Spatial and Temporal Flood Characterization of Pindul Karst System, Gunungkidul Regency

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Abstract. Pindul karst system has cave system and sinking stream recharge that cause it prone against flash flood. This research will study flood characteristics in the karst system. Water level logger was installed on karst system outlet and sinking stream of Kedungbuntung to obtain discharge data at 15 minutes interval. Rainfall data is obtained by installing automatic rain gauge on middle parts of karst system. Recording of both was done for six months (January – June). Flood characteristics was obtained by flood hydrograph and rainfall characteristics. The results indicated that Pindul karst system have faster time lag (Tlag) (1.1 and 1.7 hours) than rainfall duration (1.9 hours). Excess rainfall (Pe) is rainfall characteristic that is most influencing flood incident. Temporarily, rainfall percentage becoming surface runoff (% Pe) in outlet and Kedungbuntung were greater at end of rainy season (37% and 14%) than in early rainy season (16% and 8%). Pe percentage below 50% indicated that Pindul karst system is still good in storing groundwater. In spatial term, faster flood behavior in outlet was caused by recharge from cave system and sinking stream. Meanwhile, Kedungbuntung was recharged by aquifer with domination of diffuse fracture.

1. Introduction
Karst flash flooding is one of disasters in karst terrain. The concept was introduced by [1]. Due to its characteristics, flash flood in karst aquifer has different behaviors. Karst aquifer has three porosities (conduit, fissure, and diffuse) that make it complex [2-6]. White (1988) make conceptual model on karst aquifer recharge namely allogenic recharge, internal runoff, diffuse infiltration, and perch aquifer.

Flood characteristics of Pindul karst system is studied through flood hydrograph and rainfall characteristics. Carpenter (1999) used excess rainfall to make threshold runoff in flash flood analysis. Knowledge about rain characteristic and conceptual model of karst aquifer is important in making early warning system and flash flood karst modeling [7-9]. [10-12] used software groundwater-discharge models with rainfall input to model flash flood in karst terrain.

This research was conducted in Pindul karst system located in central part of Java Island, Indonesia (figure 2). Pindul system is interested to study because there is cave system and sinking stream recharging it [13, 14]. In addition, mass tourism in Pindul Cave and Tanding cave allows risk over flash flood. Figure 1 showed karst flash flood in Kedungbuntung sinking stream in 18 August 2016.
Figure 1. Sinking stream Kedungbuntung before and after flash flood.

Figure 2. Local and regional geology of Pindul karst system.
2. Hydrogeological Setting

Pindul karst system locates in Wonosari basin that is middle subzone of East Java south zone of Java Island physiography [15, 16]. Wonosari Basin is in south side of Gunungsewu karst that is explained by [17, 18]. This subzone is composed by limestone from Wonosari Formation and sandy marl from Kepek formation [19].

Pindul karst system has area of 15.44 km². [13, 14] classified zone with bound stone domination as conduit aquifer (1.75km²) and grain stone domination as diffuse aquifer (13.69 km²). Conduit aquifer is characterized by cave systems (Asri Cave, Greng cave, Emas Cave, Candi cave, Suruh Cave, and Siyot Cave) that connect to each other from east to west and then recharge Pindul cave. Diffuse aquifer is characterized with existence of some springs and surface streams.

Rainfall data for ten years (2006-2015) from Central River Region Serayu Opak Progo (BBWS) indicated that study area has monsoon climate. The greatest monthly rainfall occurred in December (296 mm). Rainy season occur in October-April while dry Season occurred in May-September (Figure 3). Average annual rain in study area is 1752 mm, with the least rainfall anomaly occurred in 2007 and the greatest one in 2013.

![Figure 3. Ten years rainfall data in Gedangsari station.](image)

3. Methods

This research used data couple of discharge and rainfall measured at 15 minutes interval. Water level logger was installed in outlet karst system and Kedungbuntung sinking stream. Automatic rain gauge was installed in central part of karst system. Recording of both data was done for six months (January – June 2017).

3.1. Flood hydrograph analysis

Flood hydrograph has bell-like shape. Its main component was Tp (time to peak), Qp (peak discharge), Tb (time to base flow), and Tlag (time lag) [20]. Tp is duration from rainfall peak till Qp. Qp is value of flood peak flow rate and Tb is duration after Qp till back to base flow [21, 22]. According to [23], the above parameters can be used to characterize karst aquifer because they reflect catchment area condition, aquifer storage, karst flow component, and rainfall-runoff relationship.

3.2. Excess rainfall calculation

Excess rainfall is rain that becomes surface runoff [24]. The research used excess rainfall concept to analyze how much rain becoming surface runoff and what is association with peak flow rate. According [24], excess rainfall may be calculated with following steps:
- calculate base flow at selected flood hydrograph;
- calculate total direct runoff (DROtot) by deducting total discharge with total base flow;
- calculate Volume (V) of direct runoff with following equation:

  \[ V(m^3) = DRO_{tot}(m^3 s^{-1}) t(hr) 3600(s/hr) \] (1)

  In which, t is the interval measurement of discharge and rainfall.
Figure 4. Discharge fluctuations of karst system outlet in six months.

Figure 5. Flood hydrograph of karst system outlet in 1 March 2017.

Figure 6. Discharge fluctuations of Kedungbuntung in six months.
calculate thickness of surface runoff \((rd)\) with following equation:
\[
r_d (mm) = \frac{V (m^3)}{area (m^2)} \times 1000
\] (2)

Calculate initial abstraction \(\phi\), namely, rainfall undergoing infiltration, surface storage, or evapotranspiration with following equation:
\[
r_d (mm) = \sum_{m=1}^{M} (R_m - \phi \times 1/hr)
\] (3)
\[
\phi (mm/hr) = \frac{(R_1+R_2+...+R_M)-r_d}{(1+2+...+M) \times 1/hr}
\] (4)

In which, \(R_m\) is selected maxsimum rainfall;

Calculated excess rainfall by deducting \(R_m\) with \(\phi\).

4. Results and Discussion

Karst system outlet and Kedungbuntung underwent 17 flood incidences from January to June 2017 (figure 4 and 6). In simple way, characteristic of each flood incidence may be seen from flood hydrograph (figure 5 and 7). This hydrograph shape is influenced by rain characteristic and catchment area [21].

| Seasons           | Date      | Time   | Qp (liters\(^{-1}\)) | Pe (%) | Pe Avg. (%) | Tp (hours) | Tlag (hours) | O   | KG    | O   | KG    | O   | KG    | O   | KG    |
|-------------------|-----------|--------|----------------------|--------|-------------|------------|--------------|-----|-------|-----|-------|-----|-------|-----|-------|
| Early rainy season| 5/1/2017  | 15:30  | 10,320               | 4,626  | 18.4        | 8.9        | 16.3         | 7.84 | 2.5   | 2.5 | 1.25 | 2.5 | 1.25 |
|                   | 8/1/2017  | 15:15  | 5,221                | 2,934  | 8.1         | 5.5        | 2.25         | 2.25 | 0.75  | 1   |       |     |       |     |       |
|                   | 14/1/2017 | 21:30  | 5,874                | 3,341  | 16.7        | 8.5        | 2.25         | 2.25 | 0.75  | 1   |       |     |       |     |       |
|                   | 3/2/2017  | 2:45   | 12,867               | 5,617  | 29.1        | 11.5       | 1.75         | 1.75 | 1.5   | 1   | 1.5   |     | 1.5   |     | 1.5   |
|                   | 28/2/2017 | 20:30  | 5,927                | 3,254  | 9.2         | 4.8        | 3            | 2.75 | 1.5   | 2.75 |       |     |       |     |       |
| End rainy season   | 1/3/2017  | 14:15  | 30,681               | 11,215 | 60.7        | 22.5       | 36.65        | 16.1 | 1.5   | 1   | 1.5   |     | 1.5   |     | 1.5   |
|                   | 5/3/2017  | 14:00  | 15,666               | 6,644  | 37.2        | 17.6       | 1.5          | 1.25 | 0.75  | 1.25 |       |     |       |     |       |
|                   | 16/3/2017 | 17:15  | 10,886               | 4,899  | 23.9        | 12.8       | 1.75         | 1.5  | 1     | 1.5 | 1     |     | 1.5   |     | 1     |
|                   | 26/4/2017 | 17:45  | 12,647               | 5,614  | 24.8        | 11.5       | 2.25         | 2.25 | 1.5   | 2.25 |       |     |       |     |       |
| Average           |           |        | 12,232               | 5,349  | 25.4        | 11.5       | 2.1          | 2    | 1.1   | 1.7 |       |     |       |     |       |
| Max               |           |        | 30,681               | 11,215 | 60.7        | 22.5       | 3            | 2.75 | 1.5   | 2.75 |       |     |       |     |       |
| Min               |           |        | 5,221                | 2,934  | 8.1         | 4.8        | 1.5          | 1.25 | 0.75  | 1   |       |     |       |     |       |

Okarst system outlet
KG sinking stream Kedungbuntung.
Avgaverage
Table 2. Rainfall characteristics and peak discharge.

| Seasons          | Date       | Time   | Rainfall depth (mm) | Rainfall peak (mm) | Rainfall duration (hours) | Pe (%) | Qp (liters⁻¹) |
|------------------|------------|--------|---------------------|--------------------|---------------------------|--------|---------------|
| Early rainy      | 5/1/2017   | 15:30  | 32.6                | 10.2               | 2.25                      | 18.4   | 8.9           | 10,320           | 4,626            |
| season           | 8/1/2017   | 15:15  | 14.4                | 7.2                | 0.5                       | 8.1    | 5.5           | 5,221            | 2,934            |
|                  | 14/1/2017  | 21:30  | 21.4                | 8                  | 2.25                      | 16.7   | 8.5           | 5,874            | 3,341            |
|                  | 3/2/2017   | 2:45   | 29.6                | 6.8                | 4.75                      | 29.1   | 11.5          | 12,867           | 5,617            |
|                  | 28/2/2017  | 20:30  | 19.4                | 8.4                | 1.25                      | 9.2    | 4.8           | 5,927            | 3,254            |
| End rainy        | 1/3/2017   | 14:15  | 30                  | 11.6               | 1.5                       | 60.7   | 22.5          | 30,681           | 11,215           |
| season           | 5/3/2017   | 14:00  | 21.6                | 14.2               | 0.75                      | 37.2   | 17.6          | 15,666           | 6,644            |
|                  | 16/3/2017  | 17:15  | 23.2                | 8.2                | 1                         | 23.9   | 12.8          | 10,886           | 4,899            |
|                  | 26/4/2017  | 17:45  | 30.3                | 13.8               | 2.5                       | 24.8   | 11.5          | 12,647           | 5,614            |
| Average          |            |        | 24.7                | 9.82               | 1.9                       | 25.34  | 11.51         | 12,232           | 5,349            |
| Max              |            |        | 32.6                | 14.2               | 4.75                      | 60.7   | 22.5          | 30,681           | 11,215           |
| Min              |            |        | 14.4                | 6.8                | 0.5                       | 8.1    | 4.8           | 5,221            | 2,934            |

Okarst system outlet
KG sinking stream Kedungbuntung
Pe excess rainfall
Qp peak discharge

Both locations have hydrograph with step rising limb and slow recession. It is proved with fast Tp and Tlag (table 1). Average Tp (2.1 hour in outlet and 2 hours in Kedungbuntung) has small difference with rain duration (1.9 hour). Average Tlag (1.1 hour at outlet and 1.7 hours in Kedungbuntung) is faster than rain duration.

Characteristic of rain that discussed here was rain depth, duration, peak, and excess rainfall. Calculation of excess rainfall has assumption that rainfall evenly in catchment area [24, 25]. The fact is that not all rainfall evenly in Pindul karst system. Calculation of excess rainfall may be done in 9 flood incidences of 17 incidences (table 1 and 2).

Figure 8. Parsial correlations of rainfall characteristics-peak discharge in Kedungbuntung.
Both locations have greater excess rainfall percentage (%Pe) in end rainy season than early rainy season (table 1). Karst system outlet has %Pe of 36.65% in end rainy season and 16.3% in early rainy season. Meanwhile, Kedungbuntung has 16.15% and 7.84% respectively. The Pe percentage was still below 50% indicating that Pindul karst system is still good in storing groundwater. It is influenced by aquifer with diffuse fracture domination of 13.69km2 (80% of area).

The above matter is caused by saturated karst drainage system in end rainy season, so similar intensity of rainfall will result in higher runoff in end rainy season. This concept is called infiltration excess overland flow. Table 2 indicated that 32.6 mm rainfall in 5 January 2017 (early rainy season) result in excess rainfall of 8.9%. Meanwhile, 30.3 mm rainfall in 26 April 2017 (end rainy season) can result 11.5%.

Correlation of rainfall characteristic and peak discharge is showed in figure 8 and 9. Partial correlation indicated that effective rainfall had the strongest effect with $R^2=0.97$ at outlet and Kedungbuntung. Rainfall depth and peak has low correlation on peak discharge ($R^2$ about 0.3 at both locations). Rainfall duration has the weakest correlation with $R^2=0.001$ (in outlet) and $R^2=0.002$ (in Kedungbuntung).

Rainfall depth, peak, and duration were measured before rainfall entered karst system so they have low correlation when it is tested partially. It is also indicated with simultaneously correlation test. P-values of the three characteristics were greater than significant level (0.05). Meanwhile, excess rainfall was measured after rainfall underwent interaction with karst system so it has good correlation.

Table 3. Simultan correlation and regression of rainfall characteristics–peak discharge.

| Rainfall     | Kedungbuntung | Karst system outlet |
|--------------|---------------|---------------------|
|              | P-value | Significant level | R²   | P-value | Significant level | R²   |
| Depth        | 0.31     |               | 0.35 |         |               |     |
| Peak         | 0.74     | 0.05           | 0.9  | 0.94    | 0.05           | 0.83 |
| Duration     | 0.56     |               | 0.52 |         |               |     |
| Linier regressions test formula | Qp= 639 depth + 88 peak – 2152 duration | Qp= 217 depth + 120 peak – 598 duration |
Rainfall depth, peak and duration have strong effect on Qp when simultaneous correlation test was done (table 3). R$^2$ of outlet and Kedungbuntung were 0.83 and 0.9, respectively. Meanwhile, linear regression test indicated rainfall depth and peak have positive correlation while duration has negative correlation. It means that increase depth and peak lead to increase Qp too while increase in duration will cause decrease in Qp.

Karst system outlet and Kedungbuntung have similar rainfall depth, duration, and peak. However, both locations have different flood characteristic. Outlet has slower average Tp and faster Tlag than Kedungbuntung (table 1). Kedungbuntung is located more upstream so it has faster Tp. The faster Tlag in outlet is influenced by recharge of cave system and sinking stream. Meanwhile, Kedungbuntung is recharged by domination of diffuse fracture that is slow in responding rainfall. Outlet has also greater peak discharge (Qp) and excess rainfall percentage (Pe). It is caused by wider catchment area than Kedungbuntung. In addition, conduit fracture of cave system lead to rainfall becoming stream flow and then recharge outlet.

5. Conclusions

Pindul karst system has fast flood characteristic. Measurement on outlet and sinking stream of Kedungbuntung indicated that both locations have almost same Tp with rain duration. Meanwhile Tlag show faster value.

Study on rainfall-runoff relationship indicated that excess rainfall (Pe) is rain characteristic most influencing peak discharge (Qp). Meanwhile, rainfall depth, peak and duration has strong effect when were analyzed simultaneously. In temporal term, percentage of rainfall becoming runoff (%Pe) has greater amount in end rainy season. It indicated saturation of karst system by rainfall at early rainy season.

In spatial term, karst system outlet has faster flood characteristic than Kedungbuntung. Qp and Pe of outlet is greater, while Tlag is faster than that of Kedungbuntung. It is caused by recharge from cave system and sinking stream of Kedungbuntung.

Although average %Pesis less than 50%, table 1 and 2 shows that rainfall with 30 mm depth for 1.5 hours in 1 March 2017 can result in 60.7% runoff. It may be cause by saturated diffuse fracture so rainfall becoming directly to runoff or filling conduit and fissure fracture that is previously inactive [1]. Therefore, further research on groundwater-surface water relationship modelling should be done in this study area. It is explained by [10, 11].

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