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Analysis of Flood Peak Discharge Based on Watershed Shape Factors

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Abstract. Regression analysis can develop unit hydrograph modeling by approaching the peak discharge (Qp) and time to peak (Tp) parameters. The main aim of this study is to design a model of peak discharge based on watershed shape factors. The watersheds used in this study are Bontojai Watershed, Jonggoa Watershed, Kampili Watershed, Maccini Sombala Watershed, and Jenelata Watershed, which have slopes criteria below 10% and have complete recorded data of Automatic Water Level Recorder (AWLR) and Automatic Rainfall Recorder (ARR). The validation results of corrected peak discharge data produce Root Mean Squared Error (RMSE). Then, the peak discharge model was conducted by regression analysis and validated with observed unit hydrographs. The results of this study indicate that the coefficient of determination R^2 is 0.963. It means that the independent variable (x), namely the area of the watershed, the length of the main river, and the shape factor of the watershed, influences the peak discharge (Qp) of 96.3%.

Keywords: peak discharge, model, observed hydrographs, shape factor, regression

1. Introduction

The lack of hydrograph data availability becomes a constraint for water construction planning. The unavailability of the data can be caused due to damaged recording devices, negligence of officers, damaged data so that it is illegible or lost [1], or the recording device has not been installed. These constraints mean that the HSS models will provide considerable benefits. HSS can provide critical information for evaluating water safety structures (hydraulic structures) and risks based on planning [2].

Among practitioners, the application of this model is intended to analyze the design flood using rain data input. However, so far, practitioners in Indonesia are still very dominant/fanatical about using HSS Nakayasu because considered the most practical, even though the application of this model for Java Island still requires calibration of several parameters [3].

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Limantara [4] tried to make a relatively simple HSS Limantara model by including the exact physical factors of the watershed, including the length of the main river: L, the area of the watershed: A, the mean slope of the river: S, the coefficient of the roughness of the watershed: n, the length of the river from the center of gravity of the watershed to the outlet: Lc.

Given that HSS models are researched and established in areas where the characteristics of the watershed are much different from the applied watershed, they often provide inaccurate analysis results. The impact will further lead to inefficiency in determining the dimensions of the water structures. The hydrological conditions in each area are unique, so not all existing methods and concepts can be used to solve hydrological problems in every watershed. [5].

The watershed shape factor (FD) gives a better result to be used and developed further in HSS modeling [6]. The watershed shape factor is the watershed's physical characteristics and is defined as the value of the comparison between the perimeter of the watershed boundary (km) to the area of the watershed (km^2). By observing the shape factor of the watershed, parameters of HSS models can be made, including peak discharge (Qp) and time to peak (Tp), which are a function of the watershed shape factor.

In this study, a peak discharge (Qp) and time to peak (Tp) model will be made based on the shape factor analysis of the watershed (FD). This model is expected to produce relatively simple mathematical model equations. There is no need to apply parameter calibration to produce a hydrograph model that characterizes the characteristics of studied watersheds.

2. Materials and Methods

2.1 Data Required

The data required for this analysis, namely the studied watersheds map with a minimum scale of 1: 500.000, discharge data recorded by AWLR including the relevant discharge curve, hourly rain data from ARR, manual daily rainfall station data for watersheds that do not have ARR, slope data and forest area data.

2.2 Observed Unit Hydrographs: Collins Method

Observed unit hydrograph of the watershed is calculated by Collins Method, with the following calculation stages:

1. Stage Hydrograph is converted into Discharge Hydrograph with calibration.
2. Baseflow is separated from the hydrograph by one of the empirical ways: Straight Line Method [5].
3. Adequate rainfall that causes flooding is analyzed using the Infiltration Index ϕ (Phi Index).
4. An arbitrary unit hydrograph is determined by determining the ordinates with a certain quantity.
5. The initial unit hydrograph (trial and error) is multiplied by all the adequate rainfall except for the most significant effective rainfall.
6. The direct runoff hydrograph obtained above is subtracted from the measured direct runoff hydrograph. The direct runoff hydrograph generated by the maximum rainfall is obtained, the second unit hydrograph (trial and error) is obtained.
7. The second unit hydrograph is compared with the initial unit hydrograph. If there is still a large difference (following the specified error standard), then the fifth and sixth stages are repeated based on the final unit hydrograph.
8. And so on until the most negligible possible difference is obtained between the final unit hydrograph and the previous unit hydrograph.

Looking for hydrograph units of observation for each watershed, for example, for Jonggoa Watershed, is obtained by the average of observed unit hydrographs ordinate at the same hour, the peak discharge, and the time to reach the peak discharge, with the following stages:

1. Calculate the average time to peak and average peak discharge.

2. Calculate the dimensionless observed unit hydrograph (t/TP and Q/Qp) for each watershed.
3. Calculate the dimensionless average observed unit hydrograph.
4. Calculate the average of the observed unit hydrograph.

2.3 Physical Parameters of Watershed that Influence the Model

The factors that influence the model will be determined based on the coefficient of determination. The model was analyzed using the regression method with several alternatives based on the independent variables used (five, four, three, two, and one independent variable). In this analysis, peak discharge (Qp) is a fixed variable. At the same time, the watershed's physical characteristics (A, L, and FD) are independent variables. Thus, many alternatives will be generated.

2.4 Analysis of Peak Discharge (Qp) Regression Model on Watershed Shape Factors

The selection of the model is based on a rational model with the following criteria [7]:

1. Independent and dependent variables have a reasonably strong correlation. The correlation coefficient r between 0.60 – 1.00 and the most significant coefficient of determination (R^2).
2. The slightest estimate for the standard error (SEY) value.
3. There is a significant influence between the independent and dependent variables in the regression model, and the F-test is used.
4. The deviation test in the selected hydrograph model is based on the observed unit hydrograph with a reasonably low deviation level.

After analyzing by using peak discharge (Qp) as a variable, the peak discharge value (Qp) can be calculated using the regression model equation. This model will be corrected and validated with the peak discharge (Qp) calculated by observed unit hydrographs using the Root Mean Squared Error (RMSE) method.
As for the validation method formula used in this study, namely:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (Xi - Yi)^2}{N}} \quad (1)$$

With:
Xi = observation data (actual data)
Yi = estimation data (estimation result data)
N = the number of data

Table 1. Physical Parameters of Watersheds for Observed Unit Hydrographs Calculation

Parameter	Watershed				
	Bontojai	Jonggoa	Kampili	Maccini Sombala	Jenelata
Area of watershed (km^2)	277.957	128.620	630.431	666.690	222.945
Length of the river (km)	31.001	18.749	54.677	9.621	31.239
Slope	0.0258	0.0613	0.0232	0.0186	0.0173

3. Results and Discussion

3.1 Observed Unit Hydrographs: Collins Method

Physical Parameters of Watershed

In calculating the observed unit hydrographs, several physical parameters of the watershed are required in the calculation, namely the area of the watershed, the length of the river, and the slope. Analysis of physical parameters will be calculated for each studied watershed.

Based on Table 1, then can be said that the area of the watershed, the length of the river, and the slope in each watershed have different values. However, it still belongs to the predetermined watershed category. Maccini Sombala is the largest watershed of several studied watersheds, with an area of 666.690 km^2. Kampili has the longest main river with a length of 54.677 km. Therefore, the watershed with the most significant slope is Jonggoa with 0.0613. This data will be used for further analysis.

Length of the AWLR and ARR Recorded Data

Paired water level data recorded on the AWLR and hourly rainfall data recorded by ARR are used to determine the flood hydrograph with the highest single peak, which will be used for the hydrograph simulation process of the observed unit hydrographs. Therefore, it is necessary to determine the length of the data used in this analysis.

Based on Table 2, the length of the recorded data available for each studied watersheds is different. The range of ARR and AWLR data used in this study is seven until ten years. This data will be used for further hydrograph calculations.

Time and Discharge of Observed Unit Hydrographs

After obtaining the mean of peak discharge (Qp) and time to peak (Tp) values from the HSO for each year, it can be said that the value of the time and discharge relationship to form the results of the observed unit hydrographs from the Collins method.

Table 2. Length of the AWLR and ARR Recorded Data

Watershed	Year
Bontojai	2011 – 2017
Jonggoa	2008 – 2017
Kampili	2008 – 2017
Maccini Sombala	2008 – 2017
Jenelata	2011 – 2017

Table 3. Observed Unit Hydrographs of Bontojai Watershed

t/Tp	Q/Qp	T	Q
0.00	0.00	0.00	0.000
0.08	0.08	0.16	3.557
0.23	0.21	0.44	8.991
0.31	0.29	0.59	12.072
1.00	**1.00**	**1.90**	**41.926**
1.69	0.52	3.21	22.000
2.31	0.21	4.40	8.689
3.04	0.00	5.78	0.043
3.08	0.00	5.86	0.119
2.67	0.00	5.07	0.000

Table 4. Observed Unit Hydrographs of Jonggoa Watershed

t/Tp	Q/Qp	T	Q
0.00	0.00	0.00	0.000
0.06	0.05	0.14	0.714
0.21	0.21	0.47	3.351
1.00	**1.00**	**2.20**	**15.846**
1.58	0.49	3.47	7.842
2.20	0.32	4.85	5.116
2.71	0.29	5.96	4.540
2.92	0.29	6.42	4.520
2.53	0.29	5.56	4.608
2.83	0.20	6.23	3.118
3.04	0.16	6.69	2.467
3.33	0.16	7.33	2.458
3.63	0.08	7.98	1.216
3.92	0.06	8.62	0.977
4.21	0.00	9.26	0.000

Based on Table 3 to Table 7 and Figure 1 to Figure 5, the peak discharge value (Qp) and time to peak (Tp) can be calculated. Bontojai Watershed has a peak discharge of 41.926 m^3/s with a time to peak of 1.9 hours, Jonggoa Watershed has a peak discharge of 15.846 m^3/s with a time to peak of 2.2 hours, the Kampili Watershed has a peak discharge of 67.731 m^3/s with a time to peak of 3.4 hours, Maccini Sombala Watershed has a peak discharge of 30.692 m^3/s with a time to peak of 7.5 hours, and Jenelata Watershed has a peak discharge of 13.859 m^3/s with a time to peak of 3.8 hours.

Table 6. Observed Unit Hydrographs of Maccini Sombala Watershed

t/Tp	Q/Qp	T	Q
0.00	0.00	0.00	0.000
0.08	0.02	0.56	0.517
0.12	0.07	0.89	2.061
0.23	0.19	1.72	5.730
0.25	0.28	1.91	8.672
0.34	0.35	2.52	10.702
0.47	0.43	3.52	13.339
0.54	0.50	4.06	15.314
0.69	0.67	5.21	20.618
0.85	0.90	6.35	27.480
1.00	**1.00**	**7.50**	**30.692**
1.15	0.85	8.65	26.111
1.31	0.68	9.79	20.934
1.46	0.47	10.94	14.549
1.61	0.36	12.08	10.985
1.62	0.34	12.16	10.401
1.71	0.30	12.82	9.126
1.77	0.27	13.28	8.386
1.90	0.26	14.23	8.006
2.01	0.22	15.08	6.647
2.00	0.19	15.00	5.743
2.10	0.17	15.75	5.195
2.20	0.16	16.50	4.874
2.30	0.15	17.25	4.658
2.40	0.15	18.00	4.496
2.50	0.14	18.75	4.406
2.60	0.07	19.50	2.162
2.70	0.03	20.25	1.042
2.80	0.02	21.00	0.624
2.90	0.01	21.75	0.441
3.00	0.01	22.50	0.351
3.10	0.01	23.25	0.261
3.20	0.01	24.00	0.219
3.30	0.00	24.75	0.129
3.40	0.00	25.50	0.086
3.50	0.00	26.25	0.043
3.60	0.00	27.00	0.000

Table 7. Observed Unit Hydrographs of Jenelata Watershed

t/Tp	Q/Qp	T	Q
0.00	0.00	0.00	0.000
0.09	0.01	0.35	0.076
0.18	0.02	0.69	0.223
0.27	0.03	1.04	0.355
0.36	0.04	1.38	0.488
0.45	0.05	1.73	0.620
0.18	0.05	0.69	0.739
0.17	0.10	0.66	1.359
0.38	0.19	1.44	2.532
0.50	0.35	1.91	4.735
0.53	0.54	2.00	7.293
1.00	**1.00**	**3.80**	**13.589**
1.47	0.84	5.60	11.419
1.95	0.68	7.40	9.253
2.42	0.53	9.20	7.185
2.90	0.42	11.01	5.767
3.08	0.32	11.70	4.320
3.49	0.24	13.28	3.325
4.10	0.19	15.57	2.591
3.90	0.15	14.83	2.015
4.27	0.12	16.21	1.583
3.57	0.09	13.56	1.181
3.83	0.06	14.54	0.850
4.08	0.04	15.51	0.580
3.57	0.04	13.57	0.477
3.77	0.03	14.32	0.360
3.97	0.02	15.07	0.312
3.88	0.02	14.76	0.281
4.83	0.02	18.34	0.230
5.05	0.01	19.19	0.167
5.28	0.01	20.05	0.124
6.00	0.01	22.80	0.098
6.25	0.01	23.75	0.072
6.50	0.00	24.70	0.058
6.75	0.00	25.65	0.043
7.00	0.00	26.60	0.029
7.25	0.00	27.55	0.014
7.50	0.00	28.50	0.000

Explanation: t = time (hour), Tp = time to peak (hour), Q = discharge (m^3/s), Qp = peak discharge (m^3/s), T = time (hour).

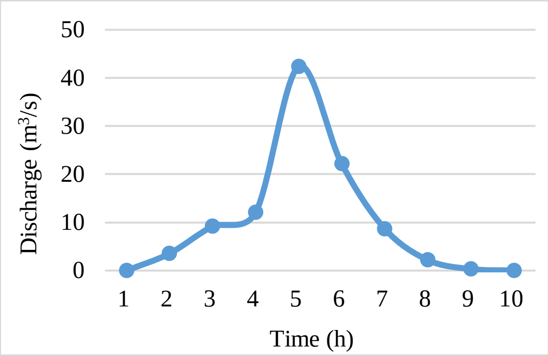

Figure 1. The curve of Collins for Bontojai Watershed

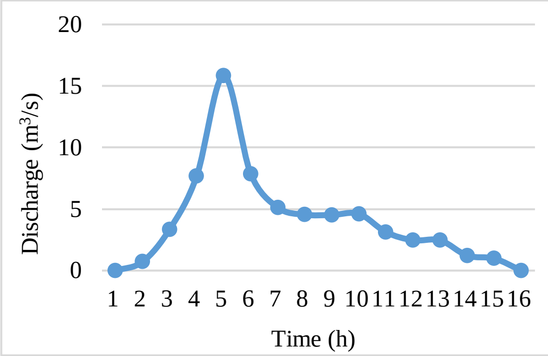

Figure 2. The curve of Collins for Jonggoa Watershed

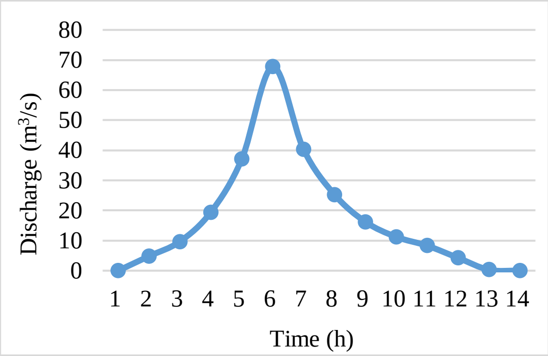

Figure 3. The curve of Collins for Kampili Watershed

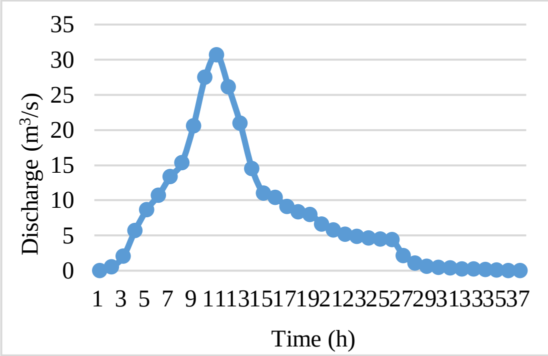

Figure 4. The curve of Collins for Maccini Sombala Watershed

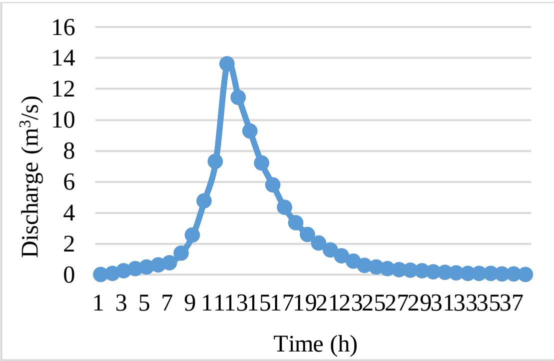

Figure 5. The curve of Collins for Jenelata Watershed

3.2 Physical Parameters of Watershed that Influence the Model

With peak discharge (Qp) as the independent variable and the area of the watershed (A), most extended river length (L), watershed shape factor (FD), namely as a comparison between the edge (K) and the area of the watershed (A) as the dependent variable, it will generate several alternative regression equations. This alternative selection is based on the rationalization of models and criteria.

From the results of morphometric map analysis using GIS applications, several physical parameters of the watershed were obtained, such as the area of the watershed (A), the length of the main river (L), the perimeter of the watershed (P), and the shape factor of the watershed (FD). Based on Table 8, it can be said that the shape factor (FD) influences the result of peak discharge value.

Table 8. Physical Parameters of Watershed that Influence the Peak Discharge (Qp) Model

No	Watershed	Tp	Qp	A	L	P	FD
		hour	(m^3/s)	km^2	km	km	
1	Bontojai	1.90	40.471	277.957	31.95	91.79	0.41434
2	Jonggoa	2.20	15.846	128.620	18.75	58.638	0.46983
3	Kampili	3.40	67.731	630.431	54.68	152.422	0.34083
4	Maccini Sombala	7.50	30.692	666.690	69.29	201.00	0.20726
5	Jenelata	3.80	13.589	222.946	31.24	82.035	0.41609

3.3 Peak Discharge (Qp) Regression Model on Watershed Shape Factor

Statistical analysis in Microsoft Excel is used for choosing the model. The model is obtained by trial and error with various regression models. From the trial and error results of various regression models, the regression model with the ln function has the highest value of coefficient determination of R squared. This shows that the equation generated from the model is the best of the other regression models that have been tried.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.981
R Square	0.963
Adjusted R Square	0.852
Standard Error	0.256
Observations	5.000

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regression	3	1.705	0.568	8.652	0.244
Residual	1	0.066	0.066		
Total	4	1.771			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-3.347	1.370	-2.443	0.247	-20.754	14.060	-20.754	14.060
X Variable 1	4.300	1.377	3.122	0.197	-13.201	21.801	-13.201	21.801
X Variable 2	-5.034	2.312	-2.178	0.274	-34.405	24.337	-34.405	24.337
X Variable 3	-0.085	1.115	-0.076	0.952	-14.258	14.088	-14.258	14.088

Figure 6. The Results of Regressions Analysis

Based on Figure 6, the results of the peak discharge (Qp) model are obtained as follows:

1. Has a regression equation model:
   $Qp = A^{4,3} \times L^{-5,034} \times FD^{-0,085} \times e^{-3,347}$
2. This peak discharge model has a coefficient of determination R^2 of 0.963. It means that the independent variable (x), the area of the watershed, the length of the main river, and the form factor of the watershed are affecting the peak discharge (Qp) value with 96.3%.

Table 9. Comparison of Trial Regression Models

No	Regression Types	Equation Models	R^2
1	Linear Regression	$Qp = -91.27 + 0.241A + 1.18L + 221.45FD$	0.907
2	Log Regression	$Qp = -0.035 + A^{4.3} - L^{5.03} - FD^{0.09}$	0.963
3	Multiplication Regression (*ln*)	$Qp = A^{4.3} \times L^{-5.034} \times FD^{-0.085} \times e^{-3.347}$	0.964
4	Logest Regression	$Qp = 64.31 \times 1.01^{A} \times 0.91^{L} \times 0.29^{FD}$	0.798

Validation of Peak Discharge (Qp) Model

Model validation is calculated in the same sub-watersheds, but using data input of peak discharge model formula that has been corrected to peak discharge that calculated by using observed unit hydrographs Collins Method.

Table 10. Recapitulation of Peak Discharge (Qp) Model and Peak Discharge (Qp) Collins

No	Watershed	Qp Model	Qp Collins	Qp Model -Collins	(Qp Model-Collins)^2
1	Bontojai	32.684	40.471	-7.787	60.632
2	Jonggoa	17.225	15.846	1.378	1.900
3	Kampili	75.246	67.731	7.515	56.478
4	Maccini Sombala	30.296	30.692	-0.396	0.157
5	Jenelata	14.182	13.589	0.593	0.352
	Total			1.304	119.519

Based on Table 10, it can be said that the value of the peak discharge model has results that are close to the observed peak discharge. Maccini Sombala Watershed has the smallest difference in peak discharge value between the model and the actual peak discharge of 0.396. It means that the modeling results describe the actual measured discharge conditions. Although, Bontojai Watershed has the most significant difference in peak discharge value between the model and the actual peak discharge that is 7.787. Therefore, it is necessary to examine the accuracy of the model for all watersheds.

To show the accuracy value of peak discharge calculated from the regression modeling a validation test was conducted using RMSE Method.

$$RMSE = \sqrt{\frac{119.519}{5}} = 4.89 \tag{2}$$

The Root Mean Square Error (RMSE) value of the model peak discharge is 4.89. It shows that the value can be considered small or close to zero (0). In other words, this modeling has a reasonably good validity value.

4. Conclusion

The peak discharge value (Qp) in the model in the five watersheds has almost the same value compared to the observed unit hydrograph (HSO) analysis results. By using statistical regression analysis, the result shows that the coefficient determination of the peak discharge model in the Jeneberang river area explained that the independent variable (x) is affecting the value of peak discharge. Furthermore, the independent variable (x) are the watershed's area, the length of the main river, and the watershed shape factor. To obtain optimal research results, use linear zero regression statistical analysis and adding complete DAS morphometric variables for further research are suggested.

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