Civilla: Jurnal Teknik Sipil Universitas Islam Lamongan
Volume 09 Number 2 Year 2024

ISSN (*Online*) 2620-7222
ISSN (*Print*) 2503-2399

Available online at
https://jurnalteknik.unisla.ac.id/index.php/CVL

https://doi.org/10.30736/cvl.v2i2

Development of Isohyet Map of Design Rainfall using Spatial Interpolation at Various Return Periods in Sadar Sub-Watershed

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A R T I C L E I N F O

Article History :
Article entry : 05-29-2024
Article revised : 06-24-2024
Article received : 07-11-2024

Keywords :
Isohyet Map, Design Rainfall, Return Period, Spatial Interpolation Method

IEEE Style in citing this article :
Donny Harisuseno, Jadfan Sidqi Fidari, and Syifa Nissa Aulia, "Development of Isohyet Map of Design Rainfall using Spatial Interpolation at Various Return Periods in Sadar Sub-Watershed", *civilla*, vol. 9, no. 2, pp. 157–170.

A B S T R A C T

The overflow of the Sadar River often causes flooding, which is detrimental to the community. Effective measures to address the flood problem require a good quality and quantity of rainfall data. This study aims to develop an isohyetal map of design rainfall for various return periods using the interpolation linear method. The design rainfall is computed using frequency analysis of Log Normal, Gumbel, and Log Person III distributions with return periods of 2, 5, 10, 25, 50, and 100 years. The isohyet map was produced using the Inverse Distance Weight (IDW) and spline interpolation methods. The map results are then evaluated against the design rainfall values obtained from the frequency analysis using the NSE and RSR parameters. The IDW and spline interpolation maps show an excellent level of fit. Furthermore, the isohyet map was compared with the design rainfall map issued by the Ministry of Public Works and Public Housing, which shows a level of fit of 49.693% for the IDW method and 33.194% for the spline method. The results confirmed that the IDW method is the most accurate to estimate isohyet map of design rainfall in the study area.

1. Introduction

Flooding is a common hydrometeorological disaster in Indonesia [1]. The high-intensity rainfall and increasing uncontrolled land use changes are known as the significant factors contributing to the flood problems [2]. Floods will certainly cause losses that need to be anticipated; hence, prevention and mitigation efforts against the risks posed by the disaster are necessary [3] [4].

Flood management is intertwined with civil engineering, particularly in water resources infrastructure [5]. A hydrological data closely related to flood events is rainfall, where the magnitude of the flood results from rainfall within the catchment [6]. Therefore, the availability of hydrological information supports the effectiveness and efficiency of water resources infrastructure planning [7].

The demand for effective water resources infrastructure planning continues to increase in flood management. The accuracy of rainfall data for estimating design rainfall has become a significant concern for hydrologists [8]. The availability of rainfall data in a watershed is commonly presented as a point of rainfall derived from rain stations, which affects the accuracy of the discharge [9]. The accuracy

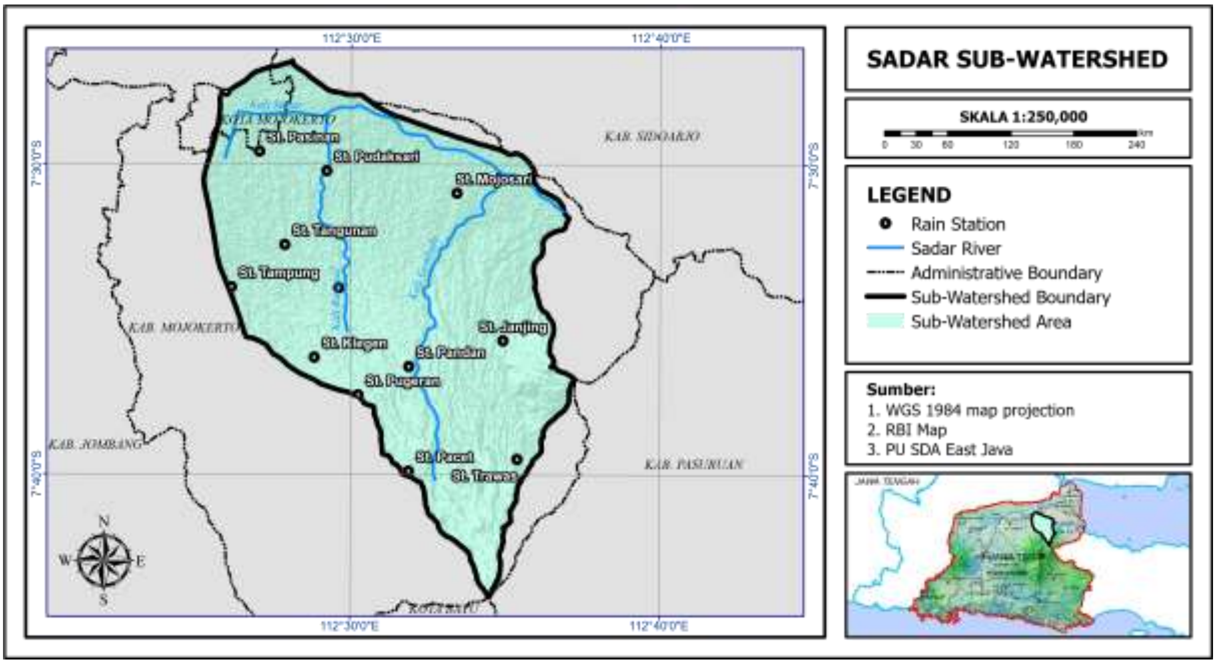
ISSN (*Online*) 2620-7222
ISSN (*Print*) 2503-2399

of the design rainfall becomes the primary input for estimating the design discharge used in the planning of water resources infrastructure. Accordingly, it would be more convenient if design rainfall information is available in the form of spatial maps that provide accurate information as a reference for planning [10]. The development of a spatial map of design rainfall can be achieved using the IDW and spline interpolation method as an alternative [11]. The results of this study are expected to serve as a guideline in determining the design rainfall for flood estimation to support an effective and efficient design of flood management infrastructure.

2. Research Method

2.1. Research Location

This study was situated in the Sadar Sub-watershed, which is part of the Brantas Watershed and has a drainage area of 386 km^2. The main river in the sub-watershed is the Sadar River, having a length of 23 km. Administratively, the Sadar Sub-watershed is located in Mojokerto Regency East Java Province, while astronomically located at 111°20 - 111°40 E and 7°18' - 7°47' N. **Figure 1** displays the Sadar Sub-watershed along with the location of the rain station.



Source: Mapping Results, 2024.
Figure 1. Map of the Sadar Sub-Watershed

2.2. Stage of Research

The first stage begins with data collection, where secondary data is used as the basis for the analysis. Furthermore, rainfall data will be examined for quality using several stages of statistical tests before calculating the design rainfall for various return periods using frequency analysis based on the selected distribution type. Subsequently, the design rainfall was mapped using linear interpolation techniques to determine the isohyetal map of design rainfall for various return periods. Ultimately, the validation of the isohyetal maps was performed to ensure their accuracy and determine the most suitable interpolation method. **Figure 2** denotes the flowchart used in the present study.

3. Description and Technical

3.1. Data Collection

The data collection stage involves the process of acquiring information from various sources. In this study, most of the data used is secondary data. The following is the required data:

a. Observed rainfall data for 1993-2022 (Source: PU SDA East Java)
b. Rainfall station coordinates (Source: PU SDA East Java)
c. Map of Sadar Sub-watershed and administrative boundaries covering the area of Sub-watershed. (Source: Indonesian Geospatial Agency)

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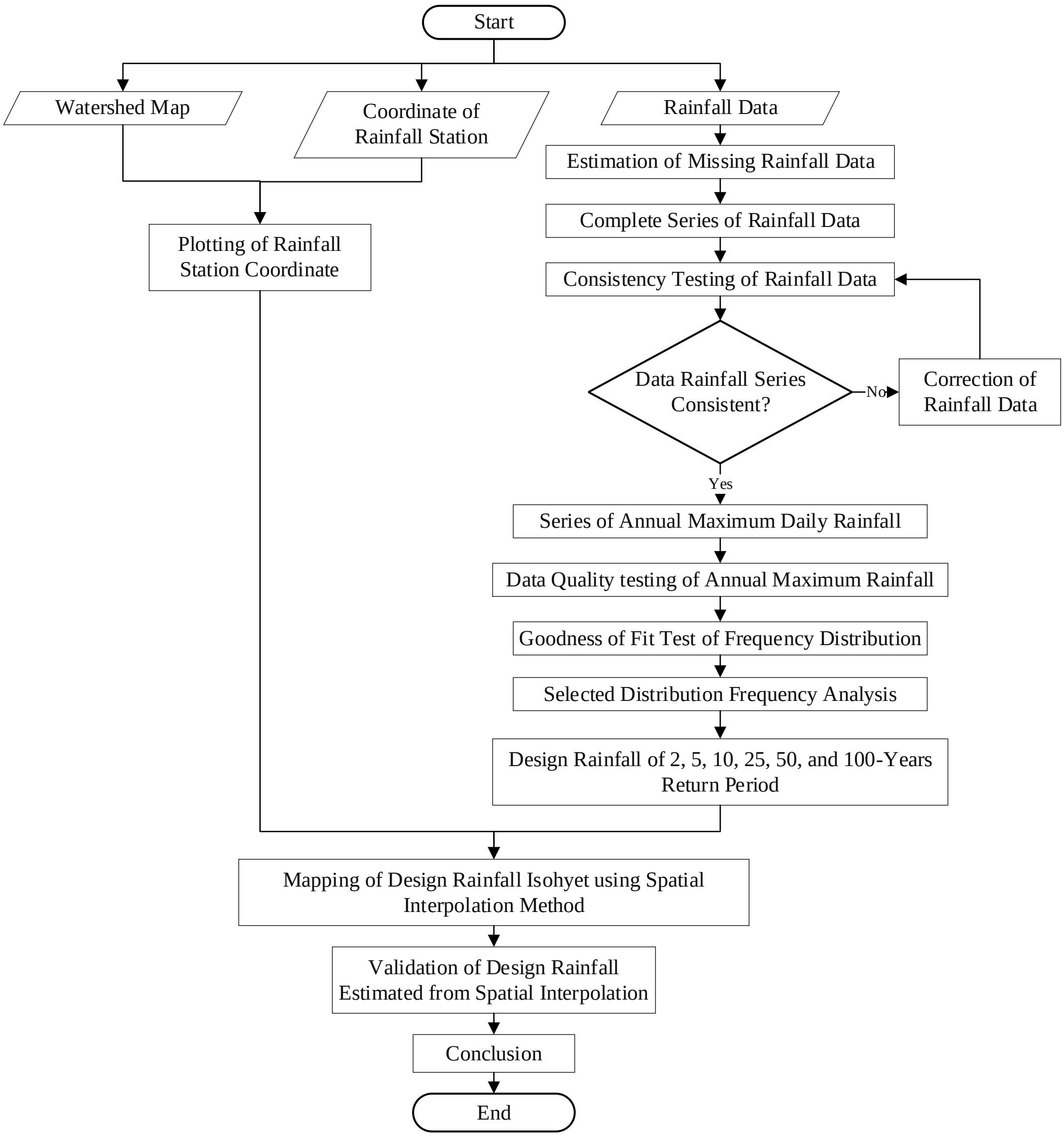

Figure 2. Flowchart of the Study

3.2. Data Analysis Techniques

a. Rainfall Data Quality Analysis

Water resource planning and management depend on the quality of the rainfall data used; thus, rainfall data must be evaluated to ensure their quality [12]. Rainfall data quality analysis involves various statistical tests, including:

1. Consistency Test (Double Mass Curve Method and RAPS)
2. Homogeneity Test (F_{test} and T_{test})
3. Persistence Test
4. Outlier Test

b. Design Rainfall Calculation

The design rainfall calculation uses frequency analysis to estimate the value of rainfall within a given return period [13]. The design rainfall is obtained by calculations using the Log Normal, Gumbel, and Log Person III frequency distributions [14]. The return periods used in the calculation of design rainfall are 2, 5, 10, 25, 50, and 100 years. The selection of the type of distribution is adapted to the results of the tests of the suitability of the distribution using the Chi-square test and the Smirnov-Kolmogorof test [15].

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c. Spatial Mapping of Design Rainfall

Mapping the spatial design rainfall using the linear interpolation method is used to estimate values in unmeasured areas in the watershed area [16]. The spatial map was presented in the form of isohyets connecting points of design rainfall with the same return period of design rainfall. Two methods were selected for estimating spatial of design rainfall, including:

- Inverse Distance Weighted (IDW)

The IDW method is a technique that assumes values based on distance as weights. The effect of the weighting is more significant for closer sample points, resulting in a more detailed surface [17]. For optimal results, the data samples used should be close and evenly distributed so that the results are most likely to be as desired. This method uses the average of the sample data, so the interpolated value cannot be greater than the maximum or less than the minimum of the sample data. Below is the equation for the IDW interpolation method:

$$F(z_x) = \sum_{i=1}^{n} w_i . z_i \tag{1}$$

$$w_i(x) = \frac{\left[\frac{1}{d}\right]^p}{\sum_{j=1}^{n}\left[\frac{1}{d}\right]^p} \tag{2}$$

Where:
n = number of points
i, j = sampling point number
w = weight factor
d = distance
p = power

- Spline

The spline method is an estimation technique that minimizes the curvature of the surface, resulting in smooth estimation curves that accurately pass through the sample points [18]. The spline method can predict minimum and maximum values with the effect of stretching the data. This method is also capable of calculating results with good surface accuracy, even with limited data. The following is the equation for the spline interpolation method:

$$S(x,y) = T(x,y) + \sum_{j=1}^{n} \lambda_j R(r)_j \tag{3}$$

Where:
j = 1, 2, …, n
n = number of points
λ_j = coefficients obtained from the linear system
r_j = distance between the two points (x, y)
$T\ (x, y)$ and (r) are interpreted differently depending on the selection method

d. Validation

Validation is an evaluation process to determine the performance of a model in estimating hydrological processes. In this study, validation was performed to evaluate the estimated value of the interpolated design rainfall distribution using the Nash-Sutcliffe Efficiency (NSE) and RMSE-Standard Deviation Ratio (RSR) parameters [19] which are shown in Equation 4 and 5.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - \overline{x_i})^2} \tag{4}$$

Where:
x_i = field observation value
y_i = interpolated calculated value

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$\bar{x_i}$ = average value of field observations
n = number of data

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}}{\sqrt{\sum_{i=1}^{n}(xi - \bar{x})^2}} \quad (5)$$

Where:
x = field observation value
$\bar{X}$ = average value of field observations
y = interpolated calculated value
n = number of data

4. Results and Discussions

The rainfall data collected cannot be used directly for hydrological analysis. The rainfall data must be statistically validated before the design rainfall calculations can be performed. The tests performed were for consistency, homogeneity, persistence, and outliers tests. The data quality analysis is obtained by testing 30 years of rainfall data from 13 rainfall stations in the Sadar Sub-watershed. Rainfall data consistency tests were conducted using the double mass curve and RAPS methods. The RAPS method is used to test individual stations as two rainfall stations have significant differences in altitude compared to other rainfall stations [20]. **Table 1** shows the summary of the rainfall data quality testing.

Table 1. The Summary of The Rainfall Data Quality Testing

Rainfall Stations	Homogeneity Test		Persistence Test	Outlier Test
	F_{test}	T_{test}		
Janjing				
Pugeran				
Pandan				
Klegen				
Mojosari				
Ketangi	Variance homogeneous	Mean homogenous	Data Random	No Outliers
Tangunan				
Tampung				
Terusan				
Pasinan				
Pudaksari				

Source: Own Analysis (2024).

4.1. Design Rainfall Analysis

The maximum daily rainfall data that will be used in the design rainfall calculation have previously been tested for suitability of frequency analysis distribution using the chi-square test and the Smirnov-Kolmogorof test [15]. The results of the Smirnov-Kolmogorov and the Chi-Square tests show that the series of rainfall data is accepted at all stations for the Log Normal, Gumbel, and Log Pearson III distribution.

Table 2 demonstrates the summary of the selected frequency analysis distribution used to estimate design rainfall for various return periods. From **Table 2,** it can be seen that two rainfall stations employ the Log Normal distribution, three rainfall stations apply the Gumbel distribution, and eight rainfall stations adopt the Log Person III distribution. **Table 3** exhibits the magnitude of design rainfall for return periods of 2, 5, 10, 25, 50, and 100 years at each rainfall station.

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Table 2. Summary of Selected Frequency Analysis Distribution

No.	Rainfall Station	Frequency Analysis Distribution	No.	Rainfall Station	Frequency Analysis Distribution
1	Trawas	Gumbel	8	Ketangi	Gumbel
2	Pacet	Log-Normal	9	Tangunan	Log Person III
3	Janjing	Log Person III	10	Tampung	Log Person III
4	Pugeran	Log Person III	11	Terusan	Log Person III
5	Pandan	Gumbel	12	Pasinan	Log Person III
6	Klegen	Log-Normal	13	Pudaksari	Log Person III
7	Mojosari	Log Person III			

Source: Own Analysis (2024).

Table 3. Summary of Design Rainfall for Various Return Periods

No.	Rainfall Station	Design Rainfall (mm)					
		R_{2th}	R_{5th}	R_{10th}	R_{25th}	R_{50th}	R_{100th}
1	Trawas	123,91	163,04	188,94	221,67	245,95	270,05
2	Pacet	99,37	130,90	151,23	174,05	194,69	213,42
3	Janjing	95,70	117,89	133,35	153,77	169,65	186,13
4	Pugeran	92,33	103,18	107,21	110,34	111,80	112,80
5	Pandan	119,58	148,44	167,55	191,69	209,60	227,38
6	Klegen	93,04	107,11	115,30	123,88	131,18	137,48
7	Mojosari	97,63	118,86	132,87	150,63	163,96	177,40
8	Ketangi	98,68	120,61	135,13	153,48	167,09	180,60
9	Tangunan	97,46	118,91	131,79	146,94	157,57	167,73
10	Tampung	91,37	107,02	114,98	123,15	128,21	132,59
11	Terusan	99,78	118,21	130,38	145,82	157,39	169,06
12	Pasinan	84,77	97,21	103,98	111,39	116,27	120,70
13	Pudaksari	95,93	112,74	120,12	126,74	130,31	133,07

Source: Own Analysis (2024).

4.2. The Spatial Mapping of Design Rainfall

In this study, the IDW and spline interpolation methods are used to map the spatial design rainfall for various return periods. The mapping was carried out using ArcGIS version 10.4 software. The input data used in the interpolation process are *X* and *Y* as the rainfall station coordinates and *Z* as the design rainfall value, as presented in **Table 3**. **Figure 3 - Figure 8** denotes the spatial map of design rainfall for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year return periods derived from the IDW and Spline interpolation method, respectively. Based on **Figure 3**, the value of the 2-year return period designed rainfall has a range of 84,77 mm to 123,91 mm for the IDW method, while the interpolation results using the spline interpolation method show a range of 83,45 mm to 126,04 mm. According to **Figure 4**, the value of the 5-year return period designed rainfall displays a range of 97,21 mm to 163,03 mm for the IDW method, while 83,45 mm to 126,04 mm for the spline interpolation method. As for the 10-year return period in **Figure 5**, the value shows a range of 103,99 mm to 188,93 mm for the IDW method, while the spline interpolation method exhibits a magnitude of 103,29 mm to 197,73 mm. Based on **Figure 6**, the value of the 25-year return period designed rainfall has a range of 110,37 mm to 221,66 mm for the IDW method, while the interpolation results using the spline interpolation method show a range of 105,76 mm to 233,11 mm. Refer to **Figure 7**, the value of the 50-year return period designed rainfall displays a range of 111,84 mm to 245,94 mm for the IDW method, while 107,25 mm to 260,46 mm for the spline interpolation method. Furthermore, as presented in **Figure 8**, the value shows a range

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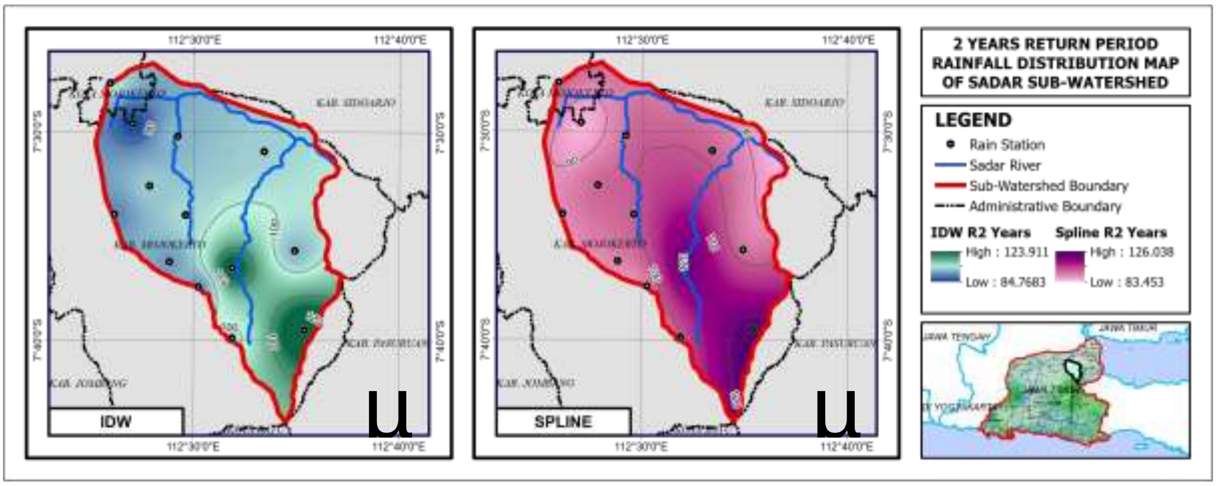
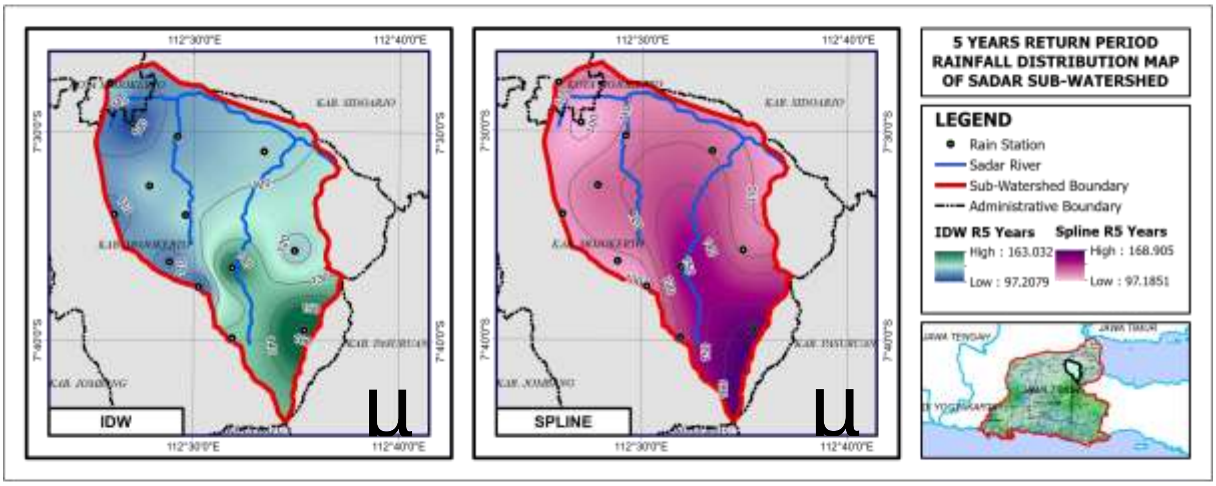
ISSN (*Print*) 2503-2399



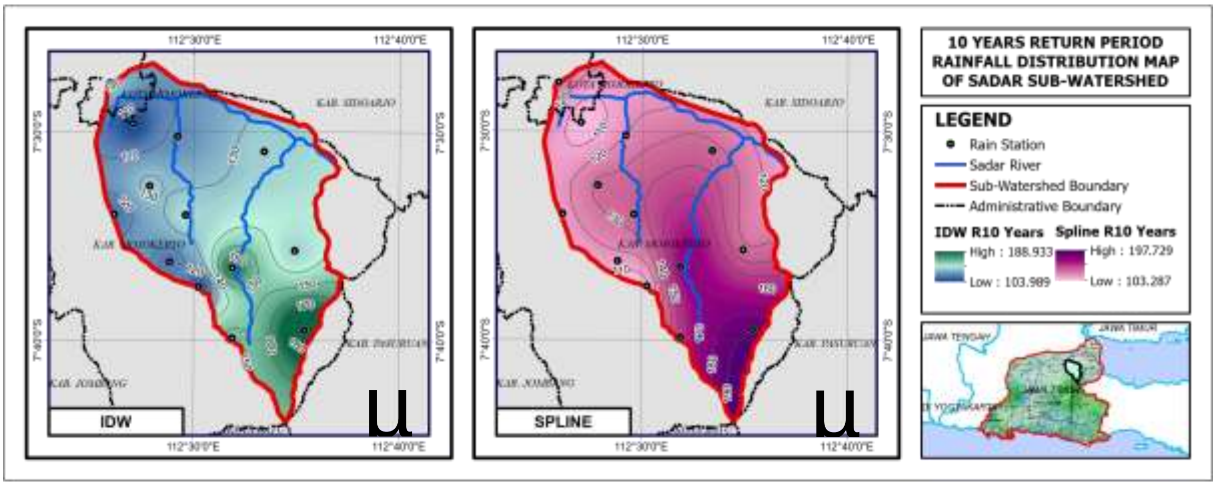
Source: Mapping Results, 2024.

Figure 3. The spatial map of the 2-year return period design rainfall for the IDW and Spline Interpolation Method



Source: Mapping Results, 2024.

Figure 4. The spatial map of the 5-year return period design rainfall for the IDW and Spline Interpolation Method



Source: Mapping Results, 2024.

Figure 5. The spatial map of the 10-year return period design rainfall for the IDW and Spline Interpolation Method

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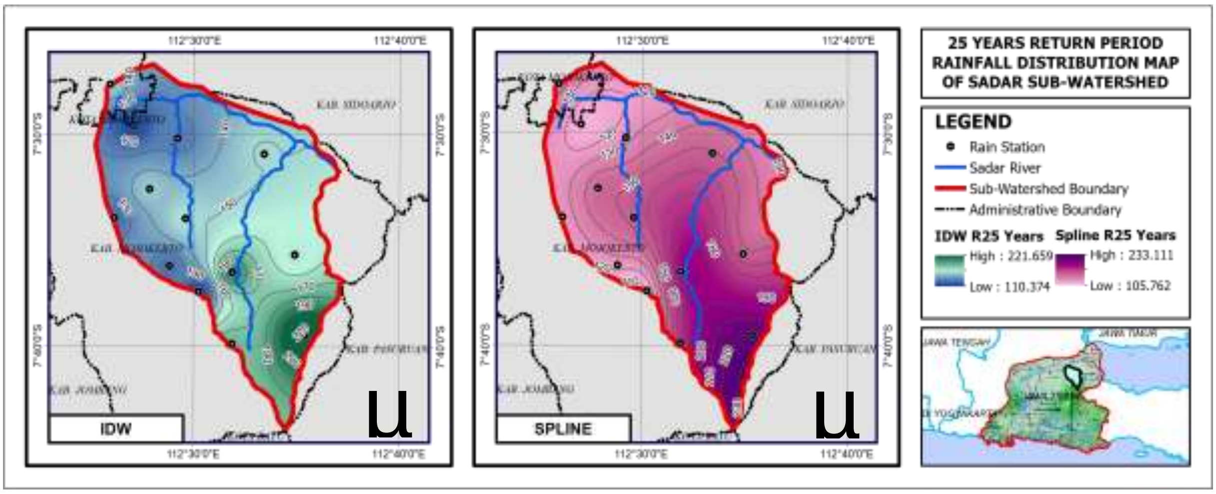
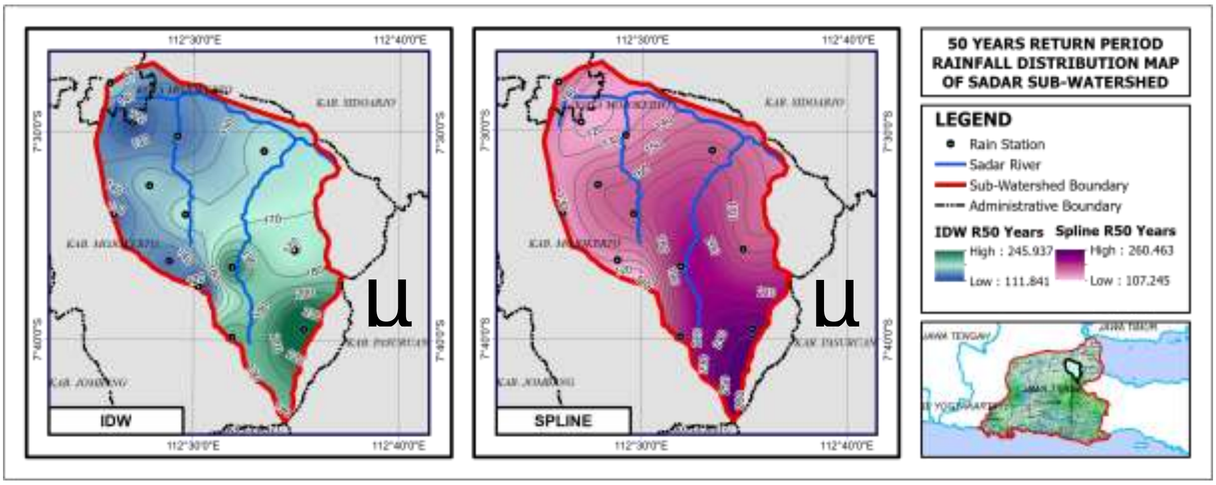


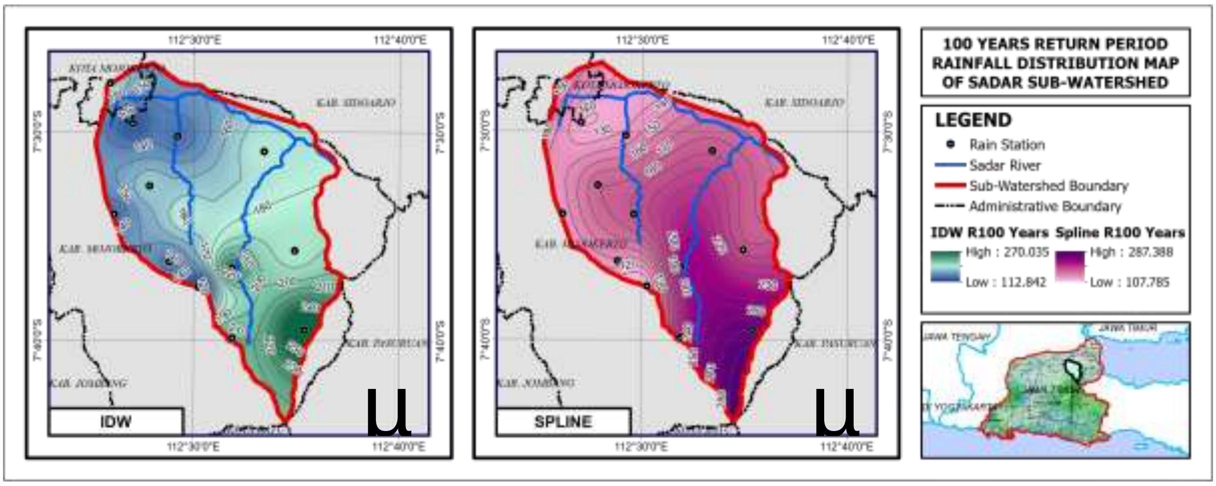
Source: Mapping Results, 2024.

Figure 6. The spatial map of the 25-year return period design rainfall for the IDW and Spline Interpolation Method



Source: Mapping Results, 2024.

Figure 7. The spatial map of the 50-year return period design rainfall for the IDW and Spline Interpolation Method



Source: Mapping Results, 2024.

Figure 8. The spatial map of the 100-year return period design rainfall for the IDW and Spline Interpolation Method

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of 112,84 mm to 270,04 mm for the IDW method, while the spline interpolation method exhibits a magnitude of 107,79 mm to 287,39 mm. For the IDW method, the isohyet lines tend to converge and be situated around the rainfall station points, while the spline method tends to exceed the rainfall station point, which is in line with the results of the study conducted by [21].

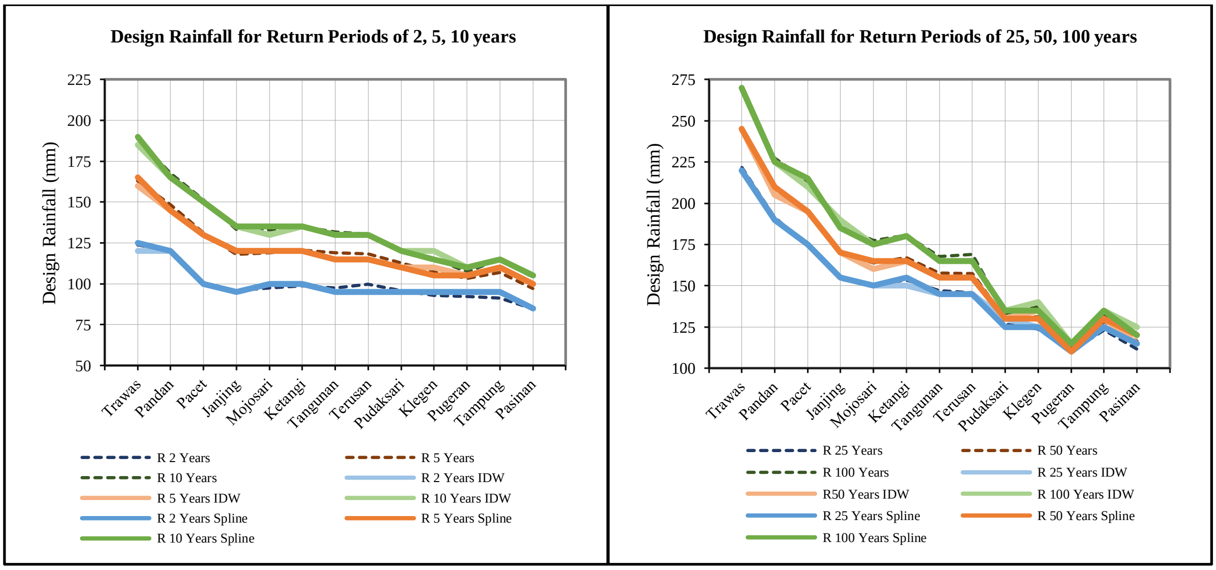
About density patterns, both methods produce contour lines that become denser as the return period increases which is linear with the study carried out by [22]. The IDW and spline interpolation results exhibit similarities in the direction pattern, with the highest value located upstream at the Trawas Station and the lowest value located downstream at the Pasinan Station for each return period. In the IDW Method, the isohyet line formed at the downstream part of the Sadar Sub-watershed appears less detailed, showing gaps due to the low density of rainfall stations in that area. It occurs because the estimation of IDW method values depends on the distance of the data samples, making the density of rainfall stations very crucial [23]. The results of the study revealed that the design rainfall value has a positive correlation with the return period, meaning that it grows as the return period increases.

4.3. Validation

Validation was performed to evaluate the estimation values of the design rainfall distribution resulting from interpolation against the design rainfall from frequency analysis and also against the spatial map of design rainfall published by the Ministry of Public Works Directorate General of Water Resources.

4.3.1. Validation Test of Frequency Analysis Results

Validation tests were performed on design rainfall estimates obtained through spline interpolation in the Sadar Sub-watershed. The data from the frequency analysis calculation is used as a comparison to evaluate the accuracy of the estimate. The following is a comparison graph between the rainfall value estimated by the IDW and spline interpolation methods and the frequency analysis data. **Figure 9** demonstrates the comparison of design discharge obtained from frequency analysis and linear interpolation IDW and Spline. According to **Figure 9**, there are similarities between the interpolated rainfall and the frequency analysis results at several stations, indicated by relatively closely adjacent graphs. The statistical measures, including Nash-Sutcliffe Efficiency (*NSE*) and RMSE-Standard Deviation Ratio (*RSR*) employed to examine the comparison quality of the interpolated rainfall and the frequency analysis. **Table 4** displays the summary of Nash-Sutcliffe Efficiency (NSE) and RMSE-Standard Deviation Ratio (RSR) for the validation results. Based on the validation results, the interpolated design rainfall was compared with the frequency analysis design rainfall using the RSR and NSE parameters.



Source: Analysis Results, 2024.

Figure 9. Comparison of Frequency Analysis Design Rainfall and Interpolation Results

ISSN (*Online*) 2620-7222
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Table 4. Summary of Nash-Sutcliffe Efficiency (*NSE*) and RMSE-Standard Deviation Ratio (*RSR*)

No.	Return Period	NSE				RSR			
		IDW	Criteria	Spline	Criteria	IDW	Criteria	Spline	Criteria
1	1	0,935		0,955		0,255		0,211	
2	5	0,990		0,992		0,100		0,092	
3	10	0,997	Excellent	0,999	Excellent	0,057	Excellent	0,036	Excellent
4	25	0,998		0,999		0,041		0,029	
5	50	0,999		0,999		0,036		0,025	
6	100	0,999		0,999		0,033		0,026	

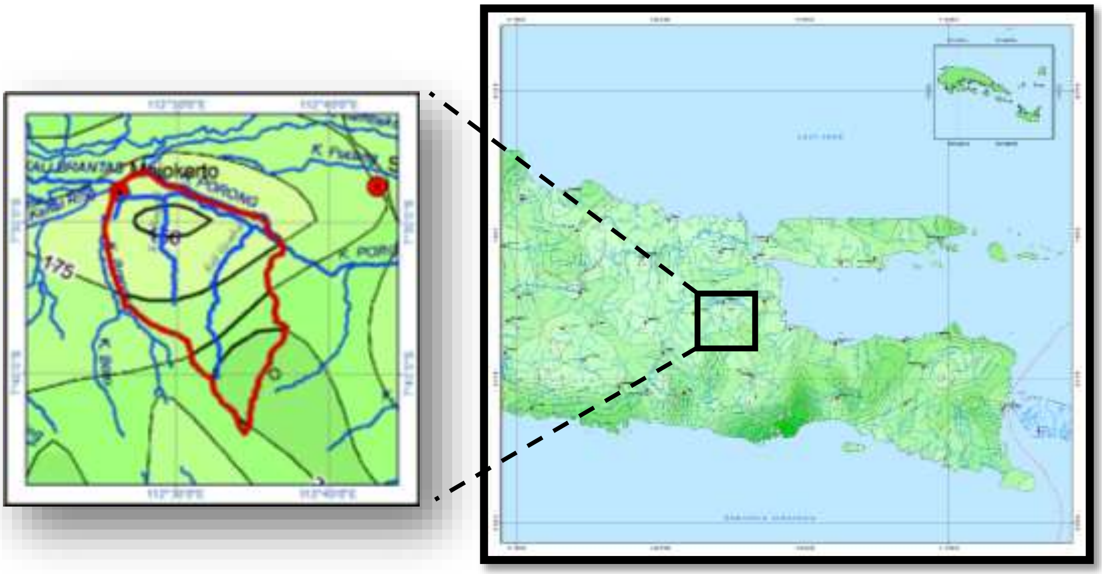
Source: Own Analysis (2024)

From the calculation results in **Table 4**, it can be concluded that the interpolated design rainfall of the IDW method has similarities with the design rainfall of frequency analysis results, where the calculation results produce excellent criteria in each return period. It is indicated by NSE values approaching one and RSR values approaching 0 [24]. The similarity of the interpolation results is due to the ability of the IDW method to assume that interpolated values will be more similar to closely sampled data [25][26]. As shown in **Table 4,** the NSE and RSR values show that the higher the return period, the better the performance and accuracy of the interpolation result.

4.3.2. Validation Test of Design Rainfall Map the Ministry of Public Works and Public Housing (PUPR)

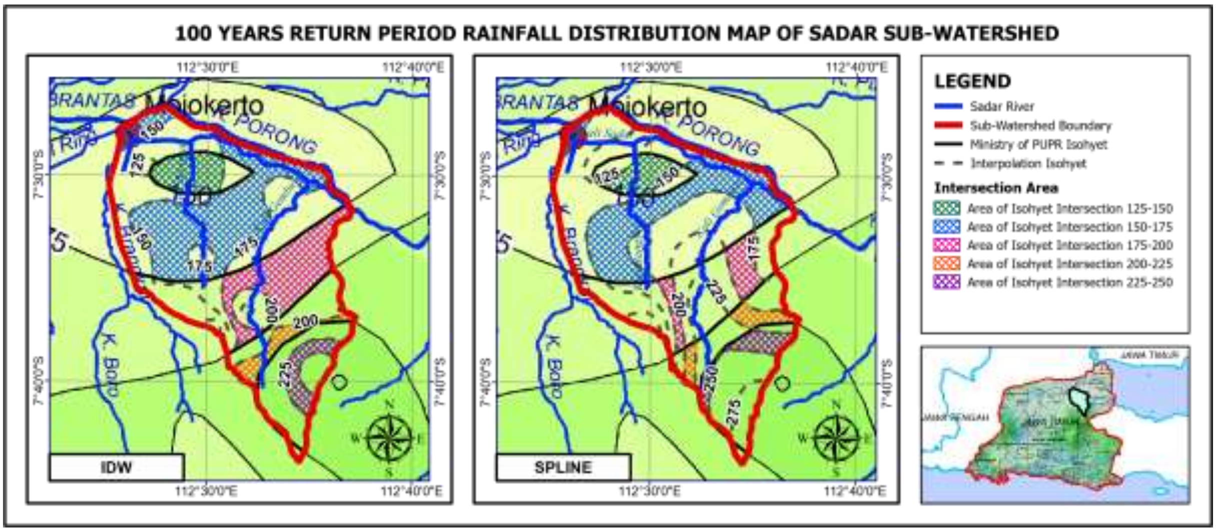
The interpolated design rainfall map was validated against the design rainfall map published by the Ministry of PUPR to determine the compatibility between the two maps. The design rainfall map published by the Ministry of PUPR is valid and accountable in terms of its accuracy. Therefore, it is used as a benchmark for validation. The design rainfall spatial map is available for return periods of 100 years, 1000 years, and PMP. However, the data limitations in this study only allow frequency analysis calculations up to a return period of 100 years, so the validation of the map can only be carried out for a return period of 100 years. **Figure 10** is the isohyet map by the Ministry of PUPR for the 100-year return period. The validation test involves overlaying the rainfall map resulting from the interpolation method with the official map issued by the Ministry of PUPR.

According to **Figure 11**, the overlay results produce intersection points between isohyets lines that are both delimited by similar isohyets lines. These intersecting areas will be evaluated to assess the extent of their compatibility. The comparison of the intersection area between the IDW and spline interpolation result map and the Ministry of PUPR map can be seen in **Table 5** and **Table 6.**



Source: Ministry of Public Works Directorate General of Water Resources, 2013.
Figure 10. Isohyet Map for the 100-Year Return Period, Java Sheet 3.

ISSN (*Online*) 2620-7222
ISSN (*Print*) 2503-2399



Source: Own Analysis, 2024.

Figure 11. Overlaying the results of IDW and Spline interpolation with the Ministry PUPR map.

Table 5. Calculation of IDW Method Compatibility with the Ministry of PUPR Map.

No.	Isohyet Boundary (mm)	PUPR Isohyet Area (km^2)	Intersection Area of IDW Isohyet (km^2)	Compatibility (%)
1	125-150	24,81	20,13	49,70
2	150-175	189,79	98,83	
3	175-200	86,19	47,67	
4	200-225	35,45	12,57	
5	225-250	50,13	12,81	
Total		386,37	192,00	

Source: Own Analysis (2024).

Table 6. Calculation of Spline Method Compatibility with the Ministry of PUPR Map.

No.	Isohyet Boundary (mm)	PUPR Isohyet Area (km^2)	Intersection Area of Spline Isohyet (km^2)	Compatibility (%)
1	125-150	24,81	15,81	33,20
2	150-175	189,79	71,07	
3	175-200	86,19	17,80	
4	200-225	35,45	11,30	
5	225-250	50,13	12,27	
Total		386,37	128,25	

Source: Own Analysis (2024).

According to **Table 5** and **Table 6**, the interpolation results of the IDW method have a suitability of 49,70%, while the spline method has a suitability of 33,20% compared to the map published by the Ministry of PUPR. The low suitability of the map results is due to several factors, including:

1. Differences in the length of rainfall data

   The interpolated design rainfall in this study was constructed from 30 years of rainfall data from 1993 to 2022. In comparison, the isohyet map published by the Ministry of PUPR was built from rainfall data for more than 30 years, from 1961 to 2011, with a lack of rainfall data from 1940 to 1950. The difference in data length will affect the calculation of the design rainfall.
2. Differences in the number and spatial location of rainfall station

   The interpolated design rainfall in this study was developed from rainfall data of 13 rainfall stations scattered around the Sadar Sub-watershed area. In comparison, the isohyet map published by the Ministry of PUPR was built from rain data of all rainfall stations on Java Island with a rainfall

ISSN (*Online*) 2620-7222
ISSN (*Print*) 2503-2399

station density of 56 km/post. This difference will affect the pattern of isohyet lines from the interpolation results.

3. Differences in interpolation methods

   The spatial map of design rainfall in this study was designed using the IDW and spline interpolation method, while the map published by the Ministry of PUPR was developed using the kriging interpolation method.

5. Conclusion and Suggestion

5.1 Conclusion

The calculation of the design rainfall for the return period of 2, 5, 10, 25, 50, and 100 years is carried out using the type of distribution that has been tested for suitability, which are two rainfall stations using Log Normal distribution, three rainfall stations using Gumbel distribution and eight rainfall stations using Log Person III distribution. The calculation results show the lowest value at the 2-year return period of 84.75 mm at Pasinan Station and the highest value at the 100-year return period of 270.046 mm at Trawas Station. The results of the design rainfall mapping using the IDW and spline interpolation methods show a similar pattern. The resulting isohyet lines become denser as the return period increases, with the highest values pointing upstream and the lowest values pointing downstream of the Sadar Sub-watershed. Validation of the maps using NSE and RSR parameters provides an excellent assessment for each return period, indicating similarity with the design rainfall from frequency analysis. In addition, validation of the map published by the Ministry of PUPR obtained a suitability of 49.70% for the IDW method and 33.20% for the spline method. Therefore, the IDW method is considered to be the most appropriate and accurate interpolation method for mapping the design rainfall distribution at the study site.

5.1 Suggestion

The suggestions that can add to the accuracy of the results in this study include the following:

1. Data validation of rainfall is necessary to ensure more accurate data and prevent calculation errors or poor test results because this study is highly dependent on the quality of the data used.
2. Further studies are needed to determine the rainfall stations and their density at the study location to optimize the interpolation results for greater accuracy.

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