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Analysis of The Rationalization of Rainfall Stations in The Kayan River Basin, North Kalimantan Province

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Abstract

The Kayan River Basin (Wilayah Sungai [WS]) covers an area of 3,178,215.72 hectares, making it one of the largest river basins in Kalimantan. However, compared with other river basins in the region, the Kayan WS currently has only seven rainfall stations, of which six are operational and one is damaged or inactive. This limited observation network is insufficient to represent the highly heterogeneous spatial distribution of rainfall across the basin, which extends from mountainous upstream areas with high precipitation to lowland coastal regions. Therefore, this study aims to determine the most appropriate rationalization method for identifying the optimal number and spatial distribution of rainfall stations capable of adequately representing rainfall variability within the Kayan River Basin. Three approaches were evaluated for rainfall station rationalization: the maximum requirement method, the minimum requirement method, and the Kagan–Rodda method. The results indicate that the Kagan–Rodda method is the most suitable approach for rationalizing the rainfall station network in the Kayan WS. Based on this method, the basin requires a total of 33 rainfall stations. Given that only six operational stations currently exist, an additional 27 rainfall stations are required to establish an optimal monitoring network.

INTRODUCTION

Hydrological analysis is one of the most fundamental components of water resources management (Baran-Gurgul & Rutkowska, 2024; Muratoglu et al., 2022). Planning and designing hydraulic structures, such as dams, reservoirs, irrigation canals, and flood control systems, depend heavily on the availability and reliability of hydrological data, particularly rainfall data (Doost et al., 2024; Jain & Singh, 2023; Oyebode et al., 2023; Thakare et al., 2026; Ukarande, 2023). Rainfall data serve as the primary input for estimating design discharge, evaluating water availability, and modeling surface runoff. Accurate hydrological analysis therefore relies not only on the quality of rainfall data but also on the number and spatial distribution of rainfall stations within a watershed (Putu Doddy Heka Ardana et al., 2023). Consequently, an adequate and well-distributed rainfall station network is essential to ensure that collected data accurately represent the spatial variability of rainfall across an entire river basin . Measurement errors frequently occur because of inadequate station density or poor spatial distribution, resulting in less reliable hydrological analyses. Such inaccuracies may reduce the effectiveness and efficiency of water resources planning. The number and distribution of rainfall stations are therefore critical factors affecting measurement accuracy (Prawati & Dermawan, 2018). Estimating the optimal number and location of rainfall stations is essential for providing representative rainfall information within a catchment area (Renaldhy et al., 2021).

The Kayan River Basin (Wilayah Sungai [WS]) is one of Indonesia's National Strategic River Basins located in North Kalimantan Province (Farid Ahmed et al., 2023; Jabarsyah et al., 2022; Sutrisno et al., 2022). According to the Regulation of the Minister of Public Works and Public Housing (Peraturan Menteri Pekerjaan Umum dan Perumahan Rakyat [Permen PUPR]) No. 4/PRT/M/2015 concerning the Criteria and Designation of River Basins, the Kayan WS is classified as an inter-regency river basin within a single province. The basin encompasses two principal administrative regions: Bulungan Regency, which includes the middle and downstream reaches where the Kayan River discharges into the Sulawesi Sea and serves as the center of economic activities, government, and urban infrastructure; and Malinau Regency, which comprises the upstream region characterized by mountainous terrain, high rainfall, and dense forest cover.

The Kayan River Basin covers a total area of 3,178,215.72 hectares (approximately 31,782 km²), making it one of the largest river basins in Kalimantan. Its physiography is highly diverse, extending from densely forested mountainous headwaters to lowland downstream areas. This variation in topography produces highly heterogeneous rainfall patterns in both intensity and spatial distribution. For example, annual rainfall in the upstream region of Malinau may be approximately twice that recorded in the coastal areas of Bulungan. Despite the basin's extensive area and complex hydrological characteristics, the existing rainfall observation network is very limited, consisting of only seven rainfall stations, of which six are operational and one is damaged or inactive.

Previous studies have demonstrated that rainfall station rationalization has been widely applied in various river basins throughout Indonesia using several analytical approaches. Ayiscy Cindy Harifa et al. (2020) evaluated the rainfall station network in the Dumoga–Sangkub River Basin, while Dehas Abdaa et al. (2021) analyzed rainfall station density in the Rokan River Basin using daily rainfall data and error variation analysis. Prawati and Dermawan (2017, 2018) applied the Kagan–Rodda method while incorporating topographic factors in the Sarokah and Kedunglarangan watersheds, and Ranesa et al. (2015) evaluated rainfall station rationalization for hydrograph calibration in the Babak Watershed. Additional studies by Imaaduddiin et al. (2022), Intan Muliawati et al. (2024), and Atika et al. (2022) also employed the Kagan–Rodda method to assess rainfall station density in various watersheds. Meanwhile, Awfa et al. (2024) applied the Stepwise method in the Porong Sub-watershed, whereas Junaidi (2015) compared the Kagan–Rodda and Kriging methods in the Parigi–Poso River Basin. Fathoni et al. (2016) further explored the use of an Artificial Neural Network to evaluate rainfall station network effectiveness. Despite these contributions, a significant research gap remains for the Kayan WS in North Kalimantan, where no previous study has specifically evaluated rainfall station rationalization across a basin of approximately 31,782 km² served by only six operational rainfall stations. The novelty of this study lies in its comprehensive application of multiple rationalization approaches, including Cluster Analysis Unit (CAU) analysis, Thiessen polygon analysis, the Kagan–Rodda method, and optimum station requirement calculations based on Garg SK (1982), to determine the optimal number and spatial distribution of rainfall stations within the Kayan WS, which exhibits highly heterogeneous topographic and rainfall characteristics.

Based on the background and research gap described above, this study aims to analyze the rationalization of rainfall stations in the Kayan River Basin, North Kalimantan Province, by determining the maximum and minimum rainfall station requirements and evaluating the adequacy of the existing rainfall station network using the Kagan–Rodda method. Specifically, the study identifies the current condition of rainfall stations within the Kayan WS, estimates the optimum number of rainfall stations using the Garg SK (1982) method and Cluster Analysis Unit (CAU) analysis, evaluates the spatial distribution and inter-station distances using Thiessen polygon and Kagan–Rodda analyses, and compares the results obtained from these methods to determine the most appropriate rationalization approach for the Kayan WS. The findings are expected to provide a technical basis for recommending the addition, relocation, and optimization of rainfall stations within the Kayan WS, thereby improving the accuracy and representativeness of hydrological data to support sustainable water resources planning and management in North Kalimantan.

METHOD

This study was conducted in the Kayan River Basin (Wilayah Sungai [WS]), North Kalimantan Province, which covers Bulungan Regency (middle and downstream areas) and Malinau Regency (upstream area), with a total area of 3,178,215.72 hectares (approximately 31,782 km²). The Kayan WS is designated as a National Strategic River Basin based on the Regulation of the Minister of Public Works and Public Housing (Permen PUPR) No. 4/PRT/M/2015. The research object consisted of rainfall stations within the Kayan WS, comprising seven stations: CH. Betayang Aru, CH. Antutan I, CH. Antutan II, CH. Kulteka, CH. PU Office, and CH. Tanjung Harapan, with one additional station recorded as inactive. The study was conducted over three months (October–December 2025), including data collection, processing, analysis, and report preparation.

The study used secondary data obtained from relevant institutions, including annual maximum rainfall data from six operational rainfall stations, watershed area and river boundary data, geographic coordinates and station elevations, as well as topographic and physiographic maps of the Kayan WS. Data analysis was performed through several stages, including Cluster Analysis Unit (CAU) analysis, Thiessen polygon analysis, and the Kagan–Rodda method, to evaluate rainfall station distribution and determine the optimal rainfall station network.

RESULTS AND DISCUSSION

Cluster Analysis Unit Analysis (CAU)

To facilitate data analysis, it is necessary to divide the analysis cluster units as a basis for calculating rainfall post requirements. In this case, the division of analysis clusters is adjusted to the existing watershed divisions in accordance with PUPR Ministerial Regulation No. 4/PRT/M/2015, as can be seen in the figure.

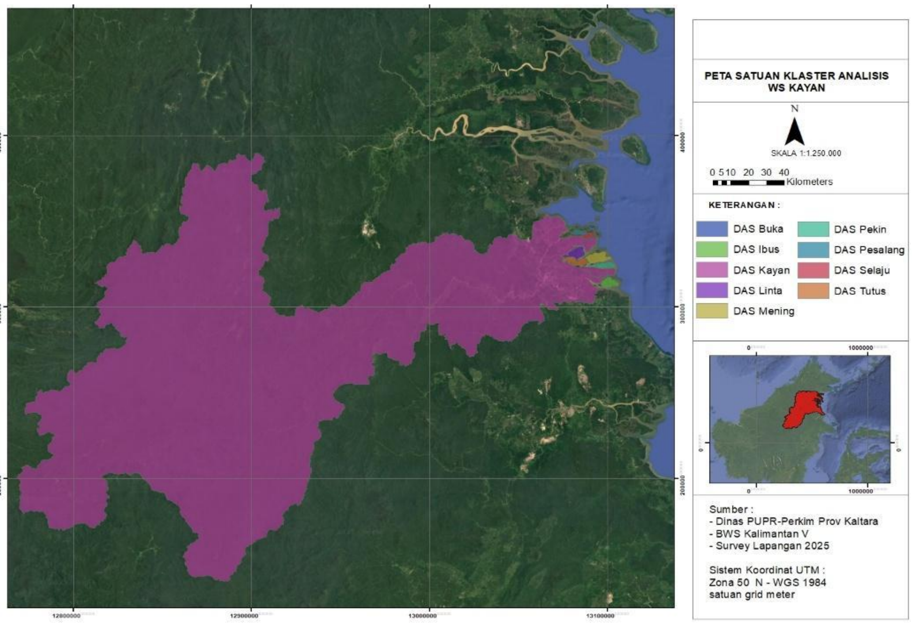

Figure 1. Division of Analysis Cluster Units According to the Number of Watersheds

Source: Analysis Results, 2025

Thiessen Polygon Analysis

Table 1. Area of Influence of Thiessen Polygon in Kayan Watershed

No	Station Name	Speed Km^2
1	CH. Hang out with Aru	2.8642,41
2	CH. Antutan I	330,36
3	CH. Antutan II	799,76
4	CH. Kulteka	1.109,50
5	CH. Public Works Office	425,98
6	CH. Tanjung Harapan	184,38

Source: Analysis Results, 2025

Determination of Optimum Requirements (GARG SK, 1982)
Number of rain stations:

$$N = (\frac{28,79}{10})^2$$

Coefficient of variation of rainfall:

$$C_{in} = \frac{100x740,43}{2.571,75}$$

Standard Deviation :

$$\sigma = \left[\frac{6}{6-1}\{\{7.070761,26 - (2.571,75)^2\}\right]^{½}$$

Average Rainfall from n stations:

$$\underline{p} = \frac{15.430,5}{6}$$

with:

N : number of rainfall stations
Cv : the coefficient of variation of rainfall is based on the existing rainfall stations
AND : percentage of permissible error
p : average annual rainfall
$\underline{p}$: average rainfall from n stations
n : number of existing rain stations
s : standard deviation

Based on the calculation results using the formula presented by Garg SK (1982), the overall optimum requirement for rainfall stations in the Kayan River Basin is 9. From all the watershed analysis cluster units, it can be seen that in the Kayan River Basin, namely the Kayan River Basin, there are additional rainfall stations. In detail, the Kayan River Basin requires the addition of 3 rainfall stations, while for the other 8 watersheds this cannot be done because there is no rainfall data that can be analyzed to calculate the optimum rainfall station requirement.

Table 2. Optimal Rainfall Station Requirements Per Analysis Cluster Unit/DAS

No	THE	Area (Ha)	Number of Existing Posts				Needs Plan	Adding New Posts
			Existing Amount	Active/ Functional	Needs Improv ement	Not active		
1	DAS Equipment	3.149. 239,3	7	6	0	1	9	3
2	Pesalang Watershed	2.981, 74	0	0	0	0	0	1
3	Open Watershed	1.208, 41	0	0	0	0	0	1
4	DAS Selaju	2.214, 06	0	0	0	0	0	1
5	DAS Linta	4.685, 37	0	0	0	0	0	1
6	THE Tutu	4.050, 21	0	0	0	0	0	1
7	Mening Watershed	6.693, 95	0	0	0	0	0	1
8	Pekin Watershed	3.232, 28	0	0	0	0	0	1
9	DAS Ibus	3.910, 4	0	0	0	0	0	1
Total Area of WS		**3.178. 215,72**	**7**	**6**	**0**	**1**	**9**	**11**

Source: Author's processing, 2025

The Kayan River Basin, with an area of approximately 31,782 km², has six rainfall stations. The distances between the surrounding stations and the correlation between the available data were then calculated. Table 3 shows the distances between stations whose locations have been confirmed. Analysis of the distribution of rainfall stations using the Kagan-Rodda method revealed 27 additional rainfall stations in the Kayan River Basin.

Table 3. Distance between rainwater posts in the Kayan watershed

Jarak (km)	CH. Hang out with Aru	CH. Antutan I	CH. Antutan II	CH. Kulteka	CH. Public Works Office	CH. Tanjung Harapan
CH. Hang out with Aru	-	13,0	140,8	14,0	101,2	118,2
CH. Antutan I	13,0	-	131,4	26,6	100,3	108,4
CH. Antutan II	140,8	131,4	-	153,8	91,2	23,7
CH. Kulteka	14,0	26,6	153,8	-	108,1	131,4
CH. Public Works Office	101,2	100,3	91,2	108,1	-	82,7
CH. Tanjung Harapan	118,2	108,4	23,7	131,4	82,7	-

Source: Author's processing, 2025

The initial step before conducting a correlation study between rainfall stations is to find out the data conditions of each rainfall station, in the form of an annual rainfall data series.

$$r_{(d)} = r_{(0)} and^{\frac{-d}{d_{(0)}}}$$

$$Z1 = Cv \sqrt{\frac{1 - r_{(0)} + 0,23 \frac{\sqrt{A}}{d_{(0)}\sqrt{n}}}{n}}$$

$$Z2 = Cv \sqrt{\frac{1}{3}} \left(1 - r_{(0)}\right) + 0,52 \frac{r_{(0)}}{d(0)} \sqrt{\frac{A}{n}}$$

Kayan Watershed Network $L = 1,07 \sqrt{\frac{A}{n}}$

$$L = 1,07 \sqrt{\frac{31.782}{33}}$$

$$L = 1,07\, x\sqrt{5.297}$$

$$L = 33.21\ km$$

Where :

$r_{(d)}$: correlation coefficient of station distance d

$r_{(0)}$: short station distance correlation coefficient

d : distance between rainfall stations (km)

$d_{(0)}$: correlation radius

Cv : coefficient of variation

A : watershed area (km^2)

n : number of stations

Z1, Z2 : alignment error (%)

THE : interpolation error (%)

L : distance between stations (km)

Based on the calculation results in determining the kagan wheel nets, the calculation for the side length of the kagan wheel nets in the Kayan watershed is 33.21 km.

After knowing several calculations of hydrological post requirements, the next step will be to choose the most appropriate method for the Kayan WS based on several considerations, namely the Kagan-Rodda method.

The table below presents a summary of the need for rain stations based on several analyses that have been used.

No	Nama DAS	LUAS	POS CURAH HUJAN						
			Eksisting	Berdasarkan WMO		Kebutuhan Optimum		Kagan-Rodda	
				Rencana Kebutuhan	Penambahan Pos Baru	Rencana Kebutuhan	Penambahan Pos Baru	Rencana Kebutuhan	Penambahan Pos Baru
1	DAS Kayan	3.149.239,30	7	53	47	9	3	33	27
2	DAS Pesalang	2.981,74	0	1	1	0	1	0	0
3	DAS Buka	1.208,41	0	1	1	0	1	0	0
4	DAS Selaju	2.214,06	0	1	1	0	1	0	0
5	DAS Linta	4.685,37	0	1	1	0	1	0	0
6	DAS Tutus	4.050,21	0	1	1	0	1	0	0
7	DAS Mening	6.693,95	0	1	1	0	1	0	0
8	DAS Pekin	3.232,28	0	1	1	0	1	0	0
9	DAS Ibus	3.910,40	0	1	1	0	1	0	0
TOTAL				61	55	9	11	33	27

Figure 2. Recapitulation of the Kayan River Basin Rainfall Post Rationalization Method

Source: Author's processing, 2025

CONCLUSION

Based on the analysis conducted for the rationalization of rainfall stations in the Kayan River Basin, the findings addressed the four research objectives. The analysis showed that the optimal rainfall station network required for the Kayan River Basin consisted of 13 rainfall stations, including the relocation of two existing stations and the addition of six new stations. Among the evaluated methods, the Kagan–Rodda method was identified as the most suitable approach for rainfall station rationalization in the Kayan River Basin.

Based on these findings, several recommendations are proposed. The addition of new rainfall stations should be prioritized in areas with limited observation coverage, particularly the mountainous upstream regions of Malinau and the middle to downstream areas of the basin, with station distribution following the optimal spacing of 33.21 km identified through the Kagan–Rodda analysis. The two stations requiring relocation should be moved to locations that better represent local rainfall characteristics by considering elevation, terrain exposure, and accessibility. Meanwhile, the inactive station should be restored to improve the overall functionality of the rainfall observation network. The government should provide adequate funding for station development, operation, and maintenance, as well as establish a regular monitoring system to ensure that the rainfall station network continues to support water resources management in the Kayan WS.

Future studies should incorporate satellite-based precipitation data and remote sensing technologies to complement ground-based rainfall observations. Further sensitivity analyses of correlation parameters are also recommended to improve the applicability of the Kagan–Rodda method for the Kayan WS. In addition, integrating rainfall station rationalization results with hydrological modeling could improve applications such as flood forecasting and water availability assessment, thereby supporting sustainable water resources planning and disaster risk reduction in North Kalimantan Province.

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