DEVELOPMENT OF METHOD TO OPTIMIZE RAIN GAUGE STATION LOCATION IN DA RANG RIVER BASIN USING SPATIAL INTERPOLATION TECHNIQUE

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Abstract

Rainfall is one of the crucial data types in meteorological research. In the context of increasingly complex climate change, meteorological forecast data is essential for modeling and predicting natural disasters, especially floods and landslides. To ensure the accuracy of rainfall prediction and the cost of building and operating rain gauge stations, determining the number of stations is crucial. Therefore, this study developed an optimization design for the rain gauge station network in the Da Rang River focusing on the quantity and spatial distribution of rain gauge stations. The geostatistical method combined with spatial interpolation algorithms was applied using rainfall data from 2015-2020. The choice of an appropriate spatial interpolation method influenced the accuracy of the optimization process. The spatial interpolation analysis showed the spatial variation of rainfall types across the entire study area by season, as well as the geographical distribution of rainfall. After determining the optimal number of stations, an approach based on geographic information systems produced a spatial distribution map of the optimal rain gauge station locations. The results indicated that an additional 14 rain gauge stations should be installed, randomly located within the rainy area with a distance of 10 km between stations. These additional stations, along with the existing ones in the area, will provide comprehensive information about rainfall, enabling accurate predictions of rainfall distribution in the research area.

Keywords: *GIS; MCDA; optimization; IDW; rain gauge stations; spatial analysis.*

1. Introduction

Vietnam is one of the six countries severely affected by extreme climate events, with floods ranking first in terms of severity, extent, frequency, and damage [1]. Floods are characterized by inundation, swift water flow capable of sweeping away houses and trees. Typically, floods have high flow rates, are sudden, and primarily occur in hilly regions with steep terrain. Flooding is the phenomenon of water inundation in a specific area for a certain period, which can be caused by excessive floodwater or a large amount of water with no drainage outlet, resulting in flooding. Floods have various causes and can lead to significant damage to both human health and property [2]. In this study, we

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DOI: 10.56651/lqdtu.jst.v6.n02.736.sce

focus on evaluating the flooding phenomenon caused by increased rainfall during the rainy season.

Under the influence of climate change, abnormal fluctuations in rainfall have occurred. Real-time rainfall data collected and continuously transmitted by rain gauges are crucial for various tasks such as flood and landslide warnings, streamflow predictions, the management of reservoir safety, and support for local development planning to cope with and mitigate natural disasters [3]. Information from rain gauges provides favorable conditions for decision-makers to issue urgent alerts in the event of floods or landslides, protecting both property and lives.

Rainfall data from rain gauges are used to estimate average rainfall for areas without rain gauges. If the density of rain gauges is insufficient or their locations do not represent the rainfall characteristics of the observed area, it can lead to inaccuracies in rainfall predictions, limiting their accuracy and usability for forecasting and research, especially climate change and weather studies. In flood forecasting and warning systems, variables such as rainfall, temperature, air humidity, wind speed, solar radiation, streamflow, and water level are essential inputs; without rain gauges, significant errors can occur when simulating peak floods [4]. A dense network of rain gauges provides better forecasting results than a sparse one [5]. However, due to various factors such as the cost of building rain gauge stations, geographical features, and more, the density of automatic rain gauge stations in Vietnam remains low, unevenly distributed, and insufficient to meet practical needs. To address this issue, determining the minimum number of suitable rain gauge stations to ensure the maximum collection of rainfall data is an optimization problem.

Anand [6] studied the spatial distribution of rainfall using rainfall data from 22 rain gauge stations over 33 years (1983-2015). The seasonal variation in rainfall is most pronounced during the Northeast Monsoon season. The results indicated that the spatial distribution of rainfall is influenced by topography, thereby affecting agricultural productivity and groundwater management throughout the river basin. In other studies, Tekleyohannes et al. [7] analyzed multi-criteria decision analysis (MCDA) combined with spatial interpolation methods using GIS to optimize the rain gauge network in the Tekeze River basin, Ethiopia. The initial analysis showed that the existing 63 rain gauge stations in the basin were insufficient, resulting in an estimated rainfall error of about 12%. Optimizing the rain gauge network for the Tekeze River created an additional 216 rain gauge stations, resulting in a total of 279 optimal rain gauge stations. The research showed that using a combination of GIS methods is useful for optimizing the spatial distribution and quantity of rain gauge stations in an area. This conclusion is consistent with the study by Barca and colleagues, who used GIS to find optimal locations for new observation stations in the existing rain gauge network [8]. Correlation analysis and entropy methods were applied in the study to design a rain gauge network for the Pagladiya River basin in Nalbari, Assam, and Bhutan, India [9]. Optimization methods with an overall objective and multiple criteria were used to determine the number of additional rain gauge stations and remove excess ones [10-12]. Some studies used the Ordinary Kriging (OK) interpolation method to optimize the rain gauge network by using interpolation errors as criteria for designing the rain gauge network [13-15]. Huifeng Wu and colleagues combined the OK interpolation method with spatial correlation analysis (SCA) to optimize the network, including removing redundant rain gauge stations and adding new ones to areas lacking coverage [16]. In Vietnam, there have also been several studies on this issue. Nguyen Duy Liem and colleagues designed a self-serving observation network for the flood warning system in the Vu Gia - Thu Bon River basin by integrating variation coefficients, spatial interpolation methods, and spatial analysis [17]. Phan Thi Thanh Truc and colleagues integrated GIS technology and statistics based on IS 4987 to suggest optimal locations and the number of rain gauge stations to be added to the La Nga River basin [18]. This equation was also successfully used by some authors in the Sabarmati River basin, India [19]. Furthermore, there exist optimized water monitoring networks and well-established dust monitoring networks aimed at preserving a sustainable and conducive environment. The significance of employing spatial interpolation tools to accomplish this objective has been emphasized in various studies, including the study conducted by Phan Chu Nam (2009) and Nguyen Dinh Phuc (2012) dust monitoring network in Vinh Phuc province. Through the utilization of these instruments, it is possible to guarantee the acquisition of precise and dependable data, thereby enabling the formulation of well-informed judgments pertaining to the safeguarding of our environment.

The previous literature review shows studies using interpolation methods to select optimal station locations have mainly chosen the Kriging interpolation method, but the accuracy of common interpolation methods like IDW, Kriging, Natural Neighbor, and Spline has not been compared for this specific issue. Therefore, the novelty in this research is that we utilized data from rainfall monitoring stations to evaluate these interpolation methods in order to propose optimal solutions for the location and number of rainfall monitoring stations in the Da Rang River area.

Based on the research conducted in Vietnam and abroad, the objective of this study is to compare the accuracy of commonly used interpolation methods such as IDW, Kriging, Natural Neighbor, and Spline to determine the most accurate interpolation method for rainfall zoning. This serves as the basis for solving the optimization problem of finding the most suitable rain gauge stations, saving installation and operation costs, and ensuring the maximum collection of rainfall data. The experiment was conducted in the Da Rang River basin, where the number of rain gauge stations is insufficient, unevenly distributed, and does not represent the entire river basin.

2. Data collection and research methodology

2.1. Description of the study area

The Da Rang River is the lower section of the Ba River, the largest river in the coastal region of Central Vietnam. The river basin covers an area of approximately 13,900 km^2, with a main stream length of 388 km. Flowing in a west-east direction, the Da Rang River passes through Phu Hoa district and Tuy Hoa city, which are part of Phu Yen province. Its geographical coordinates range from approximately 13°05'15"N to 109°19'41"E. This river serves as a year-round water source for the Phu Yen Plain (Fig. 1).

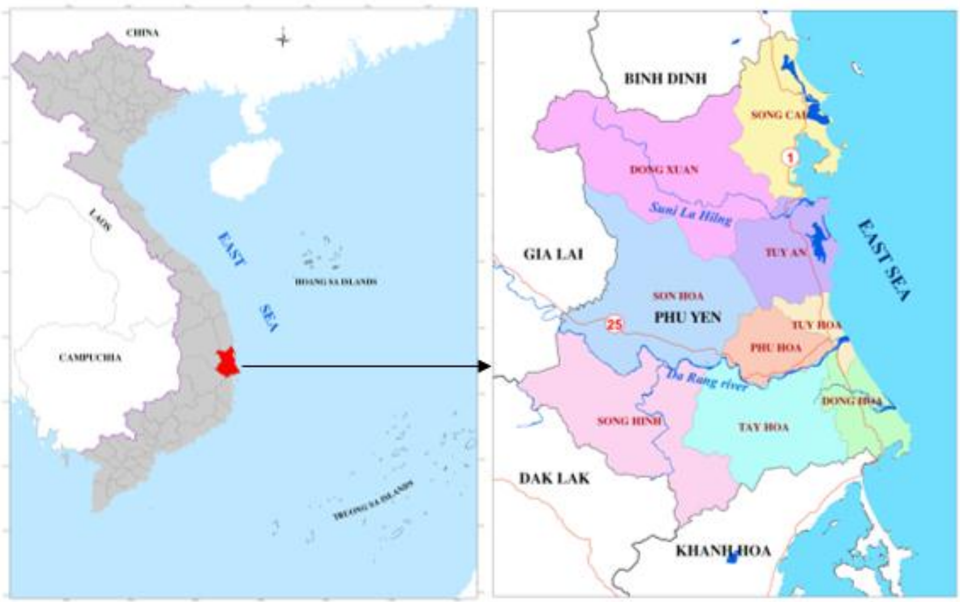

Fig. 1. The study area in Phu Yen province.

The river basin is located in a tropical monsoon climate zone, characterized by hot and humid conditions influenced by the oceanic climate, making it susceptible to extreme weather phenomena such as storms, floods, and droughts. The annual climate is distinctly divided into two seasons: the dry season from January to August, affected by hot dry westerly winds with low rainfall, and the rainy season from September to December, influenced by the northeast monsoon, low-pressure systems, and storms, resulting in heavy rainfall. The average annual temperature ranges from 23-27°C. The annual average rainfall in the region is approximately 1,600 - 1,700 mm, with uneven distribution, mainly concentrated from September to November (Fig. 2).

The Da Rang River experiences significant variations in water flow depending on the season, depending on the rainfall regime, timing, and intensity of rainfall. Under the ongoing global climate change, this region also experiences the influence of global weather cycles such as El Niño and La Niña (ENSO phenomenon) [20, 21], leading to differences in extreme climate conditions such as droughts or abnormal rainfall and flooding. Additionally, this area is the downstream region of a network of channels and streams connected to the Ba River. Hence, during heavy rainfall combined with upstream floods, it can lead to severe flooding and landslides.

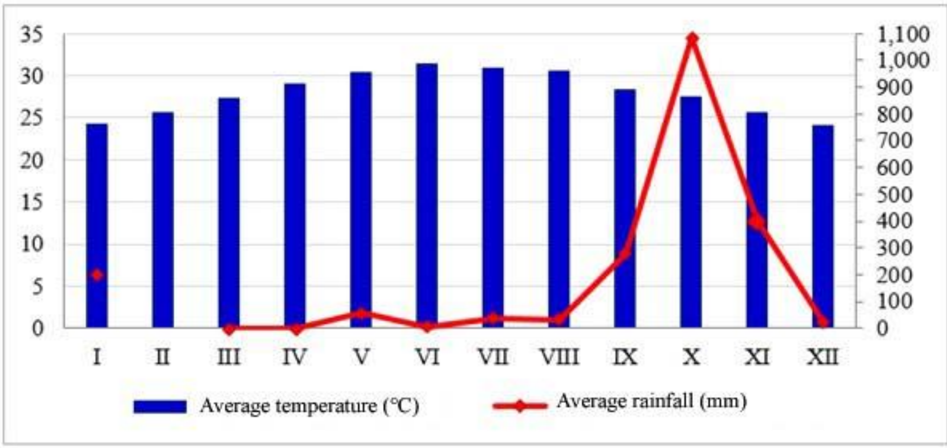

Fig. 2. Distribution of average temperature and average rainfall by month at the Tuy Hoa observation station in 2019 (According to data from the National Meteorological and Hydrological Center).

2.2. Data Collection and Research Methodology

2.2.1. Data Collection

To determine a high-accuracy precipitation interpolation model, 13 rainfall gauge stations within and outside the research area were collected to assess the errors of the precipitation interpolation methods (Table 1). The administrative boundaries of the area were collected from the administrative map of Phu Yen province. The data was set up, analyzed, and evaluated using ArcGIS 10.8 software.

Hydrological maps and digital elevation models (DEM) are used to determine the watershed of the Da Rang River area that were obtained from the Center of Survey and Mapping Data (https://www.bandovn.vn). All station data and maps are geographically referenced to the WGS84 - Zone 48 coordinate system (Fig. 2).

Table 1. Data of Rainfall gauge stations

ID	Station name	Average rainfall 2015-2020 (unit: mm)
1	Cung Son	212.2
2	Ha Bang	145.3
3	Hoa Dong	231.6
4	Phu Lac	143.4
5	Phu Lam	298.7
6	Son Thanh	211.8
7	Song Cau	248.4
8	Da Ban	159.0
9	Hon Khoi	180.8
10	Ninh Hoa	171.9
11	EaKnop	202.5
12	MdRak	266.9
13	KrongPa	155.0

(Source: National Meteorological and Hydrological Center)

Fig. 2. Distribution of collected rain gauge stations.

2.2.2. Methodology

To determine the highly accurate regional rainfall interpolation method, data from 13 rainfall measurement stations within and outside the research area were collected. Among these, 3 stations were used to calculate accuracy, while the remaining 10 stations were used for surface rainfall interpolation. The implementation process was divided into 5 main stages (Fig. 3): (1) Collecting multi-year rainfall data from rainfall measurement stations within and outside the research area; (2) Interpolating regional rainfall using the IDW, Kriging, Spline, and Natural tools; (3) Determining the river basin using an 8-direction interpolation method to calculate cumulative flow at a cell based on 8 neighboring cells; (4) Evaluating the accuracy of the current network using the Root Mean Square Error (RMSE) method and determining the optimal number of stations using the Raster Calculator tool; (5) Proposing the number of additional stations. (6) Identifying suitable locations for constructing rainfall measurement stations.

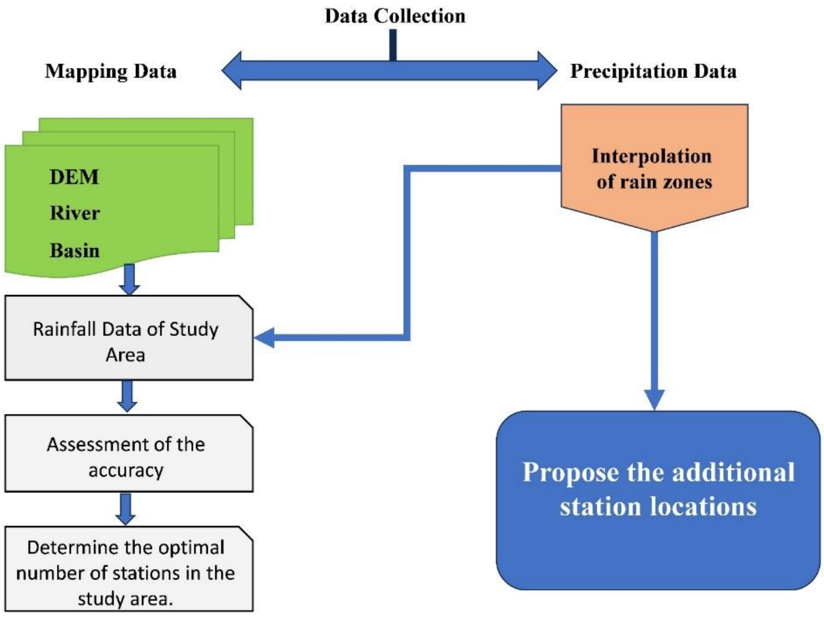

Fig. 3. Flowchart of the Implementation Process.

The optimal number of stations required in a region is determined through the IS 4987 (1994) equation. This is a widely used calculation formula in India but there have not been many scientific publications applied in practice. In order to ensure that the locations of rainfall monitoring stations are representative of the area and that the data collected from these stations reflect the spatial distribution characteristics of rainfall across the entire area, according to the Indian Bureau of Standards (BIS) IS 4987 [22], the optimal number of rainfall monitoring stations in a watershed depends on the spatial distribution characteristics and the variation in rainfall between the existing rainfall monitoring stations in the watershed, as determined by equation (1):

$$N = \left(\frac{C_v}{p} \right)^2 \tag{1}$$

where p is current level of error; C_v is coefficient of variation of rainfall from existing rain gauge stations; N is number of existing stations in the watershed. If there are n stations in the watershed, and $x_1, x_2, ..., x_n$ represent the rainfall measurements from these n stations, then C_v is calculated using the formula (2):

$$C_v = \delta / \bar{x} \cdot 100 \tag{2}$$

where

$$\delta = \sqrt{\frac{\sum_{i=1}^{n} |x_i - \overline{x}|^2}{n-1}} \tag{3}$$

3. Results and discussion

3.1. Spatial rainfall interpolation

The accuracy assessment results of the interpolation methods are displayed in Table 2. The Root Mean Square Error (RMSE) of the IDW interpolation method is the lowest, with a value of 0.000001. The following interpolation methods: Kriging, Spline, and Natural, indicate a rise in their respective RMSE values, which are 0.052633, 0.059691, and 8306.219. Therefore, among the four interpolation methods employed, the IDW interpolation approach has been determined to be most accurate and has consequently been chosen for the purpose of rainfall interpolation.

Several research have reported similar findings in the field of spatial rainfall interpolation. For instance, Almodaresi et al. (2019) conducted an assessment of water quality for agricultural purposes using the Inverse Distance Weighting (IDW) and Kriging techniques. Similarly, Jumaah et al. (2019) employed the IDW geostatistical technique to forecast air quality index [23, 24]. In a study conducted by Ryu et al. (2021), a comparison was made between two widely used spatial interpolation techniques, including IDW and Kriging. The findings indicated that the weight assigned to the inverse distance weighting IDW in a linear combination is determined entirely by the spatial separation between the respective locations. Hence, the IDW method is effective when there is an expectation that the values at unseen sets will show similarity to the values of neighbouring locations [25]. In a catchment area characterized by a dense network of rain gauges, the performance of the IDW approach was compared to that of the Natural Neighbour (NN) method. The findings of the study indicated that IDW showed a slightly superior performance in this scenario [26]. The comparison of IDW and Spline approaches demonstrates the accuracy of prediction methodologies when employing the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm. The findings suggest that the IDW method demonstrates superior performance, whilst the Spline method reveals the least desirable performance. In general, there exists a notable distinction between the IDW and Spline interpolation methods, as indicated by previous research [27].

Table 2. The Root Mean Square Error (RMSE) of spatial rainfall interpolation

RMSE			
IDW	**Kriging**	**Natural**	**Spline**
0.000001	0.052633	8306.219	0.059691

3.2. Determining the river basin

Determining the river basin area of the Da Rang River region is achieved using an 8-direction interpolation method to calculate the accumulated flow at a cell based on its 8 neighboring cells, as shown in the figure below. With a basin area formed by various tributaries, the basin flows in a north-south direction (Fig. 4).

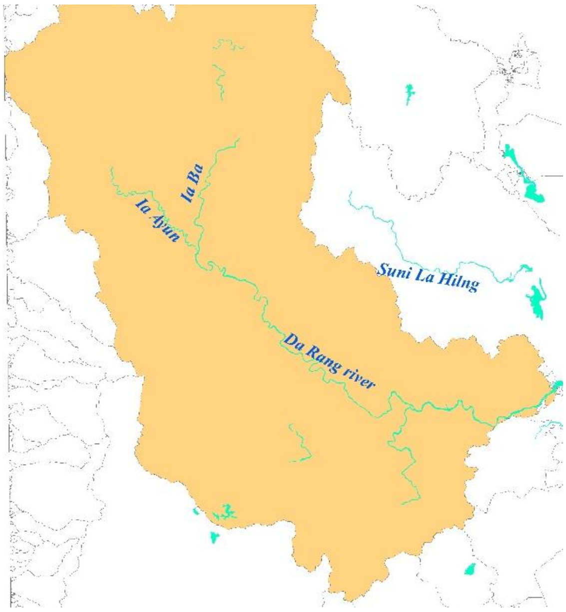

Fig. 4. Results of the Basin Calculation.

3.3. Evaluation of the accuracy of the current network, determination of the optimal number of stations

In the Da Rang River basin, 6 rainfall stations are used to assess the suitability of the current rainfall monitoring network (Table 3).

Table 3. Characteristics of the 6 rainfall stations used to assess the suitability of the current rainfall monitoring network in the basin

Station	**Average annual rainfall in units (mm)**	**The difference between the value and the mean value** $x - \bar{x}$	**The square of the difference between the value and the mean value** $(x - \bar{x})^2$
KrongPa	155.0170	-69.5207	4833.1236
MdRak	266.9000	42.3623	1794.5666
EaKnop	202.5420	-21.9957	483.8091
Son Thanh	211.8170	-12.7207	161.8154
Phu Lam	298.7170	74.1793	5502.5747
Cung Son	212.2330	-12.3047	151.4048

$n = 6$

$\bar{x} = 224.5377$

$c_v = \frac{\sigma}{\bar{x}}.100 = 22.64\%$

Therefore, the actual error level of the current station network, $p = c_v/\sqrt{N} = 9.24\% \approx 9\%$. The smaller p is, the higher the compatibility of the current rainfall stations is. Through practical research, the author proposes $p = 5\%$. So, the optimal number of stations to maintain is 20. The number of additional stations needed in the Da Rang River basin is 14.

Based on the identification of suitable areas for installing rainfall monitoring stations, the study proceeded to design a supplementary network of rainfall monitoring stations for the existing network based on randomly positioned points for each rainfall area, with a default distance of 10 km between stations. These random positioning points were determined by randomly placing a specified number of points within each rainfall area. Spatial data layers were used to select random points, including rainfall zone boundaries, suitable areas for installing supplementary rainfall monitoring stations, and the number of random points for each rainfall area with a default distance between points (10 km). Both of these data layers were imported and processed in GIS. The result of this operation is a map that shows the locations of random points within the rainfall area, and at the same time, it serves as a map illustrating the supplementary rainfall monitoring station network for the existing network in the Da Rang River. The results in Fig. 5 indicate that additional rainfall monitoring stations should be concentrated mainly in the central downstream area and gradually reduced towards the south. In contrast, only one additional rainfall monitoring station is needed in the north.

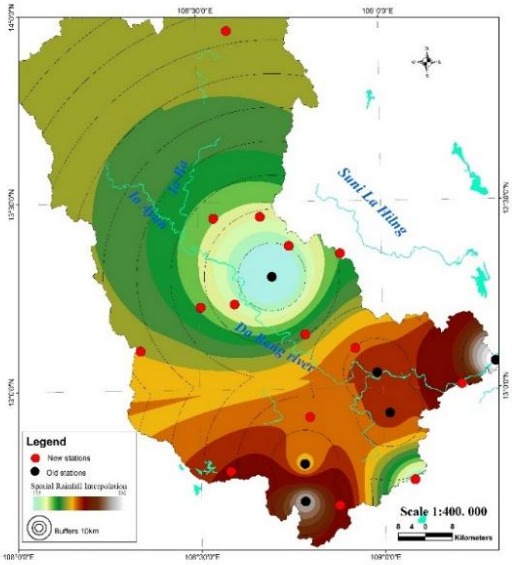

Fig. 5. Locations for required installations.

Table 4. Minimum distances between rainfall measurement stations

Shape	gridcode	id1	distance	NEAR_FID	NEAR_DIST
Point	4	1	20	10	10065,955882
Point	7	1	30	2	10065,955882
Point	3	1	20	3	12065,057047
Point	5	1	20	1	12065,057047
Point	6	1	30	3	13812,390296
Point	11	1	10	4	15125,597865
Point	8	1	20	0	15125,597865
Point	9	1	30	1	15352,727289
Point	10	1	50	10	21994,673203
Point	17	1	20	11	23233,986692
Point	2	1	30	7	23233,986692
Point	13	1	20	4	24185,979498
Point	15	1	30	6	28415,261734
Point	14	1	20	11	31553,855967
Point	12	1	80	9	55483,343957

Table 5. Coordinates of additional installation stations

FID	Shape	latitude	longtitude
0	Point	13,1198	108,926
1	Point	13,3818	108,747
2	Point	13,2274	108,597
3	Point	13,46	108,669
4	Point	13,1429	108,788
5	Point	13,0089	109,214
6	Point	12,9246	108,799
7	Point	12,6886	108,88
8	Point	13,3599	108,887
9	Point	13,4567	108,542
10	Point	13,2203	108,504
11	Point	12,7545	109,083
12	Point	12,7822	108,581
13	Point	13,1051	108,339
14	Point	13,9568	108,577

It can be said that rainfall is the most important and essential natural water source used for various purposes, especially in arid regions like Phu Yen province, where the dry season lasts for more than half a year from January to August, influenced by hot, dry westerly winds. In recent studies, hydrological modeling has become widely popular in the field of water resource management, proving highly effective in monitoring and flood forecasting in river basins. Rainfall measurement stations are a common solution used to measure rainfall, and they also provide a model for rainfall distribution. These data are very valuable and can be used for designing hydraulic structures, irrigation channel designs, and more (Table 4, 5). Therefore, rainfall data are the primary and most important input parameter for river basins, which also means that an optimal number of rainfall measurement stations is required in the river basin. This finding is consistent with a previous study conducted in the downstream Sabarmati River in India [19], which suggested the inclusion of supplementary rainfall measuring sites within the basin.

3.4. Limitations of the study

The research was undertaken within a limited timeframe in order to assess the most effective placement of rain gauge stations in the downstream area of the Da Rang River. To enhance the precision of the outcomes, it is advisable to gather rainfall data from the stations over a span of 10 - 20 years. The research objective solely revolves around constructing models to enhance the optimisation of rain gauge stations for the purpose of flood prevention. Thus, by expanding the study's scope to include the entirety of Phu Yen province, specifically focusing on the upstream terrain, the investigation will be able to provide further illumination on the many hazards associated with flash floods. There is a need for further expansion in the assessment of interpolation algorithms to incorporate additional criteria, including mean absolute error (MAE), correlation coefficient (R), and determination coefficient (R2) [28].

4. Conclusion

This study has fundamentally analyzed whether the Da Rang River basin has an optimal number of rainfall monitoring stations. If not, designing the optimal number of rainfall monitoring stations is an important task in this basin as drought conditions are increasing. According to IS 4987-1994, the analysis indicates that the optimal number of rainfall monitoring stations in the Da Rang River basin is 20, which means 14 new rainfall monitoring stations need to be added. The analysis used data from 13 monitoring stations within and near the research area to run and evaluate the accuracy of interpolation methods.

The evaluation results of interpolation methods, including IDW, Kriging, Spline, and Natural, show that IDW is the most accurate based on the Root Mean Square Error (RMSE) method. The IDW interpolation method divided the study area into 20 zones corresponding to the 20 optimal rainfall monitoring stations. Among these, the research area already has 6 stations, and the remaining 14 stations need to be installed, selected from 45 random stations, ensuring a minimum distance of 10 km between each station.

The research findings demonstrate that the combination of GIS and the IS 4987-1994 equation is effective in evaluating the efficiency of the current rainfall monitoring network and proposing additional monitoring stations. This approach affirms the timeliness and flexibility of GIS data processing. The additional stations enhance the network's ability to provide comprehensive information on rainfall and accurately reflect the distribution of rainfall characteristics throughout the Da Rang River basin. This methodology can also be applied to other drought-prone areas in the South Central Coast of Vietnam.

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ỨNG DỤNG CÁC KỸ THUẬT NỘI SUY KHÔNG GIAN ĐỂ PHÁT TRIỂN PHƯƠNG PHÁP TỐI ƯU HÓA VỊ TRÍ CÁC TRẠM ĐO MƯA TRÊN LƯU VỰC SÔNG ĐÀ RẰNG

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Tóm tắt: Lượng mưa là một trong những thông tin quan trọng trong nghiên cứu khí tượng thủy văn. Trong bối cảnh biến đổi khí hậu ngày càng phức tạp, dữ liệu dự báo khí tượng thủy văn là rất cần thiết cho việc lập mô hình mô phỏng khí hậu, dự báo thiên tai đặc biệt là lũ lụt và sạt lở đất. Để đảm bảo độ chính xác của việc dự báo lượng mưa cũng như chi phí xây dựng và vận hành trạm đo mưa thì việc xác định số lượng trạm đo mưa tối ưu là rất quan trọng. Do đó, nghiên cứu này đã phát triển một thiết kế tối ưu hóa cho mạng lưới trạm đo mưa ở sông Đà Rằng, tập trung vào số lượng và phân bố không gian của các trạm đo mưa. Phương pháp địa thống kê kết hợp với thuật toán nội suy không gian đã được áp dụng bằng cách sử dụng dữ liệu lượng mưa từ năm 2015-2020. Việc lựa chọn phương pháp nội suy không gian thích hợp ảnh hưởng đến độ chính xác của quá trình tối ưu hóa. Kết quả phân tích nội suy cho thấy sự biến đổi không gian của các kiểu mưa trên toàn khu vực nghiên cứu theo mùa, cũng như sự phân bố địa lý của lượng mưa. Sau khi xác định được số lượng trạm tối ưu, phương pháp tiếp cận dựa trên hệ thống thông tin địa lý thu được bản đồ phân bố không gian vị trí các trạm đo mưa tối ưu. Kết quả cho thấy số lượng các trạm đo mưa cần lắp đặt thêm là 14, vị trí các trạm đo được lấy ngẫu nhiên trong vùng mưa với khoảng cách giữa các trạm là 10 km. Các trạm đo mưa được lắp đặt thêm cùng với các trạm đo mưa hiện có trong khu vực sẽ cung cấp thông tin đầy đủ về lượng mưa, từ đó có những dự báo chính xác giá trị lượng mưa phân bố trên khu vực nghiên cứu.

Từ khóa: *GIS; phân tích quyết định đa tiêu chí; tối ưu; IDW; trạm đo mưa; phân tích không gian.*

Received: 27/09/2023; Revised: 26/12/2023; Accepted for publication: 27/12/2023

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