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Research article

Comparative Analysis of Data Visualization Techniques for Rainfall Data

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ABSTRACT

Rainfall data is essential for applications such as climate monitoring, agricultural planning, flood forecasting, and water resource management. However, the interpretation of this data is often hindered by its high volume, variability, and multi-scale temporal nature. Effective visualization is critical not only for summarizing complex datasets but also for uncovering patterns, detecting anomalies, and facilitating informed decision-making. Despite the availability of numerous visualization techniques, selecting the most suitable method for rainfall data, especially across varying temporal resolutions is a challenging task. This study presents a comparative analysis of widely used data visualization techniques in the context of rainfall data. The methodology was structured into three phases: understanding the nature of rainfall data, reviewing relevant visualization techniques, and conducting a comparative content analysis. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) evaluation was used to assess each technique's analytical potential, while a temporal suitability comparison was performed across five time granularities: yearly, monthly, weekly, daily, and hourly. Findings show that no single technique is universally effective. Instead, each method demonstrates specific strengths and limitations depending on the temporal scale and analytical objective. Line charts and bar charts are well-suited for lower-frequency data, while heat maps and scatter plots are more effective for high-resolution, time-sensitive patterns. Box plots and histograms provide valuable insights into data distribution and variability, whereas map-based visualizations excel in spatial analysis but require enhancements for temporal exploration. The study concludes that visualization effectiveness depends on aligning method selection with data characteristics and analytical goals. A thoughtful combination of techniques is often necessary to achieve clarity, reduce misinterpretation, and enhance decision support in rainfall data analysis.

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1. Introduction

Rainfall data plays a vital role in various domains, including climate monitoring, agricultural planning, flood forecasting, and water resource management [1]. However, its interpretation poses significant challenges due to the inherent volume, variability, and time-dependent nature of the data [2;3]. These datasets often range from coarse annual summaries to fine-grained hourly measurements, making it difficult for analysts and decision-makers to extract actionable insights without the aid of visualization.

Effective data visualization is essential not only for summarizing such large and complex datasets but also for uncovering hidden patterns, detecting anomalies, and communicating trends across different time scales [4;5]. In the context of rainfall, visualizations can highlight features such as seasonal shifts, intensity fluctuations, and extreme weather events. These features that may not be understood in raw numerical form [6].

Despite the availability of numerous data visualization tools and techniques, selecting the most appropriate method is often a non-trivial task. The process becomes even more complex when the goal is to emphasize temporal evolution, spatial variation, or interannual variability in rainfall data. Improper selection of visualization methods can obscure critical insights, mislead users, and hinder effective decision-making [7;8].

Moreover, rainfall datasets frequently require specialized visualization approaches to accommodate their granularity and dynamic characteristics. For instance, functional data analysis has been shown to provide deeper insights into rainfall behavior over time compared to traditional static charts [2;5]. Yet, not all techniques are equally effective across different temporal resolutions or application contexts, which necessitates a structured evaluation.

This article presents a comparative analysis of widely used data visualization techniques for rainfall data. By examining their strengths, limitations, and suitability across varying time granularities, the study aims to guide researchers, environmental planners, and practitioners in choosing techniques that enhance interpretability, reduce misinterpretation, and support timely and informed decision-making.

2. Literature Review

Rainfall data, due to its complexity and time-sensitive characteristics, requires advanced and context-sensitive visualization techniques to support effective analysis. Several studies have addressed the challenges and strategies for visualizing rainfall and hydrological datasets, emphasizing the importance of choosing suitable methods based on data granularity, application domains, and user interpretability [4;9].

Jeong et al [3] developed an integrated system for data retrieval, analysis, and visualization tailored to hydrological applications. Their system enhanced data interpretation and decision-making in water resource management by enabling users to interact with multi-dimensional rainfall data, such as intensity, duration, and spatial variation. The ability to visualize complex temporal and spatial patterns allowed for more accurate and timely analysis.

Hael et al [2] applied Functional Data Analysis (FDA) to visualize long-term rainfall data. Their approach converted raw time series into functional curves, allowing for smoother trend observation and anomaly detection. This technique proved more effective than traditional static plots, particularly in identifying seasonal shifts and continuous changes over time. Similarly, Chebana et al [5] used FDA to perform exploratory flood frequency analysis and detect outliers in hydrological datasets. Their visualizations provided intuitive means of identifying extreme values and inconsistencies, which are critical for flood risk assessment and water management.

The role of data visualization in decision support has also been emphasized by Joshi et al [6], who combined visualization techniques with predictive analytics to improve rainfall forecasting. They found that well-designed visuals helped users more effectively detect trends and make informed decisions. Their findings highlight that visualization quality directly affects the usability of data for planning and forecasting purposes. This is supported by Mohamad and Ishak [10], who demonstrated that effective visualization of the changes in upstream rainfall patterns can improve the accuracy of flood stage forecasting in reservoir management, especially in regions with complex topographical and hydrological conditions.

Further supporting this point, Sarda [11] explored various visualization techniques for different rainfall time scales. The study showed that while bar charts and line graphs are useful for annual and monthly data, they tend to be ineffective at higher temporal resolutions, such as hourly rainfall records, where clutter and overplotting become issues. In such cases, more specialized visualizations like heatmaps and temporal maps were recommended. This suggests that visualization methods should be matched carefully with data resolution to avoid misrepresentation and improve clarity.

Beyond the hydrological context, general visualization literature also offers insight into effective practices. Sadiku et al [4] emphasized the critical role of visualization in simplifying large datasets and enhancing user understanding in technical domains such as engineering and environmental science. Chandra and Dwivedi [9] provided an extensive overview of existing data visualization tools and techniques, highlighting that selecting appropriate tools such as D3.js, Tableau, or Python-based libraries requires consideration of the data's structure, complexity, and the specific goals of analysis.

Sinha [7] addressed this issue by identifying common pitfalls in data visualization. Through a systematic review, the study highlighted how poor design choices such as misleading axes, poor color schemes, or unsuitable chart types can distort interpretation and obscure important insights. These problems are especially significant in rainfall data, where misrepresentation can impact policy decisions, emergency response, or agricultural planning. The study advocates for careful, user-centered design in visualization efforts.

Wolfe [8] also pointed out that effective data visualization depends on aligning visual formats with the intended message. In fields like rainfall monitoring, where visualizations are often used by non-experts such as policymakers or local planners, clarity and accessibility become just as important as technical accuracy. Poorly chosen techniques may result in confusion or misinformed decisions, underscoring the need for intuitive and user-oriented visual representations.

3. Research Methods

This study was conducted in three phases as following:

Phase 1: Understanding the Nature of Rainfall Data

The first phase involved identifying and understanding the nature and characteristics of rainfall data. This step was crucial to gain in-depth insight into the structure, variability, and temporal resolution of the data that ranging from yearly to hourly intervals. Understanding these aspects is essential for determining the appropriate visualization approach and for ensuring that the visual representation effectively supports analysis and interpretation.

Phase 2: Review of Visualization Techniques

In the second phase, a range of widely used data visualization techniques were identified and reviewed. The review encompassed both general-purpose applications and specific use cases related to rainfall and hydrological data. Each technique was evaluated based on its visualization objectives, compatibility with different types of data, and common usage scenarios. To enhance this analysis, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) evaluation was also conducted for each technique. This comprehensive assessment provided a foundational understanding of how each visualization method functions and the contexts in which it is most effectively applied.

Phase 3: Comparative Content Analysis

In the third phase, a comparative content analysis was conducted to evaluate the selected data visualization techniques within the context of rainfall data. A four-point suitability scale was used to assess each technique, where 4 = Highly Suitable, 3 = Suitable, 2 = Marginally Suitable, and 1 = Not Suitable. The comparison was based on the following three dimensions:

- Strengths – The extent to which each technique effectively conveys patterns and trends in rainfall data.
- Limitations – Potential challenges or constraints associated with each technique, such as interpretability, clutter, or data compatibility.
- Suitability – The appropriateness of each method for specific types of rainfall data, including yearly, monthly, weekly, daily, and hourly timelines.

Visualization methods were matched to different temporal scales of rainfall data based on their ability to reveal patterns, anomalies, distribution, and seasonal trends. The analysis was further supported by practical examples drawn from existing hydrological research and visualization best practices.

4. Rainfall Data: Nature and Characteristics

Rainfall data exhibits a range of unique characteristics that must be understood to effectively analyze and visualize it. These characteristics influence how the data is interpreted, and which visualization techniques are most appropriate.

1) Temporal Granularity

   Rainfall data can be captured at multiple time scales, including yearly, monthly, weekly, daily, and even hourly intervals. This temporal granularity allows for both long-term trend analysis and high-resolution event detection. However, the variation in scale also demands flexible visualization strategies capable of accurately representing patterns across different time frames.

2) High Variability

   One of the defining features of rainfall data is its high variability. Rainfall amounts can fluctuate significantly within short periods, even within the same day or between neighboring locations. This makes it challenging to detect consistent patterns or averages without appropriate visual aids that can highlight these variations effectively.

3) Spatial Diversity

   Rainfall is not uniformly distributed across regions. Geographical differences, including topography and climate zones, contribute to varying rainfall intensities and frequencies. This spatial diversity necessitates location-specific analysis and often requires the use of map-based or geographically-aware visualizations to properly interpret the data.

4) Seasonality

   In many parts of the world, rainfall patterns are seasonal, following annual cycles influenced by monsoons, dry spells, or other climatic systems. Effective visualization of seasonal patterns is essential for planning in sectors such as agriculture, urban drainage design, and reservoir operations.

5) Extreme Events
Rainfall data often contains extreme values, including unusually heavy downpours or prolonged dry periods. These extremes are crucial for disaster preparedness, particularly for flood forecasting and drought management. Visualization techniques must be capable of highlighting such anomalies clearly to aid in timely response and risk mitigation.

The Importance of Visualizing Rainfall Data

Given its complexity, rainfall data must be visualized in a manner that promotes clarity and insight. Effective visualization plays a vital role in:

- Identifying long-term trends, such as increases or decreases in annual rainfall, which are important for climate change studies and environmental planning (Sadiku et al., 2016; Wolfe, 2015).
- Predicting flood risks by highlighting peak rainfall periods and intensities (Hael et al., 2020).
- Understanding seasonal behavior, which is essential for agriculture and water resource allocation (Joshi et al., 2020).
- Supporting informed decision-making for policymakers, engineers, and community planners involved in water management and infrastructure development (Sinha, 2024; Wolfe, 2015).

Without effective visual representation, the richness and variability of rainfall data can overwhelm or mislead stakeholders especially non-specialist users such as farmers, community leaders, and local officials. Visualization thus functions not merely as a communication tool, but as an essential component of hydrological analysis and environmental decision-making (Sadiku et al., 2016; Sinha, 2024).

5. Overview of Data Visualization Techniques

In this study, nine widely used data visualization techniques have been identified and evaluated for their potential to represent rainfall data effectively. Each technique presents its own set of strengths and limitations depending on the nature of the data and the analytical objective.

1) Line Chart
A line chart connects data points with a continuous line, making it particularly effective for showing trends over time. It is one of the most commonly used tools in fields such as meteorology, climate science, and economics due to its simplicity and clarity in illustrating temporal patterns. In the context of rainfall data, line charts are especially useful for visualizing daily, weekly, or monthly trends, allowing users to detect increases, decreases, and fluctuations in rainfall across time periods.

2) Bar Chart (Column Chart)
A bar chart, also referred to as a column chart, represents discrete data using rectangular bars. It is highly effective for comparing values across categories, such as rainfall amounts across different months, seasons, or years. Bar charts are easy to interpret and are well-suited for yearly or monthly aggregated rainfall data, particularly when the goal is to compare totals between distinct time periods or locations.

3) Area Chart
An area chart builds on the concept of a line chart by filling the space below the line with color or shading, which visually emphasizes the magnitude of the data over time. This technique is particularly helpful in representing accumulated rainfall or layered comparisons across multiple rainfall sources (e.g., different weather stations). Area charts are beneficial when the objective is to highlight volume and change simultaneously.

4) Heat Map
A heat map displays values in a matrix format, where variations are represented by color intensity. It is especially powerful for high-frequency data, such as daily or hourly rainfall measurements, and is commonly used to identify patterns such as peak rainfall periods, dry spells, or anomalies. Heat maps are highly effective in revealing cyclical behaviors and visually dense datasets that are difficult to interpret in traditional charts.

5) Histogram
A histogram is used to illustrate the distribution of data across value ranges or intervals. In hydrological contexts, it is valuable for analyzing the intensity and frequency of rainfall events. Histograms can help determine how often certain rainfall thresholds are exceeded, providing insight into rainfall variability, intensity classification, and event frequency—all crucial for flood risk assessment and climate modeling.

6) Box Plot

A box plot provides a summary of data distribution by showing the median, quartiles, and outliers. It is an effective tool for comparing rainfall variability across different months, seasons, or years, as well as identifying extreme values or anomalies such as unusually high rainfall or dry periods. Box plots are widely used in exploratory data analysis and are suitable for datasets with multiple time segments.

7) Pie Chart

A pie chart illustrates data as parts of a whole, showing percentage distributions. It can be used to represent the relative contribution of rainfall by region, station, or month. However, pie charts are generally not effective for time-series data, as they lack the ability to depict trends, sequences, or temporal changes. Their utility in rainfall analysis is limited to static proportional representations.

8) Scatter Plot

A scatter plot displays the relationship between two continuous variables. While not directly applicable for showing temporal rainfall trends, it is useful for correlation analysis, such as examining the relationship between rainfall and temperature, or between rainfall and river water level. This technique supports deeper analysis when rainfall data is integrated with other environmental variables.

9) Map-Based Visualizations

Map-based visualizations, such as choropleth maps or point maps, are essential when the rainfall data contains geospatial attributes. These maps help identify spatial patterns, regional disparities, and rainfall distribution across geographical areas. While they provide important spatial context, they often need to be combined with time-based charts (e.g., line or bar charts) to fully capture temporal dynamics.

6. Findings: SWOT and Comparative Analysis

A comprehensive SWOT analysis and comparative evaluation were conducted for each of the nine selected data visualization techniques. The results of the SWOT analysis, presented in Table 1, detail the strengths, weaknesses, opportunities, and threats associated with each technique, emphasizing their practical advantages and limitations in the context of rainfall data visualization.

Table 1: SWOT Analysis of Data Visualization Techniques for Rainfall Data

Technique	Strengths	Weaknesses	Opportunities	Threats
Line Chart	- Clearly shows trends over time - Easy to interpret	- Overlapping lines can clutter - Less effective for large category comparisons	- Ideal for visualizing daily to monthly rainfall patterns	- Can mislead if time intervals are uneven or data is missing
Bar Chart	- Simple comparison across time or categories - Intuitive for non-experts	- Less effective for showing trends - Takes more space with large datasets	- Useful in presenting yearly or station-wise rainfall summaries	- May misrepresent continuous data if categories are too broad
Area Chart	- Highlights volume of rainfall - Good for cumulative data	- Can become cluttered with multiple series - Less readable than line chart	- Suitable for showing combined rainfall from different sources	- Can distort interpretation if baseline isn't zero
Heat Map	- Excellent for spotting patterns in dense data - Effective color encoding	- Requires proper color scale understanding - May not show exact values	- Best for daily/hourly data patterns and seasonal rainfall distribution	- Misleading if color gradient is poorly chosen

Histogram	- Shows rainfall frequency/intensity distribution	- Doesn't represent time trends - Sensitive to bin size	- Helps in flood risk, drought frequency, and hydrological studies	- Poor choice for sparse or very small datasets
Box Plot	- Good for summarizing variability - Highlights outliers	- Not intuitive for all users - Limited temporal insight	- Useful in comparing monthly/seasonal rainfall variations	- Interpretation may be difficult for non-technical stakeholders
Pie Chart	- Shows proportional data well - Simple and familiar	- Poor for time-series - Difficult to compare multiple slices	- Useful in showing station or regional rainfall contributions	- Can mislead when used with too many categories or similar values
Scatter Plot	- Reveals relationships between variables	- Not suited for time trend visualization	- Supports analysis of rainfall vs. temperature, wind, or water level	- Ineffective when used for timeline data alone
Map-Based Viz.	- Visualizes spatial distribution - Ideal for geographic analysis	- Lacks temporal depth unless animated - Requires geolocation data	- Can be integrated with GIS or climate models - Useful for disaster mapping and planning	- Misinterpretation risk without scale or legend - Requires spatial data and tools

Table 2 presents a comparative analysis of various visualization techniques based on their suitability for representing rainfall data across different levels of temporal granularity namely yearly, monthly, weekly, daily, and hourly. Each technique exhibits distinct strengths and limitations depending on the data resolution.

As shown in Table 2, line charts are suitable used to illustrate trends over time and perform exceptionally well with monthly, weekly, and daily data, where changes occur at a pace that preserves clarity and interpretability. However, for hourly data, line charts become less effective due to visual clutter, making them only marginally suitable. Bar charts are ideal for comparing rainfall amounts across discrete time intervals, showing high suitability for yearly and monthly data. Their effectiveness decreases with finer granularity, becoming unsuitable for hourly data due to the large number of bars required.

Area charts, which emphasize cumulative values, are highly suitable for monthly data and remain effective for yearly and weekly intervals. However, they tend to become cluttered with daily and hourly data, reducing their overall usefulness at these granularities. Heat maps, in contrast, are particularly well-suited for high-frequency data such as weekly, daily, and hourly observations. Their use of color gradients effectively highlights patterns, intensities, and anomalies in dense datasets. Yet, for yearly data, heat maps are not suitable, as the limited data points fail to produce meaningful visual patterns.

Histograms are excellent tools for examining the distribution of rainfall events, especially at the yearly and monthly levels. They remain suitable for weekly and daily data but are less effective for hourly granularity, where frequency analysis becomes less stable due to fragmentation. Box plots are similarly valuable for identifying variability and outliers in rainfall patterns. They are highly suitable for monthly data and perform well across yearly, weekly, and daily levels, but offer only marginal suitability for hourly data, where excessive detail complicates interpretation.

Pie charts, though visually engaging, are limited to showing proportions and are only suitable for yearly and monthly rainfall data. They are ineffective for any form of time-series analysis, making them unsuitable for weekly to hourly data. Scatter plots serve a different analytical purpose, enabling the examination of correlations, such as between rainfall and temperature. While not optimal for depicting temporal trends, they are marginally to suitably effective across all levels of granularity, particularly for hourly data where denser patterns may reveal more meaningful relationships.

Finally, map-based visualizations are consistently suitable across all time intervals for spatial rainfall analysis. They excel when combined with time-based charts, providing comprehensive insights into both spatial and temporal rainfall patterns. These visualizations are especially beneficial in geospatial contexts, supporting detailed understanding of regional rainfall variability.

Table 2: Visualization Technique vs Rainfall Data Granularity

Visualization Technique	Yearly	Monthly	Weekly	Daily	Hourly	Remarks
Line Chart	Suitable (3)	Highly Suitable (4)	Highly Suitable (4)	Highly Suitable (4)	Marginally Suitable (2)	Effective for showing trends over time; clarity decreases with very high-frequency data.
Bar Chart	Highly Suitable (4)	Highly Suitable (4)	Suitable (3)	Marginally Suitable (2)	Not Suitable (1)	Excellent for categorical comparison; less suited for continuous or high-frequency data.
Area Chart	Suitable (3)	Highly Suitable (4)	Suitable (3)	Marginally Suitable (2)	Not Suitable (1)	Useful for emphasizing cumulative rainfall; may become cluttered with dense data.
Heat Map	Not Suitable (1)	Suitable (3)	Highly Suitable (4)	Highly Suitable (4)	Highly Suitable (4)	Ideal for dense, high-frequency data; effective at highlighting patterns and extremes.
Histogram	Highly Suitable (4)	Highly Suitable (4)	Suitable (3)	Suitable (3)	Marginally Suitable (2)	Good for analyzing rainfall distribution and event frequency; not ideal for trends.
Box Plot	Suitable (3)	Highly Suitable (4)	Suitable (3)	Suitable (3)	Marginally Suitable (2)	Highlights variability and outliers; suitable for comparing periods or locations.
Pie Chart	Suitable (3)	Suitable (3)	Not Suitable (1)	Not Suitable (1)	Not Suitable (1)	Limited to showing proportions; ineffective for time-based analysis.
Scatter Plot	Marginally Suitable (2)	Marginally Suitable (2)	Marginally Suitable (2)	Marginally Suitable (2)	Suitable (3)	Useful for correlation (e.g., rainfall vs. temperature); not ideal for timeline visualization.
Map-Based Visualization	Suitable (3)	Suitable (3)	Suitable (3)	Suitable (3)	Suitable (3)	Effective for spatial analysis; best combined with time-based charts for comprehensive insight.

Conclusion

The analysis presented in this study underscores the critical role of selecting appropriate data visualization techniques for effective interpretation of rainfall data. Given the inherent complexity, variability, and multi-scale nature of rainfall datasets, visualization serves not only as a tool for simplifying large volumes of information but also to uncover patterns, detect anomalies, and support timely decision-making across diverse application domains.

As the findings reveal, no single visualization technique is universally optimal. Instead, each method offers specific advantages depending on the temporal resolution and analytical goals. Line charts and bar charts remain strong choices for low to moderate temporal granularity, offering clarity in trend and categorical comparisons. Heat maps and scatter plots prove more effective at high-frequency levels, especially when analyzing detailed hourly and daily rainfall patterns. Box plots and histograms are well-suited for summarizing distribution and variability, whereas map-based visualizations excel in representing spatial patterns but require supplemental tools for temporal analysis. Conversely, pie charts, while familiar and simple, are limited in utility for time-series rainfall data and are prone to misinterpretation when categories are too numerous or similar in size.

The study highlights the importance of aligning visualization choices with the specific characteristics of rainfall data and the intended analytical focus. Careful selection can enhance insight and communication, while poor choices risk obscuring critical information and undermining decision-making processes. Researchers, environmental planners, and practitioners are encouraged to use a combination of techniques where necessary, ensuring both spatial and temporal dynamics are effectively captured.

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