301        |
| 16 | 20/06/2021 | 16:54  | 0.70                | 2.396        |
| 17 | 04/07/2021 | 12:05  | 0.64                | 2.279        |
| 18 | 18/07/2021 | 10:11  | 0.63                | 2.257        |
| 19 | 01/08/2021 | 08:40  | 0.64                | 2.251        |
| 20 | 15/08/2021 | 10:02  | 0.62                | 2.241        |

A simple correlation analysis was carried out to obtain a rating curve formula that could be used to convert the measured water level data into discharge data. The formula obtained from the relationship between the measured discharge and the water level as in equation (1) below

\[ y = 3857(x)^{1.1487} \]  \hspace{1cm} (1)
where $y$ is discharge (l/sec), and $x$ is water level (m). The results of the rating curve analysis (Figure 2) in Pindul Cave have a reasonably high determinant value of 0.94 so that the discharge time series generated during the water level measurement period can be considered accurate.

![Figure 2. Stage-discharge rating curve in Pindul underground river.](image)

### 3.2. Time-series Discharge and Recession Hydrograph

Furthermore, the results of converting water level data into hydrographs during the research period are presented in Figure 3.

![Figure 3. Time-series discharge hydrograf in Pindul underground river](image)

From Figure 3, it can be seen that Pindul Cave experiences various flood events during the rainy season. Based on the results of data recording, the highest discharge in Pindul Cave during the study period was 14,653.52 liter/sec on February 8, 2021 and lowest discharge in Pindul Cave 1,169.88 liter/sec on November 9, 2020 with an average discharge of 2,504.95 liter/sec. Then, the calculation of the recession constant for each flow component is chosen for flood events that meet floods with sufficient discharge to be analyzed with a recession period that can represent various time variations for base flow ($T_b$) which can show conduit, fissure, and diffuse flow releases. The results of the calculation and separation of the selected flood recession in Pindul Cave are presented in Figure 4, while the calculation of the value of the recession constant and other hydrograph parameters ($T_p$ and $T_b$) is then summarized in Table 2.

![Figure 4.](image)
Figure 4. Separation of diffuse, fissure, and conduit flows in the recession period for each selected flood event.

In general, the constant recession values for conduits ($K_c$) were 0.2-0.8; the interflow/fissure ($K_i$) is 0.7-0.94, and the baseflow/diffuse ($K_b$) is from 0.93 to 0.995 [12]. Based on the results of these calculations, the range of conduit flow recession constant values ($K_c$) is between 0.337-0.482 with a mean of 0.429; the fissure flow recession constant ($K_i$) is 0.754-0.894 with a mean of 0.754, and the fissure flow recession constant ($K_b$) ranges from 0.991 to 0.999 (average=0.996). The average time to peak value is relatively short (3.05 hours), with an average time to baseflow of 20.73 hours.

Table 2. Flood recession constant and flood hydrograph parameters.

| Flood nr. | Date       | Qp (l/sec) | Diffuse Flow (l/sec) | Kr Diffuse ($K_b$) | Kr Fissure ($K_i$) | Kr Conduit ($K_c$) | Tp (hour) | Tb (hour) |
|-----------|------------|------------|----------------------|-------------------|-------------------|-------------------|-----------|-----------|
| 1         | 02/12/2020 | 4592.15    | 2.638,78             | 0.9990            | 0.8940            | 0.337             | 5.00      | 22.00     |
3.3. **Comparison of hydrograph parameters with other karst areas on the Java Island**

Furthermore, the comparison between hydrograph parameters in Pindul Cave and other karst areas is shown in Table 3.

| Karst region | Sites name |  |  |  |  |
|--------------|------------|---|---|---|---|
| Gunungsewu   | Gilap [13] | 0.463 | 0.767 | 0.996 | 3.0 | 36.7 |
|              | Bribin [13] | 0.332 | 0.825 | 0.998 | 5.5 | 36.3 |
|              | Ngreneng [13] | 0.333 | 0.877 | 0.992 | 4.5 | 16.8 |
|              | **Pindul** | **0.429** | **0.830** | **0.996** | **3.1** | **20.7** |
|              | Guntur [14] | 0.530 | 0.906 | 0.997 | 8.7 | 64.6 |
|              | Petoyan [10] | 0.500 | 0.650 | 0.985 | 5.1 | 6.2 |
|              | Kakap [6] | 0.483 | 0.799 | 0.991 | 5.8 | 11.6 |
|              | Beton [15] | 0.380 | 0.930 | 0.995 | 2.2 | 33.6 |
| Jonggrangan  | Kiskendo [16] | 0.356 | 0.935 | 0.995 | 4.0 | 28.0 |
|              | Mudal [16] | 0.410 | 0.934 | 0.997 | 2.5 | 43.0 |
|              | Anjani [16] | 0.276 | 0.910 | 0.995 | 1.4 | 17.0 |
| Rembang      | Sumbersemen [17] | - | 0.360 | 0.988 | 3.8 | 5.5 |
| Rengel       | Ngerong [18] | 0.917 | 0.972 | 0.995 | 9.6 | 27.4 |
| Gombong      | Kalisirah [19] | 0.443 | 0.889 | 0.995 | 1.9 | 20.8 |
|              | Jumbleng [19] | 0.639 | 0.836 | 0.996 | 2.7 | 17.3 |
|              | Kalikarak [19] | 0.711 | 0.904 | 0.995 | 1.4 | 31.3 |
| **Average**  | **0.480** | **0.864** | **0.995** | **4.09** | **27.42** |

The table confirmed that the conduit ($K_c$) and fissure ($K_i$) recession constants in Pindul Cave are lower than the average in Java. This shows that the aquifer in Pindul Cave releases its storage conduit (during a flood) faster and releases its storage fissure faster than average, which indicates the development of large and medium-sized voids that are generally more developed. Meanwhile, the diffuse recession constant ($K_b$) in Pindul Cave tends to release its storage more slowly than the
average, as evidenced by the nature of the flow, which is always available during the dry season. When viewed from the $T_p$ (time to peak) value, which is the time required from the beginning of the rain to the peak discharge, Pindul Cave has a shorter time than the average. This condition involves caution for cave-tubing tour operators to be aware of rapid flash floods, which pose a high risk for tourists considering the peak discharge in this Pindul underground river, which is relatively large (>4000 l/sec).

4. Conclusion and Future Works
Pindul Cave has an average value of diffuse flow recession constant ($K_b$) = 0.996, which indicates that, in general, the release of groundwater storage (from small voids) is relatively slow when compared to that found in other karst springs on the island of Java. However, the $K_c$ value of the conduit recession constant is relatively small (0.429), which indicates that when a flood occurs, the conduit flow is released quickly. This value is also supported by a reasonably fast time to peak (3.1 hours). Meanwhile, the fissure flow recession constant is 0.830, slightly lower than the average for springs in other areas on Java Island.

This research needs to be strengthened by further research, namely with a more extended recording period up to many years. Future long-term studies will be carried out to measure variations in the discharge of springs or other underground rivers with different discharge variability. Installation of a time-series water level recorder and continuous flow recording is required because this is the primary key of any interpretation to reveal the development of voids in the karst aquifer. In addition, the results of this study need to be reconfirmed by applying other methods, such as cave surveys, tracer tests, aquifer memory systems, or hydrogeochemical modelling, to reduce bias in conclusions in defining void development in karst aquifers.

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