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The Development of Ungauged-Catchment Integrated-Similarity Unit Hydrograph to Estimate Inflow of Wonogiri Reservoir

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ABSTRACT The Wonogiri Reservoir is a multipurpose reservoir at the Upper Bengawan Solo Watershed, primarily designed to serve as a flood control system. However, there is no accurate estimation of the inflow into the reservoir due to the limited availability of hydrological stations. Observations showed only four out of ten unit hydrographs of the Wonogiri Reservoir watershed. Therefore, this study was conducted to apply an integrated similarity-based approach for designing unit hydrographs in ungauged catchments. The process involved evaluating the integrated similarity between pairs of gauged-ungauged catchments using hydrologic and physical property parameters. This led to the selection of the donor or gauged catchment with the highest similarity score to develop the unit hydrograph for the ungauged catchments. The developed UHs were further applied to estimate the reservoir inflow for the December 25, 2007, flood event. The results showed that the computed peak discharge was 10.9% lower than a previous study. Subsequently, the HEC-HMS simulation model was used to project the updated design flood hydrographs to the reservoir. The design rainfall was derived from automatic rainfall recorder (ARR) and PERSIANN satellite-based data. The ARR data showed that the extreme rainfall duration was 5 hours while satellite data indicated 6 hours. The application of the ARR 5-hour duration to the updated flood hydrographs led to a peak discharge of 5123 m^3 s^{-1}, 7041 m^3 s^{-1}, and 10,370 m^3 s^{-1} for the 60-year, 500-year, and PMF floods respectively in line with the flood design criteria of Wonogiri Reservoir. These estimates were observed to be significantly higher than the 1982 design floods which were 4000 m^3 s^{-1}, 5100 m^3 s^{-1}, and 9600 m^3 s^{-1} respectively. This updated flood control design was important to renew the operation rule of the Wonogiri reservoir during flood periods.

KEYWORDS Ungauged Catchment; Integrated Similarity; Unit Hydrograph; Wonogiri Reservoir Flood Inflow; HEC-HMS.

1 INTRODUCTION

The Wonogiri Reservoir is geographically located in the upper section of the Bengawan Solo River in the Wonogiri Regency of Central Java. It was built mainly to control and mitigate floods in the Bengawan Solo River basin (Nugroho, 2015). Due to the issue of sedimentation, the reservoir was split into two including the sediment storage reservoir (SSR) to trap the sediments from the Keduang watershed and the main reservoir (MR) to deliver water to the downstream areas (Jayadi et al., 2018; Morris, 2020; Wijayanti et al., 2021). The only catchments with rainfall and water level monitoring stations in the Wonogiri Reservoir watershed are Keduang, Temon, and Wuryantoro (Oktavia, 2013). The unit hydrograph (UH) model of these selected or donor catchments has been analyzed by evaluating the similarity of drainage density (the ratio of the total river network length over the area of the catchment) to the distance between catchments in order to construct the unit hydrograph (UH) for the ungauged catchment (Oktavia, 2013; Pradipta, 2014). Furthermore, Sulistyowati et al. (2018) identified the relationship between rainfall and discharge in the Keduang and Wiroko watersheds, and the results were used to derive the UH in these catchments region. It is pertinent to note that there are four donor catchments in Wonogiri Reservoir Watershed, and these include Keduang, Temon, Wuryantoro, and Wiroko. Previous studies showed that the UH of six catchments within the reservoir has not been observed. Meanwhile, the flood inflow needs to be evaluated to manage a reservoir with dual gated spillways, including the existing and new, as well as to develop early-warning systems for flood disaster mitigation (Renaningsih et al., 2018). According to Nugroho (2015), 149 mm of rainfall caused a peak flood discharge of 3331 to 4993 m^3 s^{-1} on December 25, 2007, and this was found to be comparatively contrasting to the peak flow of 3950 m^3 s^{-1} affected by 215 mm of rainfall in 1966 as reported by Overseas Technical Cooperation Agency (Overseas Technical Cooperation Agency (OTCA), 1974).

The selection of an ideal reference or donor catchment is the primary issue observed in the process of transferring information from catchments with hydrological gauges to ungauged ones (Patil and Stieglitz, 2012). Spatial proximity (SP), physical similarity (PS), and integrated similarity (IS) are often used in selecting these donor catchments. The IS approach has been identified as the best to deal with synthetic UHs in ungauged catchments (Khoosal, 2021). This is the reason the inflow to the Wonogiri Reservoir from the ungauged catchments was proposed to be estimated using the spatial and physical characteristics of the gauged catchments instead of focusing only on the nearest catchments. The approach has the ability to provide new insight into the assessment of the reservoir inflow from the ungauged catchments. Moreover, the flood hydrographs for the 60-year, 500-year, and PMF return periods adopted as the design criteria for the Wonogiri Reservoir need to be updated based on current hydrological conditions.

2 METHODS

2.1 Catchment Properties Analysis and Donor Catchment Selection Method for The Ungauged Catchments

The Wonogiri Reservoir watershed has ten catchments (Oktavia, 2013). These include the Pondok and Keduang draining to the SSR as well as the Kepuh, Wiroko, Temon, Upper Solo, Alang Ngunggahan, Kedungguling, Wuryantoro, and Durensewu flowing to the MR. The four gauged catchments are further visualized with grey color in the following Figure 1.

The latest available digital elevation model with the 0.27-arcsecond resolution issued by the Geospatial Information Agency of Indonesia (2018), DEMNAS, was used to identify the catchments' physical characteristics. Moreover, the length, mean slope, and catchment area of the main rivers were evaluated using a geographic information system software (QGIS version 3.16.9) and the results are presented in Table 1. The time to peak (T_p) was calculated using the empirical formula mentioned in Chow et al. (1988) as provided in Equation (1).

$$T_p = \frac{t_r}{2} + t_p \tag{1}$$

The effective rain duration (t_r) was set at one hour because the UH interval was in hourly time-step while the basin lag time (t_p) value was estimated to be $0.6T_C$ (Chow et al., 1988). Moreover, the time of concentration was computed in hours using the Kirpich (1940) formula presented in Equation (2), and this is one of the methods recommended by the Indonesia National Standard SNI 2415:2016 (National Standardization Agency of Indonesia, 2016). The equation operates as a function of the river length (L) in km unit and the watershed slope (S).

$$T_c = 0.066L^{0.77}S^{-0.385} \tag{2}$$

The distance between the combinations of the gauged and ungauged catchments is presented in Table 2 and was further applied in the spatial proximity method.

Every parameter was ranked according to the similarity of a possible pairing between the property data of gauged and ungauged catchments to determine the appropriate donor catchment for the ungauged catchment. A higher rank was obtained when the parameters of the catchments matched were more similar. Moreover, the rank for donor selection was calculated by summing up the rank of any individual properties using the same weighting ratio. This was achieved by Khoosal (2021) using characteristics such as the size of the catchment, length of a main river, length of the river from the outlet points closest to the catchment centroid, slope, and average annual precipitation. A similar approach was applied in this study based on spatial proximity, physical properties, and integrated similarity which is a combination of the first two. Furthermore, the donor catchment selection was evaluated using properties such as mean annual rainfall, river length, catchment area, drainage density, and time to

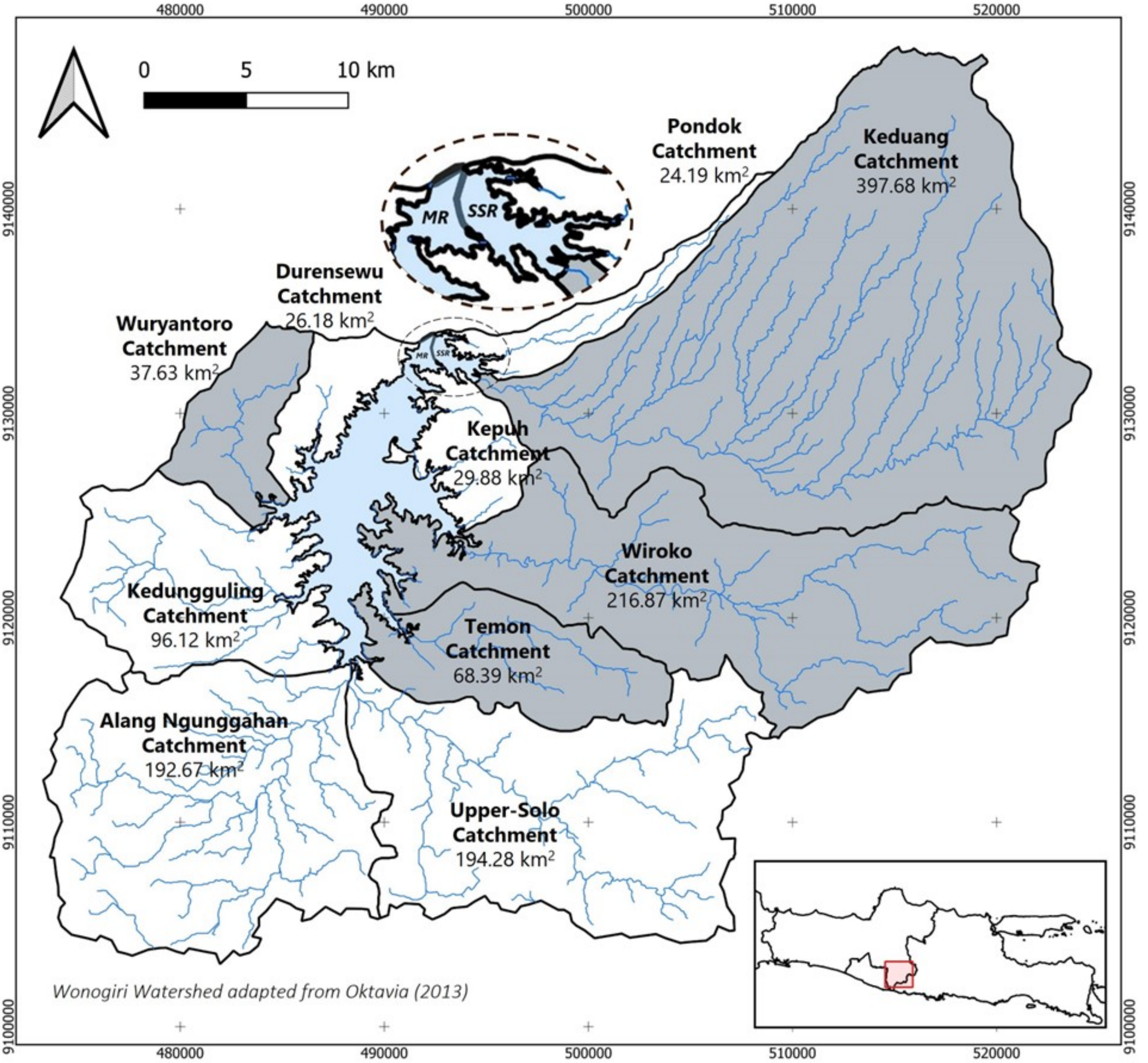

Figure 1 The ten catchments of the Wonogiri Reservoir watershed (adapted from (Oktavia, 2013))

peak. These were different from the application of only the drainage density and distance between the two catchments in previous studies.

2.2 The Transformation of the Observed Unit Hydrograph to The Ungauged Catchments

The downstream sub-catchment was interpreted by assuming it has the same physical and hydrological characteristics as the upstream sub-catchment (Sadeghi and Singh, 2010). This was implemented to ensure all the flow discharge properties were proportional to the area ratio as presented in Equation (3).

$$\frac{R_i}{R_T} = \frac{A_i}{A_T} \tag{3}$$

Where, R_i and R_T are sub-catchment i and total catchment runoff characteristics (volume and peak runoff), respectively while A_i and A_T are the areas of sub-catchment i and the whole catchment respectively.

The ungauged catchment with flow from the donor or measured catchment was examined by Oktavia (2013) and Pradipta (2014). The UH of the ungauged catchment was determined by modifying the UH measured for the donor catchment using

Table 1. Physical properties of Wonogiri Reservoir watershed

Catchment	Area, A (km)	River length, L_{River} (km)	Total river network (km)	Slope, S	Drainage density, D	Time to peak, T_p (hour)	Mean annual rainfall, Pann * (mm)
Keduang**	397.68	45.69	323.70	0.007	0.81	6	1864
Temon**	68.39	12.40	59.56	0.011	0.87	2	1698
Wuryantoro**	37.63	11.45	19.72	0.013	0.52	2	1775
Wiroko**	216.87	39.13	138.87	0.022	0.64	3	1703
Alang Ngunggahan	192.67	28.65	181.11	0.011	0.94	3	1464
Durensewu	26.18	2.98	18.68	0.011	0.71	1	1779
Kedungguling	96.12	12.16	97.80	0.026	1.02	2	1525
Kepuh	29.88	5.26	25.66	0.017	0.86	1	1767
Pondok	24.19	16.64	30.49	0.018	1.26	2	1827
Upper Solo	194.28	29.19	133.28	0.024	0.69	3	1346

Note: *Perum Jasa Tirta I (2020), ** The gauged catchments

Table 2. Distance matrix of gauged and ungauged catchment pairs

Catchment distance (m)	Alang Ngunggahan	Durensewu	Kedungguling	Kepuh	Pondok	Upper Solo
Keduang	38,545	25,030	33,629	18,944	12,298	26,878
Temon	16,533	15,613	15,878	10,560	17,433	7400
Wuryantoro	18,855	4508	8110	11,189	17,534	24,276
Wiroko	27,472	21,457	25,983	14,300	14,954	13,713

the ratio of the peak discharge to the time-to-peak. The peak discharge of the ungauged catchment was further calculated through the multiplication of the ratio of the ungauged-gauged catchment by the Q_p of the donor catchment. Meanwhile, the T_p was computed using the empirical formula associated with Kirpich's concentration time.

This study was conducted by implementing the normalization approach of the gauged catchment UH for Qt against the Q_p (y-axis) value and the variable t against T_p (x-axis). Moreover, the Q_p used for the ungauged catchments was determined by multiplying the area ratio of the catchment pair by the Q_p of the gauged catchment.

2.3 Hydrology Model for the Wonogiri Reservoir Inflow

2.3.1 Rainfall Data

Previous studies on Wonogiri Reservoir were conducted by adopting 60-year, 500-year, and PMP (probable maximum precipitation) return periods of rainfall to fulfill the requirements specified in the design of the dam (Nippon Koei Co. Ltd., 2010; Pradipta, 2014). These return periods were also applied in this study and the rainfall designed for the ten catchments in the study area is presented in the following Figure 2 based on Perum Jasa Tirta I (2020).

The ARR data from five rainfall stations, including Pracimantoro, Batuwarno, Tirtomoyo, Jatisrono, and Wonogiri Dam, were used to examine the duration of extreme rainfall events and a total of 128 precipitation cases were recorded from 2009 to 2019 (Perum Jasa Tirta I, 2020). Moreover, the PERSIANN PDIR-Now satellite precipitation data from 2001 to 2022 for five station sites were also reviewed to determine the extreme rainfall pattern for a longer historical period. Satellite data are usually required to be correlated with those from ground rainfall stations, therefore, they were only used to understand the pattern of typical extreme rainfall without focusing on the depth. It was also noted that the PERSIANN PDIR-Now data has the ability to provide highly reliable near-real-time precipitation data in addition to its easy availability like the other types of PERSIANN data (Nguyen et al., 2020).

Based on ARR datasets, 4-hour rainfall was recorded 37 times, thereby, indicating occurred at 28.9% of all extreme rainfall events followed by 5-hour rainfall at 24.2%. This statistical analysis showed that the difference between the 4- and 5-hour duration was just 5%. Meanwhile, the interpretation of the median value or percentile principle showed that the typical duration was 5 hours in line with the National Engineering Handbook Section 4: Hydrology (SCS-USDA, 1969). This means the extreme rainfall event was considered to have lasted for 5 hours and this was the representative value.

The satellite-based data was observed to have indicated 5 hours as the most frequent rainfall duration by occurring at 18.7% of the period or 117 out of 627 events followed by 6 hours at a close frequency of 17.2% or 108 out of 627 events. However, the median was found to be 6 hours. The distribution patterns for short-duration rainfalls are presented in Figure 3 and minor variations were observed between those obtained through ARR and the satellite.

The PMP design rainfall was distributed using the Huff empirical method for the 24-hour duration (Huff, 1990). This Huff distribution fit was studied by Yudianto et al. (2021) using the rainfall characteristics for the PMP design over the Ketro Dam located in the Sragen Regency of Central Java. Moreover, the duration was selected based on the Guidelines for Survey, Investigation, and Design Planning of Earthfill-Dams (Direktorat Jenderal Pengairan Departemen Pekerjaan Umum, 1999).

2.3.2 Transform Model

The UHs were utilized to establish the rainfall-runoff transformation method for each catchment. Furthermore, the average of several UHs derived from hourly rainfall-discharge data was determined to obtain the UH for the gauged catchments. The UHs used for Wuryantoro and Temon catchments were modified based on the values reported by Pradipta (2014) while those applied to Keduang and Wiroko catchments were adapted from Sulistyowati et al. (2018). The UHs for these four catchments were updated by applying new area and time-to-peak parameters as shown in Figure 4. Meanwhile, the UHs for the six ungauged catchments were developed based on the transformation model procedure.

2.3.3 SCS-Curve Number Loss Method

Land use data were retrieved from the imagery of Landsat-8 satellite data of April 20, 2021, (USGS, 2021), with relatively low cloud cover. Moreover, the land use in the Wonogiri watershed was categorized using the Semi-automatic Classification Plugin (SCP) of the QGIS program while the soil data for the hydrological soil group (HSG) was identified through the Harmonized World Soil Database (FAO and IIASA and ISRIC and ISS-CAS and JRC, 2012). Keduang and Pondok catchments were mainly classified as HSG type B while the rest were HSG type C. The land use and classification

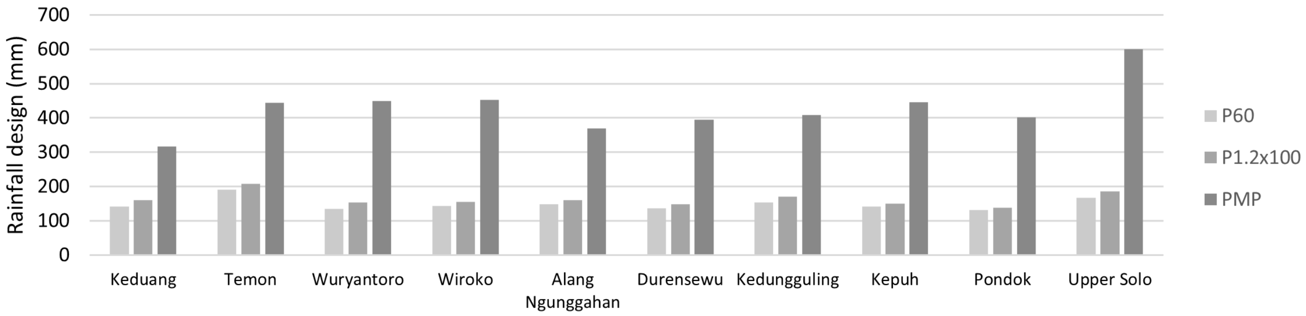

Figure 2 Design rainfall for the Wonogiri Reservoir watershed

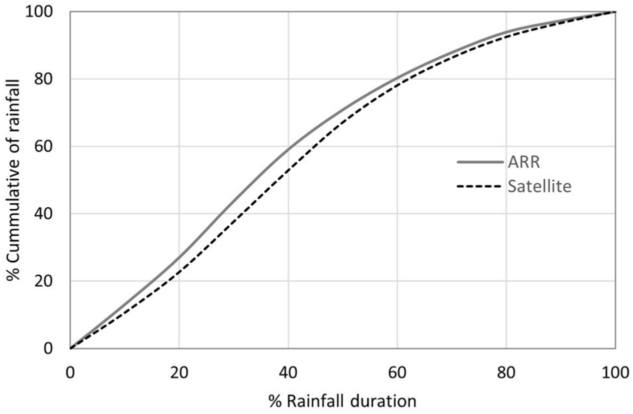

Figure 3 Rainfall distribution patterns of Wonogiri Reservoir watershed

of each catchment were later analyzed using the QGIS software.

The assessment of runoff components (effective rainfall) was observed to depend on land use based on the information presented in Technical Release 55 on Urban Hydrology for Small Watersheds (U.S. Department of Agriculture, 1986). Moreover, the SCS-CN method was used to deduct the infiltration or losses from the daily rainfall to provide effective hourly rainfall as shown in Equation (4).

$$\Sigma P_{eff} = \frac{(\Sigma P - I_a)^2}{\Sigma P - I_a + S} \tag{4}$$

Where, P_{eff} is the effective rainfall (mm), P is the rainfall depth (mm), I_a is an initial abstraction (mm), and S is the maximum potential retention (mm) calculated using Equation (5). Moreover, the CN(II) and CN(III) computed as the soil parameter of antecedence moisture content for the ten catchments of the Wonogiri watershed are listed in Table 3.

$$S = (\frac{1000}{CN} - 10)\, 25.4 \tag{5}$$

2.3.4 Baseflow

The baseflow was assessed using the average half-monthly data for the wet-year discharge during the flood period. According to the 2016 Operations Manual, flood season was defined to last from the beginning of December to the end of March (Nippon Koei Co. Ltd., 2016) and it was reported by the Perum Jasa Tirta I (2020) that the baseflows for this period were 31.4 m^3 s^{-1} and 64.2 m^3 s^{-1} to the SSR and MR, respectively.

Table 3. The composite catchments' CN of Wonogiri Watershed

Catchment Area	CN (II)	CN (III)
Alang Ngunggahan	77	89
Durensewu	79	89
Keduang	65	81
Kedungguling	76	88
Kepuh	76	88
Pondok	68	83
Upper Solo	76	88
Temon	78	89
Wiroko	75	87
Wuryantoro	78	89

2.3.5 Basin Model of Flood Hydrograph Simulation

The HEC-HMS software was used to compute the design flood hydrographs at the SSR and MR as the total inflow of Wonogiri Reservoir. The process involved assigning the downstream Keduang and Pondok catchment basins to the SSR junction while the others were projected to flow into the MR junction, as indicated in Figure 5. Moreover, the HEC-HMS basin model was suggested to be compared to the existing flood event byBunganaen et al. (2021). The hydrologic model was validated using rainfall-runoff events and data obtained from previous investigations (Nugroho, 2015). The results obtained from this study were also compared to those of previous investigations (Pradipta, 2014; Perum Jasa Tirta I, 2020; Wijayanti et al., 2021).

3 RESULTS

3.1 Selection of Donor Catchment

The ungauged catchments were listed for every probable pair to the gauged catchment according to their characteristics. Each ungauged catchment was matched with the possible donor catchments and their individual properties were ranked as in-

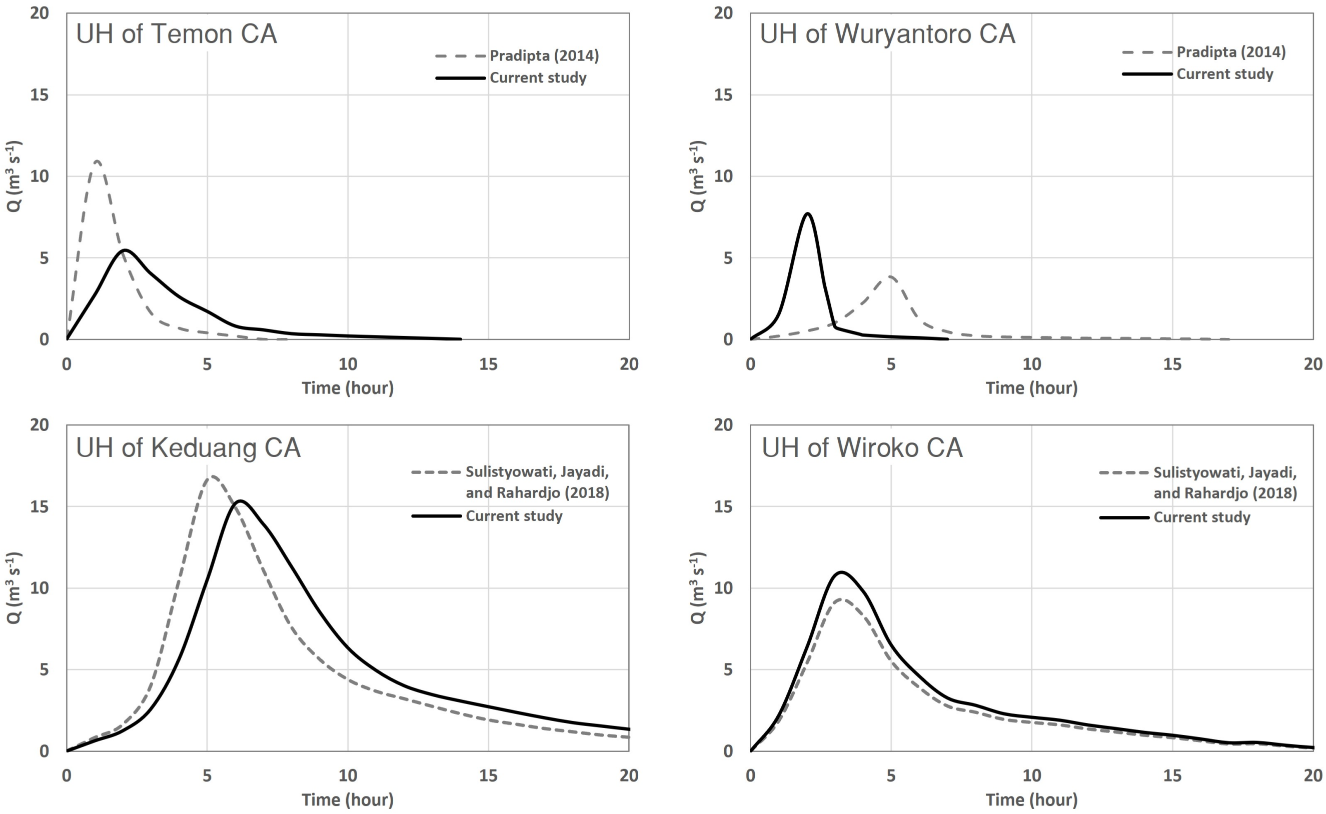

Figure 4 The gauged catchments UH adapted from Pradipta (2014) and Sulistyowati et al. (2018) with the adjustment of recently calculated area and time-to-peak parameters

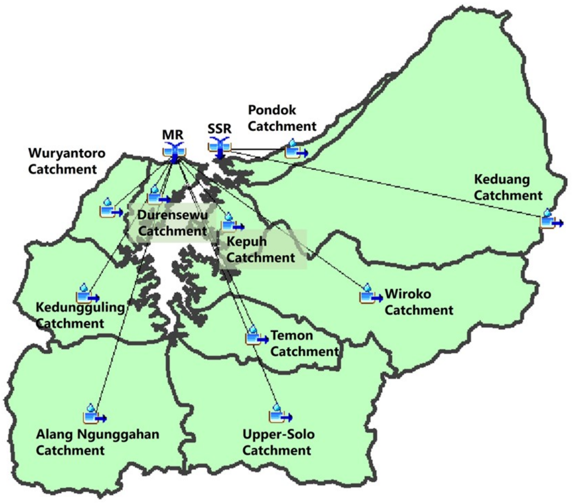

Figure 5 HEC-HMS basin model of Wonogiri Reservoir Watershed

dicated in the following Table 4. This was in line with the study conducted by Khoosal (2021) using spatial proximity, physical similarity, and integrated similarity methods.

These three methods were also applied to the ungauged catchments and the results showed that the donor catchment for Alang Ngunggahan and Kedungguling was Temon while Durensewu and Kepuh had Wuryantoro. Meanwhile, Kedungguling and Kepuh were not located close to their donor. The results further showed that the best donor for Pondok was Temon even though it was closer to Keduang. Lastly, the donor for Upper Solo was Wiroko even though it was closer and more similar to Temon.

3.2 Unit Hydrograph for The Ungauged Catchments

The UH for the ungauged catchments was derived by interpolating the dimensionless UH of the donor catchment with the y-axis of (q/Q_p) and the x-axis in the form of (t/T_p) as shown in Figure 6. The UH for Alang Ngunggahan, Kedungguling, and Pondok was adapted from the Temon UH while those for Durensewu and Kepuh UHs were from the Wuryantoro UH. Meanwhile, the Upper Solo UH was based on Wiroko UH.

3.3 Inflow Hydrograph Comparison of December 2007 Flood Event

The Wonogiri Reservoir flood hydrograph associated with December 25-27, 2007 event was pre-

Table 4. Rank of possible combinations of donor and ungauged catchments

Ungauged catchment	Potential donor catchment	Rank according to individual property							Rank		
		Dist	Pann	Lriver	S	A	D	Tp	SP	PS	IS
Alang Ngunggahan	Keduang	4	4	3	3	4	2	4	4	4	4
	Temon	1	1	2	1	2	1	2	1	1	1
	Wuryantoro	2	3	4	2	3	4	2	2	3	3
	Wiroko	3	2	1	4	1	3	1	3	2	2
Durensewu	Keduang	4	4	4	3	4	2	4	4	4	4
	Temon	2	3	2	1	2	3	1	2	2	2
	Wuryantoro	1	1	1	2	1	4	1	1	1	1
	Wiroko	3	2	3	4	3	1	3	3	3	3
Kedungguling	Keduang	4	4	4	4	4	2	4	4	4	4
	Temon	2	1	1	3	1	1	1	2	1	1
	Wuryantoro	1	3	2	2	2	4	1	1	2	2
	Wiroko	3	2	3	1	3	3	3	3	3	3
Kepuh	Keduang	4	4	4	4	4	2	4	4	4	4
	Temon	1	3	2	3	2	1	1	1	2	2
	Wuryantoro	2	1	1	1	1	4	1	2	1	1
	Wiroko	3	2	3	2	3	3	3	3	3	3
Pondok	Keduang	1	1	4	4	4	2	4	1	4	4
	Temon	3	4	1	3	2	1	1	3	2	1 *
	Wuryantoro	4	2	2	1	1	4	1	4	1	1
	Wiroko	2	3	3	2	3	3	3	2	3	3
Upper Solo	Keduang	4	4	2	4	4	2	4	4	4	4
	Temon	1	1	3	3	2	4	2	1	2	2
	Wuryantoro	3	3	4	2	3	3	2	3	3	3
	Wiroko	2	2	1	1	1	1	1	2	1	1

Note: SP = spatial proximity ranked only by distance, PS = physical similarity graded by P_Ann, L_River, S, A, D, and T_p, and IS = integrated similarity graded based on all the parameters.

* The donor for Pondok was Temon with an elongated catchment shape and relatively similar drainage density.

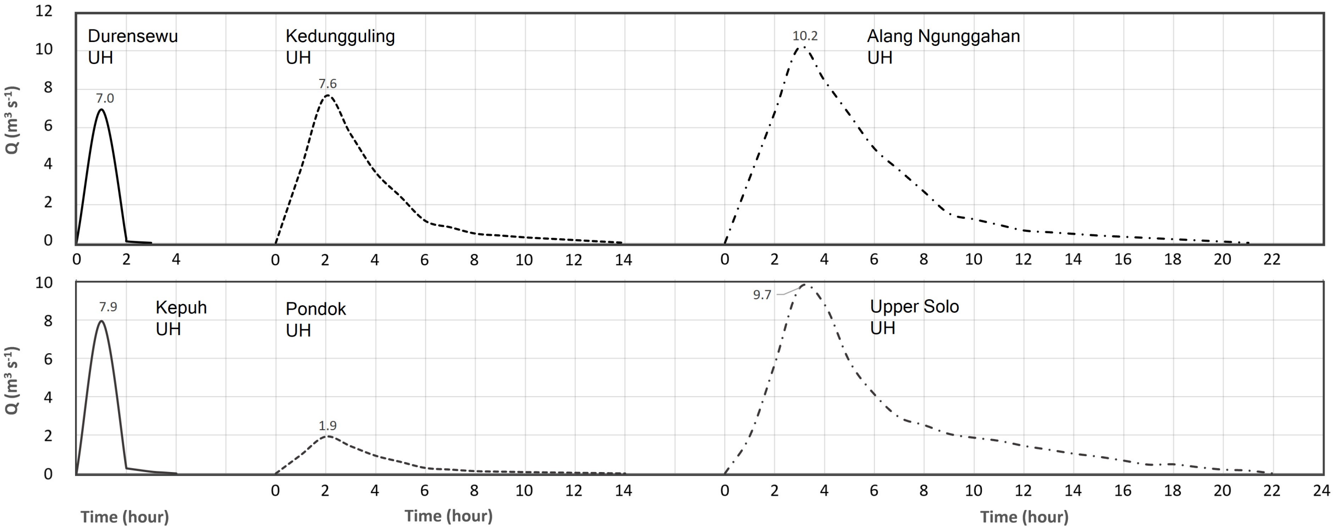

Figure 6 Proposed UHs for the ungauged catchments based on selected donor catchments through the integrated similarity method

dicted by Nugroho (2015). The Wuryantoro UH event of December 26, 2007 was used as the reference to simulate the flood hydrographs in the other nine catchments using the catchment area

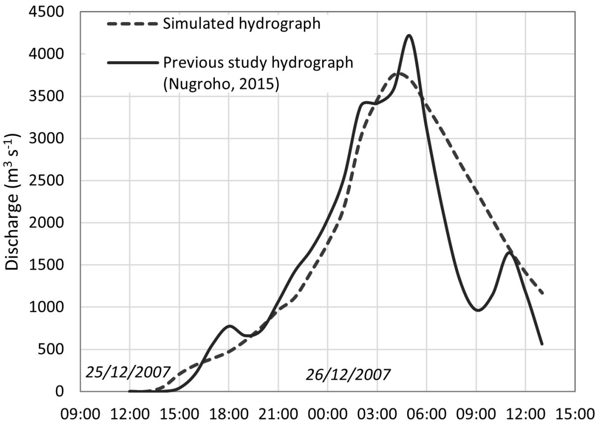

Figure 7 HEC-HMS model comparison for the December 25, 2007 flood

ratio. Moreover, the direct runoff hydrograph was utilized as the measured data input for the HEC-HMS reservoir inflow model after separating the baseflow using the straight-line approach. The hydrological behavior of reservoir inflow was later analyzed using the modified UHs data. Furthermore, the optimized HEC-HMS trial solution for the SCS-CN loss parameter was observed to have yielded soil conditions close to AMC-III with $I_a \approx 0.05\times S$.

The maximum discharge of the computed model was found to be 3754 $m^3\ s^{-1}$ while the peak discharge predicted by Nugroho (2015) was 4213 $m^3\ s^{-1}$ after baseflow separation as indicated in Figure 7. The simulation result also showed that the peak was 10.9% lower than the reference data estimated by Nugroho (2015) through the prediction of the inflow from the other catchments using transformed Wuryantoro-UH. Meanwhile, it was difficult to determine the inflow of Wonogiri Reservoir because there was no data on the discharge. This led to the application of the unit-hydrograph to determine the inflow using assumptions and simplifications of hydrological processes.

3.4 The Design Flood for Wonogiri Reservoir

The flood hydrographs of Wonogiri Reservoir were calculated for return periods of 60 years and 1.2×100 years for 5- and 6-hour rainfall durations based on the differences in the duration of extreme rainfall events from the ARR and satellite-based data. The peak discharge of 60-year flood was found to vary between 4418-4754 $m^3\ s^{-1}$, 1220-1291 $m^3\ s^{-1}$, and 4906-5123 $m^3\ s^{-1}$ at MR, SSR, and total inflow respectively as indicated on the left side of Figure 8. Meanwhile, the Q_p of the 1.2×100-year flood was between 6021-6510 $m^3\ s^{-1}$ for MR, 1779-1909 $m^3\ s^{-1}$ for SSR, and 6743-7041 $m^3\ s^{-1}$ for the total inflow. The Q_p of PMF at SSR and MR was recorded to be 2192 and 8906 $m^3\ s^{-1}$ respectively while the peak discharge of the total inflow was 10,370 $m^3\ s^{-1}$. A five-hour duration was also used for further analysis based on ground-rainfall characteristics of 60 and 1.2×100-year design flood and the 24-hour rainfall was discovered to be distributed for the PMF as presented on the right side of Figure 8. The flood hydrograph characteristics observed were compared with those reported in previous studies (Pradipta, 2014; Perum Jasa Tirta I, 2020; Wijayanti et al., 2021) in the following Table 5. The results showed that the T_p of the 1982 Design was 13 hours while Pradipta (2014) used 5 hours for all the design flood types. Moreover, Perum Jasa Tirta I (2020) was discovered to have produced 8, 7, and 17-hour for 60-year, 1.2×100-year, and PMF design, respectively while Wijayanti et al. (2021) predicted a 5-hour which was similar to the findings of Pradipta (2014) for 1.2×100-year flood and PMF but a 4-hour for the 60-year flood. Meanwhile, the T_p obtained for the 60 and 1.2×100-year floods in this study were 4 hours when the rainfall was distributed in a 5-hour duration and but the value changed to 5 hours at a 6-hour duration. The value for the PMF scenario was recorded to be 18 hours.

4 DISCUSSION

This study was observed to have applied an integrated similarity-based approach to determine the UH of ungauged catchments. The donor catchment for Alang Ngunggahan, Kedungguling, and Pondok was found to be Temon, Durensewu, and Kepuh were matched with Wuryantoro, and Upper Solo with Wiroko. The results further showed that Keduang was closer to Pondok but was unable to serve as a donor due to its size. The output from the integrated similarity was discovered to be sometimes different from the results of other methods. Khoosal (2021) also noted that the optimum method for developing UH is the integrated similarity and this is the reason it was selected to identify the donor catchments.

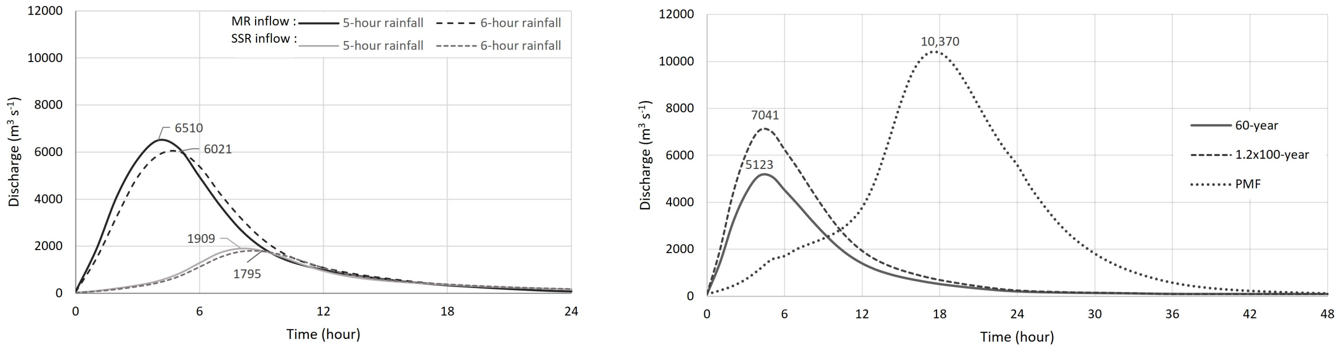

Figure 8 (a) The 60-year hydrographs for 5- and 6-hour rainfall and (b) Total inflow hydrographs to the Wonogiri Reservoir for 5-hour of 60-year 1.2×100-year design flood and 24-hour PMF design

Table 5. Comparison of the peak discharge hydrograph to previous studies

Flood return period	Peak discharge ($m^3\ s^{-1}$)					
	1982 Design	Pradipta (2014)	PJT-I (2020)	Wijayanti (2021)	Current study	
					6-hour rainfall	5-hour rainfall
60-year	4000	4373	3186	4708	4906	5123
1.2×100 year	5100	6541	4752	6780	6743	7041
PMF	9600	9707	10,106	9721	10,370	

The HEC-HMS model was verified using December 25, 2007 flood event data from Nugroho (2015). The model parameter used in minimizing the peak discharge error showed that the catchments CN should be similar to CN(III). This implies that a significant portion of the rainfall was required to transform into a runoff to achieve the desired high recorded peak discharge. Kamran and Rajapakse (2018) also reported a similar finding regarding the significance of antecedent soil moisture using CN(III) to obtain more reliable results in their model. The optimal value for I_a was reported to be a ratio of 0.05S and this was in line with the observation of Krajewski et al. (2020) that I_a was lesser than 0.20S as indicated by the 0.025S recorded for urbanized watersheds and 0.047S for agroforest basins. Moreover, the 10.9% difference recorded between the simulated peak discharge and the value in Nugroho (2015) was associated with the fact that the UH was obtained from the average of multiple flood events using a flood estimate method. The flood condition was also not constant due to the effect of certain complex natural phenomena in the hydrological basin system.

The duration of representative rainfall was found to be influencing the condition of the flood hydrograph to the MR and SSR of the Wonogiri Reservoir. This was observed in the significant increase in the hourly rainfall distribution due to the reduction in rainfall duration. Moreover, higher levels of effective rainfall were expected during periods of more extreme rainfall. The results also showed that a shorter duration of rainfall produced a more significant peak discharge when the infiltration rate was relatively small and constant. In this study, it was further observed that the peak discharge Q_p in both the SSR and MR for the 60-year flood scenario increased by 5.8% and 7.6% respectively when considering a 5-hour rainfall event compared to a 6-hour event. The same trend was observed for the 1.2×100-year flood scenario with an increment of 6.4% to 8.1% respectively for the 5-hour rainfall event. The consideration of the total inflow from both the MR and SSR showed that the Q_p for the Wonogiri Reservoir was 4.4% higher for the 5-hour rainfall event compared to the 6-hour event. The findings further showed that the peak discharge occurred 1 hour earlier when using the 5-hour event compared to the 6-hour event. The estimated Q_p for the 60-year flood was found to have increased by 23 to 28% compared to the initial design. The changes between 6-hour and 5-hour rainfall events for the 1.2×100-year flood were estimated to be 18 and 28%, respectively. Furthermore, the PMF design flood computed with a Q_p of 10,370 $m^3\ s^{-1}$ under 24 hours with the Huff distribution pattern was discovered to be 8%

higher than the original design. In terms of T_p, the 18 hours obtained in this study were found to be longer than the original design but nearly equal to the 17 hours reported by Perum Jasa Tirta I (2020).

5 CONCLUSION

In conclusion, this study found six ungauged catchments out of the ten catchments in the Wonogiri Reservoir Watershed. The accurate prediction of reservoir inflow during flood periods is crucial for effective flood control reservoir operation. Therefore, the UH of the ungauged catchments needed to be determined and this was achieved using an integrated similarity method. This method was better than using a single criterion, such as spatial proximity, because it has the ability to consider the deviation to an existing flood event in order to provide a satisfactory result. Neighboring catchments have been designated as donor catchments for UH estimation. However, this study demonstrated that the integrated similarity method is more suitable for such purposes and this led to its high recommendation for reservoir inflow prediction during flood events. Several catchment morphological parameters were also assessed comprehensively to enhance the accuracy of rainfall-runoff simulations. These include the Q_p for 60-year, 1.2×100-year, and PMF design flood which were found to be 5123, 7041, and 10,370 $m^3\ s^{-1}$ respectively, and higher than the 4000, 5100, and 9600 $m^3\ s^{-1}$ reported in 1982 Design. The results also showed that the Wonogiri Watershed experienced a 5-hour representative extreme rainfall duration and the distribution pattern observed in both the ground and satellite-based data were similar. However, further study is recommended to verify these results using available latest flood conditions.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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