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Performance of Frequency Analysis for Estimating Design Rainfall (Case Study on the Upstream Lesti Sub-watershed)

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ABSTRACT

The Lesti sub-watershed is as part of the Brantas watershed which the catchment area is 61,491.02 ha. Basically, the source of overall water that is flowing in the river and storage as the surface or sub-surface is the rainfall. Therefore, there is a relation between the rainfall and the river discharge in a watershed. The rainfall intensity in the Lesti sub-watershed is high enough and it causes the flooding, so it is needed the design of flood control. The type of rainfall that is needed for designing the water utilization and flood control is area rainfall. This study intends to estimate the design rainfall with some return periods. The methodology consists of the frequency analysis due to the distributions of Normal, Log Normal, Log Pearson Type III, and Gumbel. The result is hoped to be used for supporting the design of water utilization and flood control.

Keywords: Rainfall, Normal, Log Normal, Log Pearson Type III and Gumbel.

1. INTRODUCTION

Over the past several decades, rainfall over Indonesia has been decreasing significantly, which causes a decrease in dam inflow as a result. This has attracted significant interest and attention, particularly in terms of possible causes and policy options in response to the decrease [1]. While not conclusive in terms of possible drivers of the rainfall decrease, an important finding is that since the middle of the twentieth century, the rainfall decreases at the specific stations and the decrease occurred through reductions in the number and intensity of the extreme events [2][3].

Rainfall is a phenomenon characterized by the high variability both in the space and time [4][5], which makes its measurement difficult. Even though rain gauges provide accurate rainfall measurements, these are only representative for a limited spatial extent. Over the vast majority of the globe, rain gauge networks are too sparse (or completely missing) to capture the variability of the precipitation systems in space and time [6]. The heavy rainfall events can trigger natural disasters, such as flooding and landslides. An important concern is whether the future climate change will alter the intensity and frequency of the extreme rainfall and how it will affect the characteristics of the extreme rainfall [7]. The previous studies have indicated that the frequency and intensity of extreme rainfall on a daily basis exhibits a positive trend but that there are the large regional differences in the level of the increase or decrease [8][9]. However, such the increases are attributed especially to the uppermost percentile of the global rainfall distribution [10]. The extreme rainfall is associated with a wide variety of the weather systems, such as the mesoscale convective systems [11], the orographic precipitation in association with the low-level jets [12][13], the tropical cyclones [14].

Lesti sub-watershed is as part of the Brantas watershed which has the estuary in the Sengguruh reservoir. The higher erosion level in the Lesti sub-watershed is caused by the topographical form which part of them is mountainous with the slide slope is 8-45% and the rainfall intensity is high. The Lesti sub-watershed has complex enough problem towards the area damage, erosion, landslide, river discharge fluctuation, and the sedimentation is high enough. Therefore, the potency of water in it cannot be optimally used and it the dry season, there will be happened the water deficit, however due to the bad system of water sources in the watershed, the rainfall intensity is high enough so that it causes the flooding.

This study intends to analyze the design rainfall in the Lesti sub-watershed. To reach the objective, it has to be analyzed the area rainfall by using the methods of arithmetic. Then, it can be carried out the analysis of design rainfall by using the frequency analysis such as the distributions of Normal, Log Normal, Log Pearson Type III, and Gumbel. The suitable distribution is depended on the testing of goodness of fit by using the Smirnov-Kolmogorof test and chi-square.

2. MATERIALS AND METHODS

2.1 Study location

The upstream Lesti sub-watershed is located on the south longest of 8°02'50''- 8°12'10'' and the east longest of 112° 42'58''- 112°56'21'' and it is in the Malang regency. This area has the heterogenic characteristic on the basic physical condition. Delineation of the research area uses the ecological boundary such as the upstream Lesti sub-watershed that is determined by the Brantas watershed institution. Map of study location is presented as in the Figure 1.

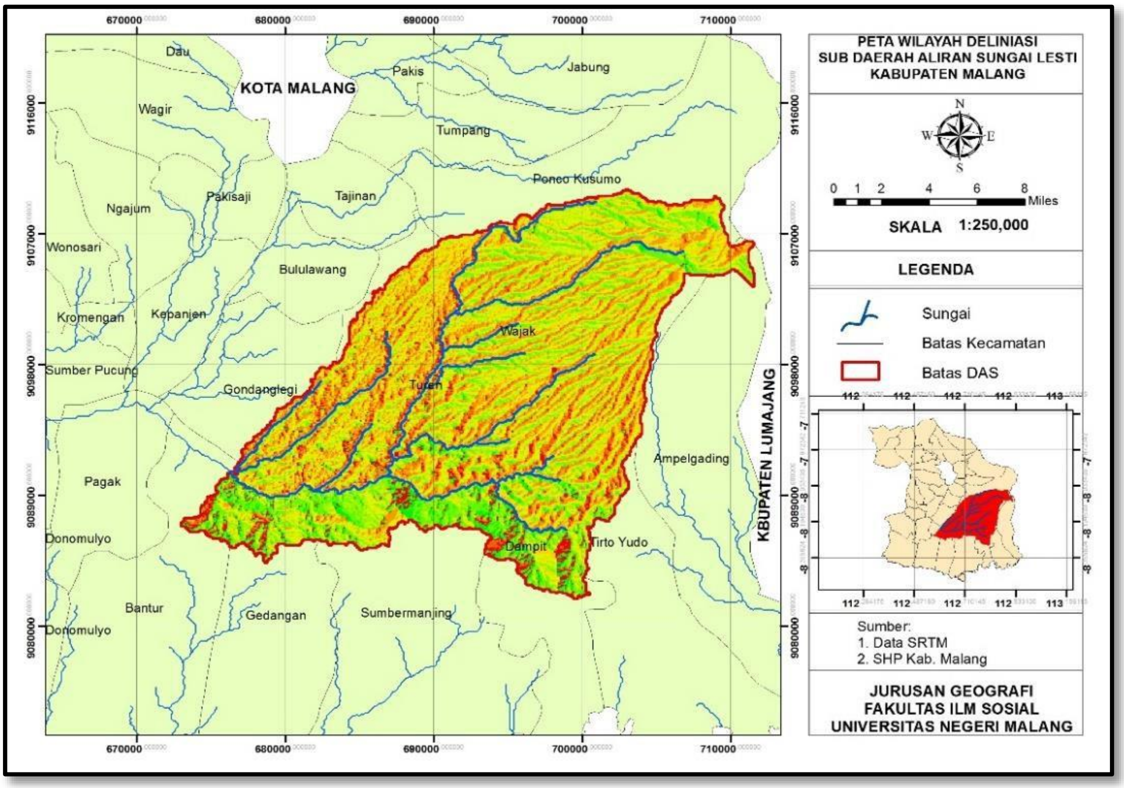

Fig. 1. Map of the upstream Lesti sub-watershed

2.2 Data collecting

The secondary data are needed in this study. The secondary data is as the data which is obtained from several sources and can be accounted the accuracy. The secondary data that is collected for this study is as follow:

1. The daily rainfall data from the Poncokusumo station (2007-2016).
2. The daily rainfall data from the Dampit station (2007-2016).

2.3 The steps of study

The steps of study are systematically set for making easy to handle the solution. The steps of analysis are as follow:

2.3.1 Analysis of area rainfall

Analysis of area rainfall is carried out by using the arithmetic mean. This method is used for the area less than 50,000 ha. The result of this method is not far different with the other method if there are many rainfall stations and the stations are equally distributed in the watershed. The advantage is this method is more objective than the Isohiet method [15]. The formula of arithmetic mean is as follow:

$$P=1/n(P_1+P_2+\ldots+P_n) \qquad (1)$$

Where:

P = area rainfall (mm)

$P_1,P_2,\ldots, P_n$ = rainfall in every observed point (rainfall station) (mm)

n = number of observed point (station)

2.3.2 Analysis of frequency distribution

There are 4 frequency distribution which will be used for analysis design rainfall in the Lesti sub-waterhed such as the methods of Normal, Log Normal, Log Pearson Type III, and Gumbel

2.3.2.1 Normal distribution

The Normal distribution or Normal curve is also mentioned as the Gauss distribution. The formula for calculating the estimation value with the return period of T (Xt) is as follow:

$$X_T=\overline{X}+K_T S \qquad (1)$$

Where

X_T : estimation of value which is hoped to be happened by the return period of T

X : mean

S : deviation standard

K_T : factor of frequency which is as the function of probability or return period and as the type of mathematical modeling of the probability distribution that is used for the probability analysis

2.3.2.2 Log Normal distribution

The formula of Log Normal distribution is the same as the Normal distribution, but the data have to be transformed into log.

$$X_T = \overline{X} + K_T S \qquad (2)$$

Where

X_T : estimation of value which is hoped to be happened by the return period of T (in the log)

X : mean (in the log)

S : deviation standard (in the log)

K_T : factor of frequency which is as the function of probability or return period and as the type of mathematical modeling of the probability distribution that is used for the probability analysis

2.3.2.3. Log Pearson Type III distribution

To use the Log Pearson Type III, the data have to be transformed into the Log form. The formula of Log Pearson Type III with the return period of T (Xt) is as follow:

$$\text{Log } X_T = \text{Log } X + K.s \qquad (3)$$

Where:

Log X_T : estimation of value (in the Log from) which is hoped to be happened by the return period of T

X : mean (in the Log form)

S : deviation standard (in the log form)

K_T : factor of frequency which is as the function of probability or return period and as the type of mathematical modeling of the probability distribution that is used for the probability analysis

2.3.2.4. Gumbel distribution

The formula of the Gumbel distribution that is used for estimating the value which is hoped to be happened with the return period of T(Xt) is as follow:

$$Xt = \overline{X} + \frac{(Y_t - Y_n)}{S_n} \times Sx \qquad (4)$$

Where,

Xt = design rainfall in the return period of T year (mm)

X = mean rainfall of the observed result

Yt = reduced variate that is as the Gumbel parameter for the return period of T year

Yn = reduced mean that is as the function of the data number= f(n)

Sn = reduced deviation standard that is as the function of the data number = f(n)

Sx = deviation standard

2.3.2.5. Smirnov–Kolmogorov Test

This test intends to evaluate the horizontal deviation such as the maximum deviation between theoretical and empirical distribution. The formula is as follow:

$$\Delta \text{ maks} = [\text{ Sn - Px}] \qquad (6)$$

Where:

Δmaks = the deviation between theoretical and empirical distribution

Sn = theoretical probability

Px = empirical probability

If Δ maks < Δcr, the data are suitable with the distribution. The steps of Smirnov-Kolmogorof test are as follow:

a. To rank the data (from small to big or big to small) and to calculate each probability due to the ranking, it is mentioned as the empirical probability.
b. To determine each of the theoretical probability.
c. To analyze the deviation between the theoretical and empirical probability
d. Δ maks is compared with the Δ critic form Smirnov-Kolmogorof table (Dcr).

2.3.2.6. Chi- Square test

Chi-square test intends to evaluate the difference between the sample data and the probability distribution. The formula of chi-square test is as follow:

$$X^2 = \sum_{i=1}^{N} \frac{(Oi - Ei)^2}{Ei} \qquad (7)$$

Where:

X^2 = calculated chi-square

Ei = frequency that is hoped regarding to the class division

Oi= frequency on the same class

N =number of class. The formula of Ei is as follow:

$$Ei = \frac{n}{N} \qquad (8)$$

Where:

n = number of data

N= number of class

3. RESULTS AND DISCUSSION

Analysis of area rainfall in the Lesti sub-watershed is due to the method of arithmetic mean. Then, it is carried out to analyze the design rainfall with some return periods by using the distribution methods of Normal, Log Normal, Log Pearson Type III, and Gumbel.

3.1. Analysis of area rainfall

There are 2 rainfall stations in the study location. In hydrological analysis, the rainfall data are come from the two station which is influenced to the Lesti sub-watershed. The rainfall data is from 2007 until 2016. Table 1 presents the mean rainfall in the Lesti sub-watershed.

Table 1. Mean rainfall in the Lesti sub-watershed

No.	year	Poncokusumo station	Dampit station	Mean
1	2007	151.00	137.00	144.00
2	2008	150.00	117.00	133.50
3	2009	85.00	106.00	95.50
4	2010	94.00	108.00	101.00
5	2011	79.00	89.00	84.00
6	2012	110.00	109.00	109.50
7	2013	115.00	79.00	97.00
8	2014	81.00	107.00	94.00
9	2015	89.00	117.00	103.00
10	2016	50.00	155.40	102.70

Source: own study

3.2. Analysis for selecting the suitable frequency distribution

Table 2 present the analysis for selecting the suitable distribution for Lesti sub-watershed.

Table 2. Analysis for selecting the suitable frequency distribution in the Lesti sub-watershed

No	Year	Max rainfall
1	2011	84.000
2	2014	94.000
3	2009	95.500
4	2010	97.000
5	2010	101.000
6	2013	102.700

7	2015	103.000
8	2011	109.500
9	2008	133.500
10	2007	144.000
Mean (X)		106.42
Deviation standard (S)		18.48
Skewness (Cs)		1.26
Kurtosis (Ck)		0.96
Coefficient of variation (Cv)		0.17

Source: own study

3.3. Analysis of frequency distribution

To select the method of frequency distribution analysis for the rainfall in the Lesti sub-watershed, there is used the methods of Normal, Log Normal, Log Pearson Type III, and Gumbel.

3.3.1. Metode Normal

Table 3 presents the analysis and the result of design rainfall by using the Normal method. However, Table 4 and 5 present the testing of goodness of fit each for Smirnov-Kolmogorof Test and chi-square test.

Table 3. Design rainfall by using Normal method

No	Tr (year)	Probability (%)	R mean (mm)	Deviation standard (Sd)	K	Design rainfall (X) (mm)
[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**
1	1.25	80.000	106.420	18.484	-0.840	90.894
2	2	50.000	106.420	18.484	0.000	106.420
3	5	20.000	106.420	18.484	0.840	121.946
4	10	10.000	106.420	18.484	1.280	130.079
5	20	5.000	106.420	18.484	1.640	136.734
6	25	4.000	106.420	18.484	1.708	137.997
7	50	2.000	106.420	18.484	2.050	144.312
8	100	1.000	106.420	18.484	2.330	149.487
9	200	0.500	106.420	18.484	2.580	154.108
10	1000	0.100	106.420	18.484	3.090	163.535

Source: own study

Table 4. Smirnov-Kolmogorof for Normal method

a	D critic	D max	Note
0.2	0.320	0.209	Accepted
0.1	0.370	0.209	Accepted
0.05	0.410	0.209	Accepted
0.01	0.490	0.209	Accepted

Source: own study

Table 5. Chi-square test for Normal method

No.	Pr	K	X	Boundary of class	Oi	Ei	$(Oi-Ei)^2/Ei$
[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**
1	80	-0.840	90.894	X ≤ 90.894	1	2.00	0.50
2	60	-0.253	101.740	90.894 < X < 101.740	6	2.00	8.00
3	40	0.250	111.041	101.740 < X < 111.041	1	2.00	0.50
4	20	0.840	121.946	111.041 < X < 121.946	0	2.00	2.00
5				X ≥ 121.946	2	2.00	0.00
				Total	10	10	11.00

Source: own study

Number of class distribution:

G = 1+ 3,322 log n = 1 + 3,322 log 10 = 5

dk = k - (P + 1) = 5-(2+1)= 2

For a = 5% so X^2 table = 5.991

X^2 calculated = 11.00

If X^2 calculated > X^2 table, it means that the distribution is not suitable.

3.3.2. Metode Log Normal 2 Parameter

Table 6 presents the analysis and the result of design rainfall by using the Log Normal method. However, Table 7 and 8 present the testing of goodness of fit each for Smirnov-Kolmogorof Test and chi-square test.

Table 6. Design rainfall by using the Log Normal 2 Parameter method

No	Tr (year)	Probability (%)	R mean (log)	Deviation standard (log)	K	Design rainfall (mm)	
						Log	mm
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1	1.25	80.000	2.022	0.071	-0.840	1.962	91.661
2	2	50.000	2.022	0.071	0.000	2.022	105.103
3	5	20.000	2.022	0.071	0.840	2.081	120.517
4	10	10.000	2.022	0.071	1.280	2.112	129.473
5	20	5.000	2.022	0.071	1.640	2.138	137.294
6	25	4.000	2.022	0.071	1.708	2.142	138.831
7	50	2.000	2.022	0.071	2.050	2.167	146.777
8	100	1.000	2.022	0.071	2.330	2.186	153.628
9	200	0.500	2.022	0.071	2.580	2.204	160.014
10	1000	0.100	2.022	0.071	3.090	2.240	173.876

Source: own study

Table 7. Smirnov-Kolmogorof test for Log Normal 2 Parameter method

a	D critic	D max	Note
0.2	0.320	0.209	Accepted
0.1	0.370	0.209	Accepted
0.05	0.410	0.209	Accepted
0.01	0.490	0.209	Accepted

Source: own study

Table 8. Chi-square test for Log Normal 2 Parameter method

No.	Pr	K	X	Boundary of class	Oi	Ei	$(Oi-Ei)^2/Ei$
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1	80	-0.840	90.894	$X \leq 90.894$	1	2.00	0.50
2	60	-0.253	101.740	90.894 < X < 101.740	6	2.00	8.00
3	40	0.250	111.041	101.740 < X < 111.041	1	2.00	0.50
4	20	0.840	121.946	111.041 < X < 121.946	0	2.00	2.00
5				$X \geq 121.946$	2	2.00	0.00
				Total	10	10	11.00

Source: own study

Number of class distribution:

G = 1+ 3,322 log n = 1 + 3,322 log 10 = 5

dk = k - (P + 1) = 7-(2+1)= 4

For a = 5% so X^2 table = 5.991

X^2 calculated = 11.00

If X^2 calculated >X^2 table, it means that the distribution is not suitable

3.3.3. Metode Log Pearson

Table 9 presents the analysis and the result of design rainfall by using the Log Pearson Type III method. However, Table 10 and 11 present the testing of goodness of fit each for Smirnov-Kolmogorof Test and chi-square test.

Table 9. Design rainfall by using Log Pearson Type III method

No	Tr (year)	R mean (Log)	Deviation standard (log)	Skewness (Cs)	Probability (%)	K	Design rainfall	
							Log	Mm
[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**
1	1.25	2.022	0.071	0.990	80.000	-0.852	1.961	91.479
2	2	2.022	0.071	0.990	50.000	-0.162	2.010	102.358
3	5	2.022	0.071	0.990	20.000	0.759	2.075	118.938
4	10	2.022	0.071	0.990	10.000	1.340	2.116	130.743
5	20	2.022	0.071	0.990	5.000	1.807	2.149	141.081
6	25	2.022	0.071	0.990	4.000	2.041	2.166	146.553
7	50	2.022	0.071	0.990	2.000	2.538	2.201	158.917
8	100	2.022	0.071	0.990	1.000	3.016	2.235	171.787
9	200	2.022	0.071	0.990	0.500	3.481	2.268	185.300
10	1000	2.022	0.071	0.990	0.100	4.526	2.342	219.710

Source: own study

Table 10. Smirnov-Kolmogorof test for Log Pearson Type III

a	D critic	D max	Note
0.2	0.320	0.124	Accepted
0.1	0.370	0.124	Accepted
0.05	0.410	0.124	Accepted
0.01	0.490	0.124	Accepted

Source: own study

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Table 11. Chi-square test for Log Pearson Type III

No.	Pr	K	Log X	X	Boundary of class	Oi	Ei	$(Oi-Ei)^2/Ei$
[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**
1	80	-0.852	1.961	91.479	$X \leq 91.479$	1	2.00	0.50
2	60	-0.392	1.994	98.595	91.479 < X < 98.595	5	2.00	4.50
3	40	0.145	2.032	107.611	98.595 < X < 107.611	2	2.00	0.00
4	20	0.759	2.075	118.938	107.611 < X < 118.938	0	2.00	2.00
5					$X \geq 118.938$	2	2.00	0.00
Source: own study					Total	10	10	7.00

Number of class distribution:

G = 1+ 3,322 log n = 1 + 3,322 log 10 = 5

dk = k - (P + 1) = 7-(2+1)= 4

For a = 5% so X^2 table = 5.991

X^2 calculated = 11.00

If X^2 calculated >X^2 table, it means that the distribution is not suitable

3.3.4. Metode Gumbel

Table 12 presents the analysis and the result of design rainfall by using the Gumbel method. However, Table 13 and 14 present the testing of goodness of fit each for Smirnov-Kolmogorof Test and chi-square test.

Table12. Design rainfall by using Gumbel method

No	Tr (year)	Probability (%)	R mean (mm)	Deviation standard (Sd)	Variant reduction (Yt)	Mean reduction (Yn)	Variant standard deviation (Sn)	K	Design rainfall (X) (mm)
[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**	**[10]**
1	1.25	80.00	106.420	18.484	-0.476	0.4952	0.9496	-1.0226	87.518
2	2	50.00	106.420	18.484	0.367	0.4952	0.9496	-0.1355	103.915
3	5	20.00	106.420	18.484	1.500	0.4952	0.9496	1.0581	125.977

4	10	10.00	106.420	18.484	2.250	0.4952	0.9496	1.8483	140.584
5	20	5.00	106.420	18.484	2.970	0.4952	0.9496	2.6064	154.595
6	25	4.00	106.420	18.484	3.199	0.4952	0.9496	2.8468	159.040
7	50	2.00	106.420	18.484	3.902	0.4952	0.9496	3.5876	172.732
8	100	1.00	106.420	18.484	4.600	0.4952	0.9496	4.3228	186.322
9	200	0.50	106.420	18.484	5.296	0.4952	0.9496	5.0554	199.863
10	1000	0.10	106.420	18.484	6.907	0.4952	0.9496	6.7524	231.230

Source: own study

Table 13. Smirnov-Kolmogorof test for Gumbel method

a	D critic	D max	Note
0.2	0.320	0.153	Accepted
0.1	0.370	0.153	Accepted
0.05	0.410	0.153	Accepted
0.01	0.490	0.153	Accepted

Source: own study

Table 14. Chi-square test for Gumbel method

No.	Pr	K	X	Boundary of class	Oi	Ei	$(Oi-Ei)^2/Ei$
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1	80	-1.023	87.518	$X \leq 87.518$	1	2.00	0.50
2	60	-0.431	98.449	$87.518 < X < 98.449$	4	2.00	2.00
3	40	0.262	111.269	$98.449 < X < 111.269$	3	2.00	0.50
4	20	1.058	125.977	$111.269 < X < 125.977$	0	2.00	2.00
5				$X \geq 125.977$	2	2.00	0.00
				Total	10	10	5.00

Source: own study

Number of class distribution:

G = 1+ 3,322 log n = 1 + 3,322 log 10 = 5

dk = k - (P + 1) = 5-(2+1)= 2

For a = 5% so X^2 table = 5.991

X^2 calculated = 5.00

If X^2 calculated <X^2 table, it means that the distribution is suitable

4. CONCLUSION

Based on the analysis as above, the arithmetic mean for analyzing the area rainfall in the Lesti sub-watershed is suitable. However, for the frequency distribution analysis for calculating the design rainfall, the suitable method is Gumbel. It is due to the testing of goodness of fit is accepted for the Smirnov-Kolmogiorof test as well as the chi-square test. Table 15 presents the recapitulation of design rainfall by using the methods of Normal, Log Normal, Log Pearson Type III, and Gumbel and Table 16 present the recapitulation of testing of goodness of fit for the four methods.

Table 15. The recapitulation of design rainfall result in the Lesti sub-watershed

No	Return period (year)	Design rainfall (mm) Method			
		Log Pearson Type III	Gumbel	Normal	Log Normal 2 Parameter
1	1.25	91.479	87.518	90.894	91.661
2	2	102.358	103.915	106.420	105.103
3	5	118.938	125.977	121.946	120.517
4	10	130.743	140.584	130.079	129.473
5	20	141.081	154.595	136.734	137.294
6	25	146.553	159.040	137.997	138.831
7	50	158.917	172.732	144.312	146.777
8	100	171.787	186.322	149.487	153.628
9	200	185.300	199.863	154.108	160.014
10	1000	219.710	231.230	163.535	173.876

Source: own study

Table 16. Recapitulation of testing of goodness of fit

No	Testing of goodness of fit Method	Design rainfall (mm) Method			
		Log Pearson Type III	Gumbel	Normal	Log Normal 2 Parameter
1	Smirnov-Kolmogorof	Accepted	Accepted	Accepted	Accepted
2	Chi-Square	Non accepted	Accepted	Non accepted	Non accepted

Source: own study

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