Increasing surface impermeability influences peak discharge with the Snyder method in the Ngadipiro sub-watershed of the Bengawan Solo watershed

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Abstract. This research was conducted to determine the effect of increasing soil impermeability in the Ngadipiro Sub-watershed on Cp and Ct numbers in 2015 and 2021. The measured unit hydrograph is used as a reference in calculating the Synder synthetic unit hydrograph method. Test the validation of the two methods using the correlation coefficient. The results of this study showed an increase in tightness in the form of an increased runoff coefficient from 0.26 in 2015 to 0.34 in 2021. This increase in tightness is also in line with the increase in peak discharge using the Measured unit hydrograph in 2015 of 73.3757 m³/s and 2021 of 139.1005 m³/s. The results of the correlation test between the two methods obtained very strong correlation results with a 2015 R-value of 0.96 and a 2021 R-value of 0.92. The non-physical parameters of the watershed, namely Ct and Cp, were optimal in the Ngadipiro Sub-watershed in 2015, the Ct value was 2.2 and the Cp value was 0.9, while in 2021 the Ct value obtained was 1.3 and the Cp value was 1.1.

1 Introduction

The Ngadipiro Sub Watershed is one of the Sub Watersheds in the Bengawan Solo Hulu River Watershed which is located in Wonogiri Regency, Central Java Province. The Ngadipiro Sub Watershed has an area of 133492.13 Ha with a main river length of 37.4578 km and the length of all rivers in the Ngadipiro Sub Watershed 825.4248 km.

Data from the Directorate General of Dukcapil, Ministry of Home Affairs (Kemendagri), Indonesia's population in 2021 is 273,879,750 people, with a population growth rate of 0.98%. This increase in population will certainly have an impact on increasing land use for community activities. Changing open green land into residential areas or commercial areas increases the tightness of the land surface. Increasing tightness causes a reduction in the amount of water that can seep in, which ultimately also changes the river flow (Rahmad et al, 2017). Population growth will result in a shift in land function to residential, industrial, and service areas which tends to increase the tightness of the land surface (Wardana et al, 2018).

Measurable unit hydrographs can be carried out if discharge data is available at the measuring post on the river to be reviewed. Several rivers have complete data in the form of water level data and rainfall data. There are river data that are complete, partially complete and some don't even have it. If data is incomplete or partially complete, analysis can be carried out using the Synthetic Unit Hydrograph (SUH) method (Irawan, 2020). SUH is a method that is often used to analyze watershed flood discharge from incomplete water level and rainfall data.

This SUH method is considered simple because it only requires data on watershed characteristics in the form of watershed area and watershed river length (Natakusumah, 2011).

According to Surentu et al (2016), determining peak discharge using the Snyder, Weduwen and Haspers SUH method appears to have a difference of approximately 20% or almost the same. Of the three methods, calculations using Snyder's SUH provide more appropriate results.

Land use changes tend to increase rapidly due to population growth and the development of urban areas. Changes in land use result in an increase in discharge, therefore it is necessary to analyze the relationship between land use and the increase in discharge that occurs in the watershed. The method used to analyze peak discharge is Snyder SUH. Correlation analysis to obtain a more appropriate peak discharge value (Putri, 2019).

Research on the Katulampa watershed to determine peak discharge using Snyder SUH. The accuracy of the measured flow hydrograph and Snyder's SUH was carried out by optimizing the ant colony algorithm. The results of the Snyder equation obtained Ct and Cp values of 1.4 and 0.19, but after Snyder's optimization, the Ct value was 1.55 and the Cp value was 0.55. The Ct and Cp values after optimization are considered better as evidenced by the standard deviation value of 0.95, before optimization the standard deviation value was 2.9 (Barid, 2020).

Using the Snyder SUH method, it is necessary to analyze the increase in land tightness in the Ngadipiro sub-watershed in 2015 and 2021, which affects the Cp and Ct numbers. Correlation or suitability to the Measurable

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Unit Hydrograph (UH) uses the correlation coefficient (R).

2 Research methods

Research methods include :

a. Secondary data in this research are discharge data and rainfall data obtained from the Bengawan Solo River Region Center (BBWS Bengawan Solo).

b. The Thiessen polygon method requires data on rainfall watershed.

c. SNI 2415:2016 explains the range of runoff coefficient values for each land use.

d. Baseflow analysis

e. Hydrograph analysis

f. Snyder SUH analysis

g. Validation and calibration

Rainfall data

This research uses daily rainfall recording data at rain stations in 2015 and 2021. Rainfall data was obtained through the BBWS which was downloaded via the site https://bbwsbengawansolo.net/lisa/.

Discharge data

This research uses recorded hourly discharge data at rain stations in 2015 and 2021. Discharge data was obtained through the BBWS which was downloaded via the website https://bbwsbengawansolo.net/lisa/. The discharge data obtained is discharge data at 6, 12, and 18 o’clock so interpolation needs to be done to get the hourly discharge.

Data analysis

The data needed in this research is in the form of secondary data such as daily rainfall in 2015 and 2021, and daily discharge data per 4 hours in 2015 and 2021, this data was obtained from the Bengawan Solo River Region Center located in Banaran, Pabelan, Kec. Kartasura, Sukoharjo Regency, Central Java 5716.

The data used to create watershed maps and land function divisions are geospatial data and topographic map data obtained from DEMNAS and Google EarthPro. This data is then processed using ArcGIS. Apart from that, Indonesian landform map data was also used which was obtained from the satellite image data provider site in Indonesia, namely Tanahair. Indonesia.go.id/portal-web. The data used was data for 2015 and 2021.

Increased surface impermeable

Data obtained from satellite imagery is then processed to obtain changes in land use in 2015 and 2021. The results of the processed data will produce the area of each land use, and then the runoff coefficient (C) value is analyzed which is used to calculate the measured unit hydrograph value. Runoff coefficient(C) is calculated using the U.S. Forest Service method.

The runoff coefficient formula is as follows.

\[ C = \sum \left( \frac{A_n}{\sum A \times C_n} \right) \]  

where:
- \( C \): Runoff coefficient
- \( A_n \): Watershed land use area (m²)
- \( \sum A \): total land use area/Watershed area (m²)
- \( C_n \): Flow coefficient

Thiessen polygons

Thiessen polygons are a method that is very popular among hydrology practitioners in calculating regional average rainfall which is called Thiessen Original (TO) compared to algebraic and isohyet methods (Wulandari, 2020).

The Thiessen polygon method is used based on the assumption that rainfall between one rain station area and another is considered linear and can represent the nearest rain station area. This method divides areas based on rain stations which represent a certain area in the watershed (Suripin, 2004).

The Thiessen Polygon formula used is:

\[ R_{\text{tot}} = \frac{R_a \cdot A_a + R_b \cdot A_b + R_c \cdot A_c}{A_{\text{tot}}} \]

where:
- \( R_a, R_b, R_c \): High rainfall at each rain station
- \( A_a, A_b, A_c \): Area affected (area of Polygon Thiessen station)
- \( A_{\text{tot}} \): Total area (km²)
- \( R_{\text{tot}} \): Average rainfall (mm)

Planned rainfall intensity

This rainfall data was obtained using an automatic rain recording device. However, if the available rainfall data is only daily rainfall data, then short-term rainfall intensity or hourly rainfall can be calculated using the Mononobe formula.

\[ I = \frac{R_{24}}{24} \left( \frac{24}{t_c} \right)^{2/3} \]

where:
- \( I \): Rainfall intensity (mm/hour)
- \( R_{24} \): Maximum rainfall in 24 hours (mm)
- \( t_c \): Concentration time (hours)

Baseflow

The base flow discharge is calculated using a formula because the observed discharge data for the base flow at the research location is not adequate (Amri, K, et al, 2021). The base flow discharge is calculated using the following equation.

\[ Q_b = 0.4751 \times A^{0.6444} \times D^{0.9430} \]

Where the D value is calculated using the following equation.

\[ D = \frac{L}{A} \]
D = River Network Density
L = Length of river (km)
A = Watershed area (km²)

**Rain distribution analysis**

The rain distribution used refers to research conducted by Sobriyah (2005) which has also been used in Wardhani’s (2012) research that for the Bengawan Solo watershed using a rain duration of 4 hours, the rainfall ratio pattern for consecutive hours is 40.50%, 31.25%, 14.75%, 13.50%.

**Measurable unit hydrograph**

According to Triatmodjo (2008), the decrease in the UH from the measured UH obtained from effective rainfall is calculated using the following equation.

\[
Q_n = \sum_{m=1}^{M} P_m q_{n-m+1}
\]

where:
- \(n = 1, 2, 3, 4, 5, \ldots, N\)
- \(m = 1, 2, 3, 4, 5, \ldots, M\)
- \(Q_n = \) Direct runoff hydrograph
- \(P_m = \) Effective rain
- \(q_{n-m+1} = \) Unit hydrograph
- \(N = \) Number of ordinates of the direct runoff hydrograph
- \(M = \) Number of durations of consecutive rain

**Snyder SUH**

According to Natakusumah et al (2011), the HSS method is a method that is quite often used to analyze unmeasured watershed flood discharge. Sri Harto (2000) states that the Snyder SUH is determined by peak discharge (m³/sec), base time, peak time, and lag time. These elements are related to the area of the watershed, the length of the main river flow, and the length of the main river which is measured from the discharge to the center of gravity of the watershed.

To obtain the Snyder synthetic unit hydrograph value, the following equation is used.

\[
T_p = C_t (L \times L_c)^{0.3}
\]

\[
Q_p = C_p \frac{A}{T_p}
\]

\[
T = 3 + \frac{T_p}{8}
\]

\[
t_D = \frac{T_p}{5.5}
\]

If the effective rain duration \(tr\) is not the same as the standard rain duration \(tD\), then:

\[
tpr = tp + 0.25 (tr - tD)
\]

\[
Qpr = Q_p \frac{t_p}{t_D} \frac{tp}{PR}
\]

where:
- \(tD\) = Standard duration of effective rain (hours)
- \(tr\) = Effective rain duration (hours)
- \(tp\) = Time from the center of gravity of the effective rainfall duration \(tD\) to the peak of the unit hydrograph (hours)

**Correlation coefficient (R) method**

According to Arun Goel (2011) Correlation Coefficient (R) is one of the criteria used to determine the error rate. The R-value is calculated with the following equation.

\[
R = \frac{\sum xy}{\sqrt{\sum x^2 \sum y^2}}
\]

where:
- \(x = X - X'\)
- \(y = Y - Y'\)
- \(X = \) Observation value
- \(X' = \) Average value of \(X\)
- \(Y = \) Predicted value
- \(Y' = \) Average \(Y\) value

The association or statistical measurement of covariance between two variables is the value that determines the correlation coefficient (Mahyudin, 2014).

To make it easier to determine the strength of correlation, the following criteria were created.

- \(R = 0:\) There is no correlation between two variables;
- \(0 < R \leq 0.25: \) Very weak correlation;
- \(0.25 < R \leq 0.50: \) Fair correlation;
- \(0.50 < R \leq 0.75: \) Strong correlation;
- \(0.75 < R \leq 0.99: \) Robust correlation, and
- \(R = 1.00: \) Perfect correlation

3 Results and discussion

**Land use changes**

Land use changes that occurred in the Ngadipiro sub-watershed can be seen in Figures 2 and 3.
Figures 2 and 3 explain that there has been an increase in the value of C. The C values obtained in 2015 and 2021 were 0.26 and 0.34, respectively, there was an increase in tightness of 0.08. This value shows that in 2015, 26% of the rain that falls in the Ngadipiro sub-watershed area will become surface flow, while in 2021, 34% of the rain that falls will become surface flow. The difference in runoff coefficient that occurred in the Ngadipiro Sub-watershed in 2015 and 2021 was caused by changes in land use which increased in severity. The transition of land function into residential and production land results in reduced land for water absorption, so the runoff coefficient increases.

The results of the analysis of land use changes that occurred in the Ngadipiro Sub-watershed occurred in line with population growth and increased needs for the food industry, this was proven by a significant increase in the plantation sector from 11.12% to 21.76%, apart from that it also occurred quite a large increase in housing, namely from 20.15% to 28.15%. Meanwhile, a very large decrease occurred in the use of water catchment land, namely forests, from 24.76% to 7.12%. Changes that occur in forest land greatly influence the runoff coefficient that occurs in the Ngadipiro sub-watershed, the reduction in infiltration land means that rainwater takes a long time to soak into the ground and more water runs off on the ground surface.

Measurable unit hydrograph peak discharge

The results of the measured unit hydrograph research are described as follows:

Selected rainfall in 2015 = 11.06 mm/day
Selected rainfall for 2021 = 36.36 mm/day
Rainfall intensity 2015 = 1.52 mm/hour
Rainfall intensity 2021= 5.00 mm/hour

Table 1 explains the percentage rainfall distribution multiplied by the runoff coefficient multiplied by the rainfall intensity.

<table>
<thead>
<tr>
<th>hour</th>
<th>Distribution (%)</th>
<th>2015 (Distribution %× C × It)</th>
<th>2021 (Distribution %× C × It)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40,50</td>
<td>0,1702</td>
<td>0,6843</td>
</tr>
<tr>
<td>2</td>
<td>31,25</td>
<td>0,1313</td>
<td>0,5322</td>
</tr>
<tr>
<td>3</td>
<td>14,75</td>
<td>0,0619</td>
<td>0,2492</td>
</tr>
<tr>
<td>4</td>
<td>13,50</td>
<td>0,0567</td>
<td>0,2281</td>
</tr>
</tbody>
</table>

From Fig. 4, the peak discharge values for 2015 are obtained, as follows:
Peak Discharge (Qp) = 73.3757 m$^3$/sec
Peak Hour = 18th Hour.

<table>
<thead>
<tr>
<th>Where:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HS Terukur</td>
<td>measured UH</td>
</tr>
<tr>
<td>HSS Snyder</td>
<td>Snyder SUH</td>
</tr>
<tr>
<td>Waktu (jam)</td>
<td>time (hour)</td>
</tr>
<tr>
<td>Debit (m$^3$/detik)</td>
<td>Q, discharge (m$^3$/second)</td>
</tr>
</tbody>
</table>

From Fig. 5, the peak discharge values for 2021 are obtained, as follows:
Peak Discharge (Qp)= 139.1005 m$^3$/sec
Peak Hour = 12th Hour
Snyder SUH

Effective Rain Duration \((Tr) = 4\) hours
Sub-watershed area \((A) = 1334.9212\) km\(^2\)
River Length \((L) = 37.4578\) km
Length of Center of Gravity \((Lc) = 18.7288\) km
The results of peak discharge calculations using the Snyder SUH 2015 method can be seen in Fig. 6.

Ct and Cp number coefficients

According to Baird et al (2020), a small Cp value indicates that the water reservoir is very wide, thereby reducing peak runoff discharge. Therefore, the greater the Cp value the smaller the DAS reservoir. Ct is the value of the soil and river gradient parameters. If the watershed becomes more sloping, the Ct value will be smaller. The optimal Ct and Cp values in the Ngadipiro Sub-watershed can be seen in Table 2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Ct</th>
<th>Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>2.2</td>
<td>0.9</td>
</tr>
<tr>
<td>2021</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

After testing the level of correlation with the Ct and Cp values contained in Table 2, it is considered optimal and can be used to calculate the Snyder synthetic unit hydrograph in the Ngadipiro Sub-watershed in 2015 and 2021. The comparison graph of the measured UH and Snyder SUH can be seen in Figures 8 and 9.

Validation test

The hydrograph validation test was carried out to determine the suitability between the Measured UH method and Snyder's SUH. This suitability validation test uses the Correlation Coefficient \((R)\) method by testing the volume of each method.

From the validation test results obtained, the R-value obtained was 0.96 so the correspondence between the Measured UH method and the Snyder SUH in the Ngadipiro Sub-watershed in 2015 was included in the robust correlation and the Ct coefficient was 2.2 and Cp 0.9 is considered optimal.

From the validation test results obtained, the R-value obtained was 0.92 so the correspondence between the Measured UH method and the Snyder SUH in the Ngadipiro Sub-watershed in 2021 is a very strong correlation. So the Ct and Cp values of 1.3 and 1.1 are considered optimal.

4 Conclusion

From the results of research regarding peak discharge in the Snyder synthetic unit hydrograph due to changes in land use in the Ngadipiro sub-watershed, the following conclusions can be drawn:

- Changes in land use in 2015 and 2021 saw an increase in the runoff coefficient. The runoff coefficient value in 2015 was 0.26 and in 2021 it was 0.34.
The results of peak discharge analysis using the measured unit hydrograph method using the same land use data in 2015 produced a peak discharge of 73.3757 m³/s with a peak hour of 18 hours, while in 2021 the peak discharge results obtained were 139.1005 m³/s with peak hours at noon.

The peak discharge of HSS Snyder in 2015 was 75.10 m³/s with a peak hour of 18 hours, while in 2021 the peak discharge results were 148.89 m³/s with a peak hour of 12 hours.

An increase in tightness of 0.08 causes a decrease in the Ct value of 0.9 and an increase in the Cp value of 0.2.

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References