Study of design discharge and river capacity in Celeng Sub-watershed, Special Region of Yogyakarta

A W Abadi, B I D Astuti, Kurniasari, Y V O Siahaan, U A Jamil, W Widyaningrum, A P Jatti, N H Putri, R D Astabella, C B I Pratiwi, N Ayumi, D M Hayat, J H Putra and R F Putri*

1Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia

*Corresponding author: ratihfitria.putri@ugm.ac.id

Abstract. Celeng sub-watershed is a catchment area located in the Oyo watershed. This catchment has circular shape which is situated in the alluvial plain. In the 2018, there was a huge flood occurred in the area that was triggered by Savana Cyclone. The cyclone itself contributed in extreme precipitation, resulted in high discharge in a very short time, and spilled over the riverbank. The research aims (1) to analyze the discharge capacity in the Celeng sub-watershed, (2) to determine the design discharge of Celeng sub-watershed for 2, 5, 10, and 25 years return period, and (3) to evaluate whether the design discharge exceed the Celeng river capacity or not. The research uses quantitative analysis through rational method and slope area method. The design discharge measured by rational method and applied to evaluate the river capacity along with rational method. The result shows that the area does not experience flood in all return period.

1. Introduction

Indonesia’s physiography and climate configuration play important role in the dynamic of hydrological system. The hydrological system in Indonesia is controlling great water resources represented in its numerous watersheds. Watershed is defined as a topographically-bordered landscape which function to collect, store, and drain water flows, sediments, and nutrients through a single outlet [1]. The importance of watershed can be seen in how its properties build the occurring natural processes and control the quantity, quality, and continuity of water resources which impact to the watershed and the socioeconomic lives within as well as the surrounding environment. However, it seems that some of watershed properties is disturbed and results in the declining of watershed performance.

Recently, watershed performance becomes a serious concern in Indonesia itself, which most of its watershed is in critical condition. Major problems such as intensive erosion and land conversion in upper watershed has resulted potential hazards for whole watershed. Unfortunately, anthropogenic activities seem to have caused the problems and are inseparable from the population dynamic. For the few decades, population increases following the urban growth in vast majority in Indonesia. The increasing population has been leading to the rising of demand, especially the land demand for settlement. The significant increase of land demand has caused any landuse conversion identified in most of watersheds in Indonesia. Moreover, human activities regarding to economic motives also accelerates the landuse conversion and possibly bring more disturbance to the whole systems of watershed. Thus, the government of Indonesia,
collaborated with the local government and the participation of local community alongside with private parties and academicians, are forced to do proper watershed management.

Watershed management is watershed-based development approach in which watershed is as fundamental concern in integrated planning and management of water and land resources [2]. Watershed management also includes the evaluation and monitoring hydrological parameters across a watershed, especially run-off which has the potential to become a flood hazard and damage watershed sustainability. As an example, flood hazard exists in Celeng sub watershed due to its dynamic human activities are so influential towards the physical processes of the watershed.

The hydrological analysis can be used to determine and identify the existing condition of Celeng sub watershed. The research has taken consideration that run-off parameters can be applied to evaluate the capability of Celeng sub watershed during storm event. The Celeng stream capacity is compared with the design discharge of Celeng sub watershed to know whether the predicted discharge exceeds the stream capacity or not.

2. Materials and Methods

2.1. Study Area

The area studied in this research is Celeng sub watershed (Figure 1) which intersects with the administrative region of Bantul Regency. This catchment area has Celeng river as the main stream flow and is part of Oyo watershed. The logical reasonings of choosing Celeng sub watershed as study area due to the availability of data and the catchment area covers tourism area and surrounding settlements which experienced flood in the last March 2019.

![Figure 1. Map of Celeng sub watershed](image)

2.2. Data

The data used in this research comprises of primary data and secondary data. The primary data is taken by survey method using field survey and open questionnaire. The sample for open questionnaire is chosen randomly regarding to the flood buffer area. The results of the interview with the locals are descriptively analyzed in order to explain the flood event with the existing condition of the watershed. Meanwhile, the field survey is conducted in the watershed outlet point which experienced previous flood to collect data of morphology and morphometric of the stream. It will be used to determine maximum stream capacity of the Celeng river. The secondary data is DEM (Digital Elevation Model), Digital Topographic Map of Indonesia – Imogiri Section, and rainfall data. The DEM and topographic map were taken from Indonesia Geospatial Information Agency while the rainfall data is obtained from the Global Weather Data. The DEM is used to determine the watershed area, the topographic map is used to know the landuse type, and the rainfall data for 10 years (2004-2013) is for design discharge analysis.
2.3. Research Design
The research consists of three main steps as shown on Figure 2. The first step is determining design discharge using rational method. The second step is measuring the maximum stream capacity of Celeng river. The third step is evaluating the existing condition of Celeng sub watershed from the design discharge and stream capacity. Later, the data are analyzed descriptively to describe the objective of the study.

![Flowchart of the research design](image)

**Figure 2.** Flowchart of the research design

2.3.1. Design Discharge. Design discharge is a hydrology model that attempts to estimate flood through frequency analysis based on certain hydrological parameters such as rainfall and morphometric of watershed [3]. Design discharge can be calculated by rational method by some certain assumptions. To determine design discharge, it requires rainfall intensity, morphometric data of the watershed, and the landuse that exist in the watershed.

2.3.1.1. Rainfall Intensity. Rainfall intensity can be obtained empirically through rainfall frequency analysis [4]. The first step is determining the annual maximum series of rainfall data which will be processed by probabilistic approach based on the data distribution. There are four probabilistic methods namely Gumbel distribution, Normal distribution, Log-Normal distribution, and Log-Pearson III distribution. To decide the suitable distribution, the data is tested statistically by Chi-square ($\chi^2$) and Kolmogorov-Smirnov test.

The suitable distribution will be used to calculate the design rainfall in different return period. Subsequently, the design rainfall is then calculated to determine the daily rainfall intensity for different return period. Rainfall intensity is determined using Mononobe equation as shown on the following formula.

$$ I = \frac{R_{24}}{24} \left( \frac{24}{t} \right)^{\frac{2}{3}} $$

in which $I$ represents rainfall intensity, $R_{24}$ describes total rainfall in 24 hours, and $t$ is for rainfall duration.
2.3.1.2. **Rational Method.** Rational method is used to determine the design discharge of a watershed with considering some assumptions. These assumptions are (1) rational method can be used when there is little availability of flow rate or flood discharge data and (2) rational method can explain the relationship of flood discharge and rainfall intensity for a specific time in a watershed which its area is less than 5000 acre or 50 square kilometers [5]. Rational method uses this following equation

\[ Q = 0.278 \times C \times I \times A \]  \hspace{1cm} (2)

\[ I = \frac{R^{2.4}}{24 \times (24 + tc)^{2}} \]  \hspace{1cm} (3)

\[ tc = 0.0195 \times L^{0.77} \times S^{-0.385} \]  \hspace{1cm} (4)

in which Q describes design discharge, C is for run-off coefficient, I is rainfall intensity which determined by time of concentration through Monobe equation, and A is watershed area. C represents the percentage of rainfall that turns into a run-off. C is different based on the landuse types. The value of C is determined subjectively using the following reference.

| Description of Area          | C          | Character of Surface       | C            |
|------------------------------|------------|---------------------------|--------------|
| Business                     | Pavement   |                          |              |
| Downtown                     | 0.70 - 0.95| Asphaltic and concrete    | 0.70 - 0.95  |
| Neighborhood                 | 0.50 - 0.70| Brick                     | 0.70 - 0.85  |
| Residential                  |            | Roofs                     | 0.75 - 0.95  |
| Single-family                | 0.30 - 0.50| Lawns, sandy soil         |              |
| Multiunit, detached          | 0.40 - 0.60| Flat, 2%                  | 0.05 - 0.10  |
| Multiunit, attached          | 0.60 - 0.75| Average, 2-7%             | 0.10 - 0.15  |
| Residential (Suburban)       | 0.25 - 0.40| Steep, 7%                 | 0.15 - 0.20  |
| Apartment                    | 0.50 - 0.70| Lawns, heavy soil         |              |
| Industrial                   |            | Flat, 2%                  | 0.13 - 0.17  |
| Light                        | 0.50 - 0.80| Average, 2-7%             | 0.18 - 0.22  |
| Heavy                        | 0.60 - 0.90| Steep, 7%                 | 0.25 - 0.35  |
| Parks, Cemeteries            | 0.10 - 0.25|                           |              |
| Playgrounds                  | 0.20 - 0.35|                           |              |
| Railroad yard                | 0.20 - 0.35|                           |              |
| Unimproved                   | 0.10 - 0.30|                           |              |

**Sources:** Run off coefficient data [6]
Composite C value is calculated for generalizing the run-off coefficient for a watershed. Composite C is determined by following formula

\[
Composite\ C = \frac{\sum C_i A_i}{\sum A_i}
\]

in which C describes watershed’s run-off coefficient, A is landuse area, and i represents landuse types.

2.3.2. **Slope Area Method.** Slope area method is a discharge estimating method which is applied whilst measurement with more accurate method like velocity area method is not possible [7]. This method can only be used in river with long straight segment, free from drawdown or backwater, and accessible measurement point. Otherwise, this method is not good for big river with very gentle slope and high concentration of sediments. The method is formularized mathematically by this following equation

\[
Q = \frac{1}{n} \times A \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}
\]

in which Q describes water discharge, n is the Manning roughness coefficient, A is cross-section area, R is for hydraulic radius, and S is riverbed slope.

2.3.3. **Flood.** Flood is a natural or manmade phenomenon where water overflows river bank and creates inundation in the surrounding flatter area like alluvial plain, floodplain, or back swamp [8]. Flood is caused by interaction of natural factors along with human activities throughout a watershed. Flood occurred when the watershed’s capacity is lower than the design discharge and the stream capacity is lower than the design discharge [9]. It means that the existing river capacity is exceeded by the design discharge.

3. **Results and Discussion**

3.1. **Rainfall Analysis**

The rainfall data distribution in Celeng sub-watershed is calculated to obtain the design rainfall. The design rainfall is best modelled by Normal distribution based on Chi-square and Kolmogorov-Smirnov test as shown on the Table 2. The design rainfall in shorter return period has lower value compared to design rainfall in longer return period. Rainfall probability in shorter return period is higher than rainfall probability in the longer return period which means lower rainfall is more frequent to occur.

| P (x ≥ Xm) (Probabilities) | T (Return Period) | XT (mm) |
|---------------------------|------------------|---------|
| 0.5                       | 2                | 86.30   |
| 0.2                       | 5                | 115.02  |
| 0.1                       | 10               | 130.03  |
| 0.04                      | 25               | 146.04  |

Source: Data processed, 2019

Design rainfall is then used to calculate design discharge. By combining C value, along with rainfall intensity from design rainfall and watershed area results in design discharge for different return period. Design rainfall and design discharge for 2, 5, 10, and 25 years return period is shown on Table 3.
Table 3. Design rainfall for 2, 5, 10, and 25 years return period

| Rainfall Duration (hours) | 2 Years Return Period | 5 Years Return Period | 10 Years Return Period | 25 Years Return Period |
|---------------------------|-----------------------|-----------------------|------------------------|------------------------|
| 1                         | 29.92                 | 39.88                 | 45.08                  | 50.63                  |
| 2                         | 18.85                 | 25.12                 | 28.40                  | 31.89                  |
| 3                         | 14.38                 | 19.17                 | 21.67                  | 24.34                  |
| 4                         | 11.87                 | 15.82                 | 17.89                  | 20.09                  |
| 5                         | 10.23                 | 13.64                 | 15.42                  | 17.31                  |
| 6                         | 9.06                  | 12.08                 | 13.65                  | 15.33                  |
| 7                         | 8.18                  | 10.90                 | 12.32                  | 13.84                  |
| 8                         | 7.48                  | 9.97                  | 11.27                  | 12.66                  |
| 9                         | 6.91                  | 9.22                  | 10.42                  | 11.70                  |
| 10                        | 6.45                  | 8.59                  | 9.71                   | 10.91                  |
| 11                        | 6.05                  | 8.06                  | 9.11                   | 10.24                  |
| 12                        | 5.71                  | 7.61                  | 8.60                   | 9.66                   |
| 13                        | 5.41                  | 7.21                  | 8.15                   | 9.16                   |
| 14                        | 5.15                  | 6.86                  | 7.76                   | 8.72                   |
| 15                        | 4.92                  | 6.56                  | 7.41                   | 8.32                   |
| 16                        | 4.71                  | 6.28                  | 7.10                   | 7.97                   |
| 17                        | 4.53                  | 6.03                  | 6.82                   | 7.66                   |
| 18                        | 4.36                  | 5.81                  | 6.56                   | 7.37                   |
| 19                        | 4.20                  | 5.60                  | 6.33                   | 7.11                   |
| 20                        | 4.06                  | 5.41                  | 6.12                   | 6.87                   |
| 21                        | 3.93                  | 5.24                  | 5.92                   | 6.65                   |
| 22                        | 3.81                  | 5.08                  | 5.74                   | 6.45                   |
| 23                        | 3.70                  | 4.93                  | 5.57                   | 6.26                   |
| 24                        | 3.60                  | 4.79                  | 5.42                   | 6.08                   |

Source: Data processed, 2019

Figure 3. Graphic of design rainfall for 2, 5, 10, and 25 years return period
The result shows that the rainfall occurs in Celeng sub-watershed is distributed logarithmically throughout a day. In the first hour, the rainfall has the biggest intensity and the intensity decreases following longer duration. The pattern of rainfall intensity distribution can be identified in different return period. The rainfall intensity in different return periods express the same pattern where rainfall intensity decreases by the time the rainfall occurs (Figure 3).

The rainfall intensity value varies in each return period. The various value of rainfall intensity is determined by the design rainfall. The design rainfall is greater following longer return period. It affects the rainfall intensity which follows the rainfall value. This means that, the greater the design rainfall, so does the rainfall intensity. Rainfall intensity in 2 years return period has the lowest value whilst the highest value is in 25 years return period rainfall.

Rainfall intensity has different level which represents how strong the rainfall is. Rainfall intensity has been classified into 4 classes: low intensity (less than 2 mm/hour), medium intensity (2 < I ≤ 10 mm/hour), high intensity (10 < I ≤ 50 mm/hour), and very high (more than 50 mm/hour) [10]. The rainfall occurs in different return period has indicated the existence of extreme rainfall or rainfall with high-very high intensity. In 2 years return period, extreme rainfall occurs during the first 5 hours. The longer extreme rainfall occurs in the 5 years return period during the first 7 hours. Rainfall in 10 years return period shows extreme intensity in the first 9 hours. The longest duration of extreme rainfall occurs in the 25 years return period, approximately during the first 11 hours.

3.2. Analysis of Design Discharge
The highest discharge occurs on 25 years return period, followed by 10, 5, 2 years return period as shown on Table 4. Discharge decreases with increasing duration of rainfall events. Discharge during the 2-years return period is 8.07 m³/s. During the 5 years return period, the discharge is higher, roughly 10.75 m³/s. Greater discharge occurs in 10 years return period which valued 12.16 m³/s. Discharge during the 25 years return period is the largest discharge which reaches 13.65 m³/s.

Table 4. Design Discharge for 2, 5, 10, and 25 years return period

| Return Period (Years) | C  | Rainfall Intensity (mm/hour) | A (km²) | Design Discharge (m³/s) |
|-----------------------|----|-----------------------------|---------|-------------------------|
| 2                     | 7.09| 8.07                        |
| 5                     | 9.45| 10.75                       |
| 10                    | 10.69| 12.16                       |
| 25                    | 12.00| 13.65                       |

Source: Data processed, 2019

3.3. River Capacity

Table 5. Celeng river capacity at outlet point

| Parameters | River Capacity (m³/s) |
|------------|-----------------------|
| n 0.0775   | A (m²) 33.75 P (m) 11.1 R 3.04I S 0.04 | 182.7971 |

Source: Data processed, 2019

Table 6. Celeng sub-watershed evaluation

| Return Period | Design Discharge (m³/s) | River Capacity (m³/s) | Result |
|---------------|-------------------------|-----------------------|--------|
| 2             | 8.07                    |                       | No flood occurs |
| 5             | 10.75                   | 182.7971              | No flood occurs |
| 10            | 12.16                   |                       | No flood occurs |
| 25            | 13.65                   |                       | No flood occurs |

Source: Data processed, 2019
Design discharge calculation is used to evaluate the capacity of the Celeng sub-watershed. The maximum discharge that can be accommodated at the Celeng river outlet is 182.79 m$^3$/s as shown on Table 5. Meanwhile, discharge during the return period of 2 years, 5 years, 10 years, and 25 years has a smaller value than the storage capacity as expressed on Table 6. This means that the Celeng river can support maximum flood discharge at different times. It indicates that the latest flood considered as flood that occurs in longer return period (more than 25 years) or triggered by specific weather phenomenon like tropical cyclone. Weather phenomenon occurs in about short period like tropical cyclone is considered as extreme weather since it has less possibility to occur frequently [11].

Tropical cyclone may have effect on rainfall characteristics, especially rainfall intensity. The southern coast of Java has experienced the effect of cyclone tails for approximately 6 times during this century and it has affected on the rainfall intensity. The presence of tropical cyclone itself increases daily rainfall intensity and the effect becomes stronger when a region is closer to the center of cyclone [11]. Increasing rainfall intensity has also impact to the raindrop diameter. The greater the rainfall intensity, the greater the possibility to form bigger raindrop [12]. The bigger raindrop will contribute to greater volume of rainwater which fall upon earth surface. The continuous torrential rain during Savan cyclone has brought greater volume of water accumulated in Celeng sub-watershed. Water accumulation during extreme rainfall has led to increase in overland flow and cumulative run-off, results in even greater run-off coefficient [13]. As a consequence, there will be great discharge entering the main stream during the rainfall, causing water in the outlet starts to overflowing its bank like what has happened in Celeng river.

4. Conclusions
The research emphasizes on study of surface hydrology for watershed evaluation. According to the methods and results of this research, the conclusions were drawn as follows:
1. Slope area method uses in this research result in the main river capacity of Celeng sub-watershed. The result shows that Celeng river can accommodate the accumulated water within its sub-watershed no greater than 182.79 m$^3$/s for a storm event.
2. Design discharge of the Celeng sub-watershed varies throughout different return period. The design discharge modelled by rational method valued 8.07 m$^3$/s, 10.75 m$^3$/s, 12.16 m$^3$/s, and 13.65 m$^3$/s for 2, 5, 10, and 25 years return period.
3. Based on the design discharge and considering river capacity, flood does not occur in 2, 5, 10, and 25 years return period since the river capacity is bigger than the flood discharge and is capable to support the accumulated discharge within the sub-watershed. The latest flood occurred in the Celeng river is most likely related to more extreme rainfall which may happen in longer return period or because an extreme weather phenomenon like tropical cyclone which contributes to increased rainfall intensity.

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