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Frequency Analysis of Design-Flood Discharge Using Gumbel Distribution At Katulampa Weir, Ciliwung River

S. Syafalni[1)], Oki Setyandito[1)], Fikri Ramadhan Lubis[1)], Yureana Wijayanti[2)]
[1)]*Civil Engineering, Faculty of Engineering, Bina Nusantara University, Palmerah, Jakarta Barat – 11480, Jakarta, INDONESIA*
[2)]*Environmental Engineering, Faculty of Climate Change and Clean Energy, Surya University, Sumarrecon Serpong, Tangerang, Banten, INDONESIA*
Corresponding Author: osetyandito@binus.edu ; okisetyandito@gmail.com

Abstract

Floods in Jakarta region is an annual problem. Overflow of Ciliwung River is one of rivers that causing floods in Jakarta. Katulampa Post / Weir is an early warning system of flooding occurrence in Ciliwung River before entering the city. The discharge at Katulampa weir measured by using manual or conventional system. This paper presented study result of frequency analysis of maximum dischargeat Katulampa Weir. The outcome will be utilized as the basis in the prediction of design-flood discharge for flood management plan. Flood often occurs in Ciliwung River which detected at Katulampa Weir. This study is preceded by analyzing the discharge and precipitation data using approach hydrology and statistics. Based on the calculated discharge by using rational method, correlation between the discharge at Katulampa Weir and upstream rainfall of Ciliwung River showed linear trendline. The study showed that Gumbel distribution is the best method in calculating design-flood discharge.

Based on ratios among Katulampa Weir and Panus Bridge post Depok, Mean Absolute Percent Error (MAPE) on Katulampa Weir has large error percentage compare to Panus bridge post Depok. Hence, conventional water level recording system in the Katulampa Weir is not effective to minimize the error in data recording. Design-flood discharge of 1078,62 m^3/s; 1177,61 m^3/s; and 1276,61 m^3/s was obtained using maximum discharge analysis with 25, 50 and 100 years return periods and 10% risk level. It will be utilized to design flood control structures.

Keywords: Design-flood discharge, Annual Maximum Series, Gumbel Distribution

Introduction

Katulampa Weir is functioned as an early warning information system at upstream of Ciliwung River before the flood enter Jakarta. Water level data in the Katulampa weir is an estimated average high water level (potentially flooding), which about 3-4 hours long before the water will reach the area of Depok and 10 hours later the water will arrive in Manggarai Water Gate. Katulampa Weir began to operate in 1911, however, the construction has started since 1889, since the floods hit Jakarta in 1872. Over the time, the Ciliwung River Basin has undergone a lot of changes in land use that are both downstream lowlands, middle zone, until the upstream area. Land use changes include a shift of land into a green open space as well as the region woke up and the extent of reduction in the number of lakes that has a function as a store of water, which led to increasingly complex problems. In addition, high rainfall intensity is one of the causes of the large water discharge and the too large discharge is one of the causes flooding. Moreover, the available stream flow and rainfall records for both stations are provided by department of public work for a certain durations from 1990 until 2012 that can be used for estimating of maximum rainfall and peak flood for a certain return period at specified location etc.

This information regarding the magnitude and frequency relationship can be used in the design of flood control structures, dams, barrages and hydroelectric power plants. The flood discharge rate should be used in designing these buildings which is an important aspect, called the design-flood discharge [1]. In order to determine the discharge using rational method, rainfall data is needed. Hence, probability of rainfall distribution should be carefully estimated [2]. There are several types of theoretical probability distributions (or frequency distribution functions) that have been successfully applied to hydrologic data [3]. Some of the probability distributions commonly used for hydrologic variables were normal distribution, log normal distribution, exponential distribution, gamma distribution, Pearson Type III distribution, Log-PearsonType III distribution and extreme value distribution. Extreme value distribution is further subdivided into three form - EVI (Gumbel distribution), EVII (Frechet distribution) and EVIII (Weibull distribution)[4]. According to Onni S. Selaman et al[5] the most popular theoretical probability distributions (or frequency distribution functions) have been the lognormal, log-Pearson Type III and Gumbel distributions. In these analysis were applied the Normal, Gumbel and log Pearson Type III distributions which can be evaluated by using Chi-Square and Kolmogorov-Smirnov test.

This paper objective is to conduct research, which can estimate the flooding in the future from Katulampa Weir and Panus Bridge Post Depok using Probability distributions analysis approach for estimating return period associated with flood peaks of varying magnitudes from recorded floods using the observed data from both locations.

Methodology

The research was performed at the Katulampa Post and the Panus Bridge Post Depok using rainfall and discharge data collected from both stations. Initial stages of this research are to determined discharge and maximum daily rainfall data on the same day each year by using Annual Maximum Series. Discharge data utilized for calculation is 23 years data (1990 to 2012) which recorded at Katulampa Weir/Post. Second stage is to determine average daily maximum rainfall area with 23 years of data (1990-2012) obtained at Ciliwung-Cisadane Watershed Management Bureau (BBWS). Furthermore, it can be obtained IDF Curve and the river discharge by rational methods.

Third step is to determine the maximum discharge frequency analysis using the statistical approach Gumbel distribution method. The Gumbel distribution is a two-parameter extreme values distributions widely used in Annual Maximum Series [6].

Gumbel distribution method applied in this study was based on the hypothesis which compared well with analysis using the methods of normal distribution and Log Pearson III.

Having obtained the distribution in accordance with the requirements and calculation of parameters, then testing the suitability of the distribution, by using Chi-Square and Kolmogorov-Smirnov test. The next step is to perform a comparison between the result of calculation and direct measurement at the location.

Result and Discussion

Calculation of Average Rainfall

Determination of catchment area that corresponds to each of rainfall station was established by Gunawan[7]. He determined areas which correspond to average rainfall data within Katulampa Ciliwung watershed. The calculation results of area for each station [7] are as follows:

- Rainfall Station of Katulampa = 5,4 km^2
- Rainfall Station of Gadog = 54,86 km^2
- Rainfall Station of Gunung Mas = 90,04 km^2

Total Catchment Area = 150,3 km^2

If it converted into percentage, the areas correspond to each station are as follows:

- Rainfall Station of Katulampa $= \frac{5,4}{150,3} \times 100\% = 3,59\%$
- Rainfall Station of Gadog $= \frac{54,86}{150,3} \times 100\% = 36,50\%$
- Rainfall Station of Gunung Mas $= \frac{90,04}{150,3} \times 100\% = 59,91\%$

Hence, we use the percentage of this area to calculate average rainfall using Thiessen Method.

Table 1: Calculation of the Average Rainfall using Thiessen Method

Years	Gunung Mas (59,91%)		Gadog (36.50%)		Katulampa (3.59%)		Average Rainfall (mm)
	Rain fall (mm)	%area x rain fall (mm)	Rain fall (mm)	%area x rain fall (mm)	Rain fall (mm)	%area x rainfall (mm)	
1990	34	20.37	50	18.25	45	1.62	40.23
1991	35	20.97	56	20.44	80	2.87	44.28
1992	82	49.13	58	21.17	39	1.40	71.70
1993	48	28.76	31	11.32	18	0.65	40.72
1994	70	41.94	39	14.24	70	2.51	58.69
1995	70	41.94	59	21.54	52	1.87	65.34
1996	162	97.05	141	51.47	211	7.57	156.09
1997	50	29.96	5	1.83	17	0.61	32.39
1998	89	53.32	138	50.37	110	3.95	107.64
1999	85	50.92	86	31.39	90	3.23	85.54
2000	85	50.92	127	46.36	71	2.55	99.83
2001	28	16.77	125	45.63	102	3.66	66.06
2002	59	35.35	127	46.36	92	3.30	85.00
2003	61	36.55	55	20.08	35	1.26	57.88
2004	45	26.96	96	35.04	90	3.23	65.23
2005	77	46.13	97	35.41	60	2.15	83.69
2006	58	34.75	67	24.46	46	1.65	60.85
2007	156	93.46	229	83.59	172	6.17	183.22
2008	35	20.97	97	35.41	48	1.72	58.10
2009	90	53.92	85	31.03	52	1.87	86.81
2010	111	66.50	153	55.85	145	5.21	127.55
2011	24	14.38	64.5	23.54	58	2.08	40.00
2012	96	57.51	0	0.00	84	3.02	60.53

Rainfall Intensity

The calculation result of average rainfall of the area has been obtained, it can be seen that its intensity can be expressed by using Intensity-Duration-Frequency (IDF) curve. The pattern of rainfall distribution was obtained by using Gumbel distribution method. Rainfall frequency analysis results for various return periods are shown in the following table:

Table 2: Rainfall Frequency Analysis

T	Yt	K_T	X_T (m^3/s)
2	0.37	-0.15	71.67
5	1.50	0.90	110.98
10	2.25	1.59	137.01
25	3.20	2.47	169.90
50	3.90	3.12	194.30
100	4.60	3.77	218.52

Hourly rainfall intensity of daily rainfall data was calculated using Mononobe equation [8] as follows:

$$I_t = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{\frac{2}{3}} \quad (1)$$

where:

I_t = the rainfall intensity for trainy duration(mm/hour),

t = the duration of rainfall (hour),

R_{24} = themaximum rainfall for 24 hours (mm)

From the calculation, Intensity Duration Frequency (IDF) curve was generated at certain return period as shown in Figure 1.

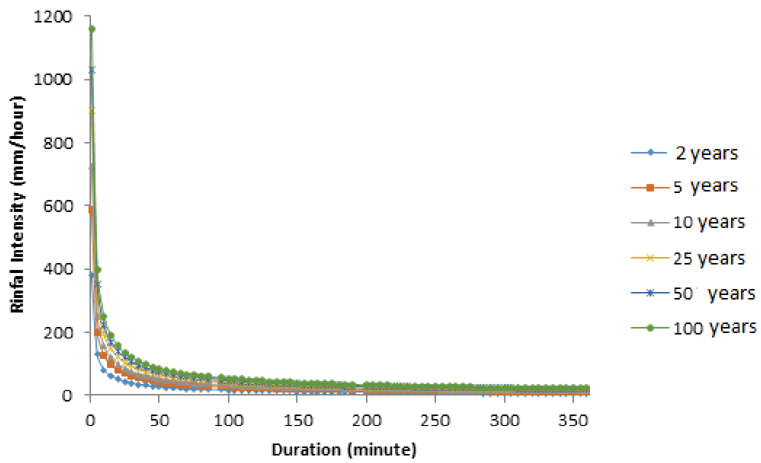

Figure 1: IDFCurve at various return period developed by using Gumbel Distribution

Correlation Between Rainfall And Discharge

Rational Method

Rational Method was applied in order to calculate discharge. Parameters used in the calculation are catchment area, runoff coefficient and time of concentration. Time of concentration was obtained using Kirpich method [9] with the formula shown below:

$$t_c = 0.0195\left(\frac{L}{\sqrt{S}}\right)^{0.77} \quad (2)$$

Where:

t_c = the time of concentration (minutes)

L = the channel flow length (meters)

S = the dimensionless main-channel slope

Based on the calculations can be obtained by the value of tc = 77.91 minutes, or 1.27 hours. In this case the time of concentration (tc) is equal to the rainfall duration parameter in rainfall intensity equation of Mononobe method.

Determination of Ciliwung River catchment area for Katulampa Weir was based on a study by Gunawan [7], and the area is 150.3 km^2. Runoff coefficient value was obtained by interpolating runoff coefficient with built in area which greatly influenced by population growth. Hence, the runoff coefficient (c) in 2013 is 0.4401. Finally, Calculation in obtaining the discharge from 1990 to 2012, were performed by using these parameters. The calculation result can be seen in Table 3 (column number 2).

Statistical analysis was conducted to examine the correlation between rainfall and discharge. The data that is being utilized was the Katulampa Weir maximum discharge and the region daily rainfall height, as shown in Table 3. The result shown (Figure 2) positive correlation (R = 0.8988) between the discharge data (Y) with rainfall data (X), which means the greater the rainfall, the greater the discharge which measured at the Katulampa Weir. Coefficient of determination (R^2) is 0.8079 or 80.79%. It means that increases or decrease in the discharge (Y) within 80.79% of overall data can be explained by the linear relationship (dotted line in Figure 2) between rainfall and discharge by the equation Y = 3,53X + 81.68, while the remaining 19.21% of overall data is due to other factors not included in this analysis. Hence, there is good correlation between rainfall and discharge.

After that, another statistical analysis was performed to verify the linear correlation between rainfall and discharge from previous analysis result. It was conducted by using the data of region daily rainfall and discharge using Rational Method calculation. The graph in Figure 3 shows linear trend line of Rational Method discharge. The data of Katulampa discharge is plotted in this graph (red dot). It can be concluded that Katulampa discharge trendline correspond to Rational Method discharge trend line.

Table 3: The Rainfall Intensity to Calculate Discharge using Rational Method, Calculated Result, Region Daily Rainfall and Maximum Discharge at Katulampa Weir

Year	Intensity of Rainfall (mm/hour)	Discharge usingRational Method (m^3/s)	Region Daily Rainfall (mm) (X)	Max. Discharge at Katulampa (m^3/s) (Y)
	(1)	(2)	(3)	(4)

1990	11.87	218.10	40.23	202.76
1991	13.06	240.03	44.28	276.25
1992	21.15	388.65	71.70	307.47
1993	12.01	220.72	40.72	276.25
1994	17.31	318.12	58.69	307.47
1995	19.27	354.18	65.34	339.68
1996	46.05	846.14	156.09	629.97
1997	9.56	175.58	32.39	188.88
1998	31.75	583.48	107.64	552.27
1999	25.24	463.71	85.54	514.66
2000	29.45	541.14	99.83	477.89
2001	19.49	358.10	66.06	339.68
2002	25.08	460.79	85.00	441.98
2003	17.07	313.73	57.88	216.91
2004	19.24	353.60	65.23	216.91
2005	24.69	453.66	83.69	307.47
2006	17.95	329.87	60.85	216.91
2007	54.05	993.18	183.22	629.97
2008	17.14	314.93	58.10	307.47
2009	25.61	470.58	86.81	307.47
2010	37.63	691.42	127.55	629.97
2011	11.80	216.85	40.00	216.91
2012	17.86	328.11	60.53	246.05

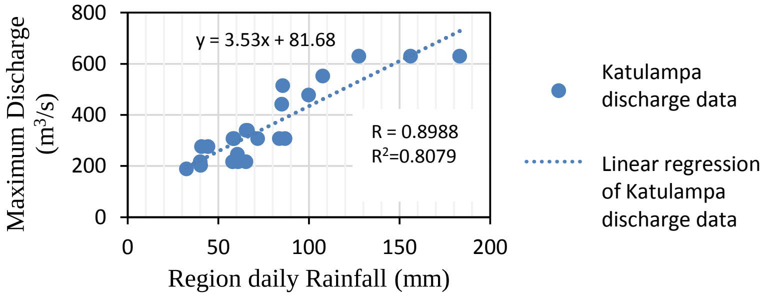

Figure 2: Correlation between Rainfall and Discharge using Katulampa Discharge data

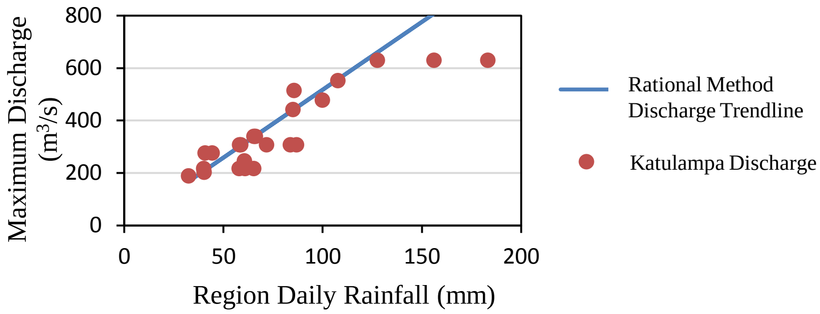

Figure 3: Correlation between Rainfall and Discharge using Rational Method calculation discharge trend line in comparison with Katulampa discharge.

The Analysis of Discharge Frequency Distributionat Katulampa Weir and Panus Bridge Post Depok

Equality assessment between parameters calculation result and the specification of each distribution method at Katulampa Weir and Panus Depok Bridge can be seen in table 4 and Table 5, respectively.

Table 4: Distribution method specification and Assessment result at KatulampaWeir

Distribution Method	Specification		Calculation Result	Description
Gumbel	Cs	≤ 1.14	0.61	Fit
	Ck	≤ 5.4	2.17	Fit
Normal	Cs	= 0	0.61	Unfit
	Ck	≈ 3	2.17	Unfit
Log Pearson III	Cs	≈ 0	0.24	Unfit

Table 5: Distribution Methods Specification and Assessment Result at Depok Panus Bridge Post

Distribution Method	Specification		Calculation Result	Description
Gumbel	Cs	≤ 1.14	0.16	Fit
	Ck	≤ 5.4	2.15	Fit
Normal	Cs	= 0	0.16	Unfit
	Ck	≈ 3	2.15	Unfit
Log Pearson III	Cs	≈ 0	0.55	Unfit

Based on the description of the assessment, it can be concluded the distribution method that meet the specification is Gumbel distribution method. This conclusion is for both Katulampa Weir and Depok Panus Bridge Post

Compatibility Test of Distribution Method

Based on Chi-Square and the Smirnov-Kolmogoroftest, Gumbel Distribution at Katulampa Weir and Panus Bridge Post Depok were given a reasonable results with confidence interval of 95 %.

Comparison between Observed Discharges and Estimation Discharges at Katulampa Weir andPanus Bridge Post Depok

The evaluation of measurement device/system at water level monitoringpost is one important aspect in flood control. Measurement system at Katulampa Weir will be compared to measurement system at Panus Bridge post Depok, which both serves to monitor water level and discharge of Ciliwung river.

Actual discharge at Katulampa Weir were obtained using a conventional system or manual system, while actual discharge at Panus Bridge post Depok were measured using Telemetry System AWLR (Automatic Water Level Recorder). Estimation discharge was calculated using Gumbel distribution of formula (3). Comparison of observed discharge and calculation or estimation discharge using Gumbel distribution can be seen in Figure 4.

Equation: $x_T = \bar{x} + K_T\ s$ (3)

Frequency factor K for Gumbel extreme values written by the following formula, Chow [3]:

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\} \quad (4)$$

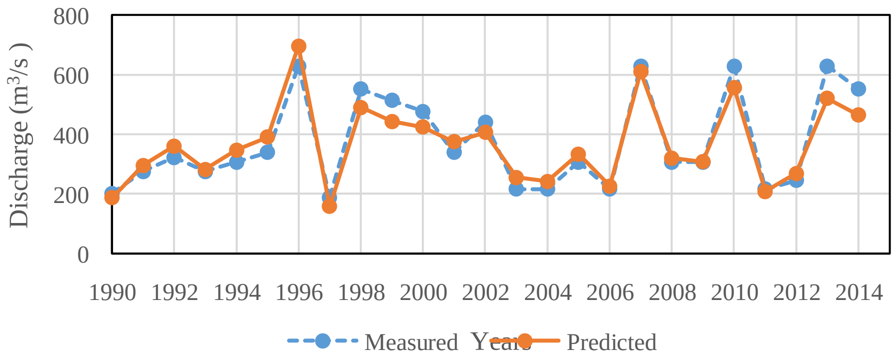

Figure 4: Comparison between Measurement and Estimation (Predicted) of the Discharge at Katulampa Weir (1990-2014)

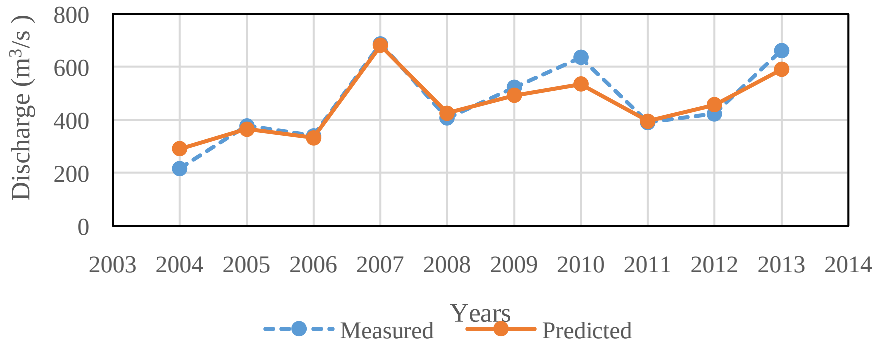

Figure 5: Comparison between Measurement and Estimation (Predicted) of the Discharge at Panus Bridge Post Depok (2004-2013)

Based on the statistical calculation of the Mean Absolute Percent Error (MAPE) at the Katulampa Weir is 9.85%, whereas at Panus Bridge post Depok is 3.49%. However, if the KatulampaWeir data was divided into the same period (2004-2013), the percent of error is 6.35%. Based on the calculation results of the second post, it can be considered that the predictions of the Katulampa/weir is categorized as 'quite precise' (<10%), while the prediction at Depok Post categorized as 'very precise' (<5%).

Calculation of Design Discharge with Risk Level and Reliability [10]
The result of the design discharge with various return period using Gumbel Distribution

Table 6: Estimation Discharge using Gumbel Distribution

Return Period T (years)	Discharge Q (m^3/s)
20	721,76
50	854,61
100	954,16
200	1053,34
1000	1283,10

The calculation of design discharge withrisk level and reliability was conducted by using Gumbels distribution. Calculation of designdischargewas based on risk level of 10%, which is associated with various return design life of the building. The following are the results of the calculation.

Equation : $\overline{R}= 1- (1 - \frac{1}{T})^n$ (5)

Table 7: Design Flood Discharge using Gumbel Distribution Risk Level

Design life of the Building (n)	Discharge Q (m^3/s)
25	1078,62
50	1177,61
100	1276,61

Conclusion

The relationship between rainfall and discharge at the Katulampa a positive correlation with linear trendline. Based on the analysis and the statistical test result, data confidence level with interval of 5% at the Katulampa Weir and Panus Bridgepost Depok is 95%. Hence, it can be concluded that Gumbel distribution method is correspond with Ciliwung river discharge distribution. Criterion calculation result of MAPE during the period 2004-2013 at the Katulampa Weir (using conventional discharge measurement device) is ‘quite precise’. However, criterion calculations result at the Panus Bridge post Depok (using automatic discharge measurement device or telemetry) is ‘very precise’. Design discharge of 1078,62 m^3/s; 1177,61 m^3/s; and 1276,61 m^3/s was obtained using maximum discharge analysis with 25, 50 and 100 years return periods and 10% risk level. With a maximum discharge analysis with the design life of the building 25, 50, and 100 years, with 10% risk level, the obtained design-flood discharge is 1078,62 m^3/s; 1177,61 m^3/s; and 1276,61 m^3/s.

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