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Original Research Paper

The Role of Precipitation in Sustainable Water Management: Insights from Atmospheric Science

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Abstract

Water scarcity is a growing challenge in many regions around the world, including Nigeria, where precipitation patterns have a significant impact on water availability for human and ecological systems. This research paper explores the role of precipitation in sustainable water management, drawing insights from atmospheric science research. In particular, we conduct a trend analysis of precipitation in key areas of Nigeria using the new Innovative Trend Analysis (ITA) method. ITA is a powerful statistical method that allows for the detection of trends and periodicities in time series data, even in the presence of non-linear trends and data uncertainties. Our analysis aims to provide a better understanding of how precipitation has changed over time in Nigeria and what implications these changes have for water management strategies and practices. The potential for atmospheric science research to inform future water policy and planning decisions are also discussed. The examination of precipitation trends using the ITA approach revealed a range of patterns, from reducing or trendless scatter points in the southern vegetation zones to increasing precipitation trends in the savannah regions; this emphasizes the need for context-specific water management strategies. Regions experiencing declining precipitation may necessitate adaptive measures to address potential water scarcity, while those with increasing trends require strategies to mitigate potential flooding risks. By combining meteorological data with reviewed insights from other disciplines such as hydrology, ecology, and economics, we can work towards a more sustainable and equitable management of water resources in Nigeria and even beyond.

Keywords: Water management, sustainability, vegetation, innovative trend analysis, Nigeria

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1. Introduction

The sustainable management of water resources requires a comprehensive understanding of its complex dynamics, as it is a vital resource that is essential to both ecological and societal well-being (Gain et al., 2021). Precipitation has a significant role in this setting, affecting ecosystem resilience, water quality, and availability. Given the effects of global climate change, it is critical to understand precipitation patterns and how they affect water management. Using insights from atmospheric science, this study explores the complex relationship between precipitation and sustainable water management with a focus on the vegetation zones in Nigeria. Precipitation is a key component of the Earth's hydrological cycle; it includes both rainfall and snowfall, etc., and influences the distribution and accessibility of freshwater resources (Yang et al., 2021). Because precipitation dynamics are complicated and characterized by both temporal and geographical variability, understanding its intricacies will require a multifaceted approach. One important field that provides a lens through which we can understand the mechanisms underlying precipitation patterns and possible changes in the context of climate change is atmospheric science.

The Intergovernmental Panel on Climate Change (IPCC, 2023) emphasizes the undeniable influence of human activities on global climate patterns, resulting in the variations of precipitation regimes. The consequences of these shifts go beyond meteorological issues, it affects the availability of water resources, ecosystems, and community livelihoods. While precipitation plays an important role in water management, there is a crucial research gap in combining atmospheric science insights with diverse stakeholder insights to establish sustainable and context-specific water management policies in Nigeria. Furthermore, the new innovative trend analysis (ITA) method proposed by Şen (2012, 2017) is being adopted to provide novel insights, and will help close the gap in current atmospheric science research that only focuses on holistic statistical analysis. It will further help discern the variation of the atmospheric parameter across different data ranges.

In his work, Şen (2012, 2017), developed the innovative trend analysis (ITA) approach to analyze trends pertaining to the impact of hydrological and metrological elements on water resources. Numerous studies have furthre employed this method in order to obtain comparable results. The ITA method was adopted by Zhou et al. (2018) to determine the trend of China's solar radiation between 1962 and 2015. Sen's slope and Mann-Kendall tests were used by Pingale et al. (2014) to investigate the spatiotemporal trends revealed by extreme temperature and precipitation in the Indian Rajasthan region. The results indicate both positive and negative trends in the Rajasthani urban centers. Sen ITA test has also been used with the non-parametric Mann-Kendall (M-K) tests in Nigeria by Oguntunde et al. (2012) to determine the variability in evaporation and hydro-meteorological parameters in Ibadan. The results showed a trend wherein solar radiation, wind speed, and evaporation were significantly reduced over the four-decade interval under consideration, while rainfall, temperature, and relative humidity did not show a significant change.

The ITA technique will be used in this study to determine the precipitation trends for the classification of high, medium, and low data ranges over selected locations across Nigeria's vegetation zones. The classification of data across these three value ranges will be useful for the stakeholders in decision making that relates to water management.

The study aims to address the following research questions: How have precipitation patterns in Nigeria evolved over time, and what factors may be influencing these changes? How can insights from atmospheric science inform future water policies and planning? How can interdisciplinary collaboration among stakeholders and researchers contribute to more sustainable water management in Nigeria?

2. Study area and Data

Nigeria, a Sub-Saharan nation, has a variety of vegetation zones that are brought together as a result of the climate zones. The Atlantic Ocean to the south and the Sahara Desert to the north, are arguably the greatest influences to its Vegetation and Climate. According to Körner (2007), altitude is another notable factor that influences vegetation. This is also the case in Nigeria where the variation of meteorological parameters in different regions are also affected by their variated heights above the sea level (Agbo, Ettah, et al., 2021; Agbo & Edet, 2022; Agbo & Ekpo, 2021). Adamawa's highland vegetation serves as one illustration. Nigeria is home to a wide variety of plant zones with distinct features (**Figure 1**). The Figure shows that there are about seven distinct vegetation zones across the country, their distinct characteristics are presented below:

- The *Mangroove swamp* is identified by its wet, muddy soil, saline surroundings, and a weather that is humid (Agbo et al., 2021; Agbo et al., 2022). The dense bushes, which vary in height from shrubs to massive trees, also define this vegetation.
- Due to the heavy rainfall in the region, the *Rainforest vegetation* zone contains a dense tropical forest. The trees have large, well ingrained roots (Eyre, 2017). The zone's mountainous topography is also covered with dense bushes.
- The country's Niger Delta region contains *Freshwater vegetation*. Throughout the year, evergreen trees abound in this vegetation zone (Seiyaboh & Izah, 2017). The vegetation is characterized by a lot of precipitation, warm weather, and humidity.

- As one proceeds north, the tall trees of the *Guinea savannah* give way to shrubs and shorter trees. Rainfall is decreased and the environment is less humid (Abdullahi, 2020). From Enugu, which is close to the south, through Kaduna, the climate and grassland stretch with less trees and less rainfall.
- The Jos plateau, portions of Taraba, and mountainous regions of Adamawa are home to *Montane vegetation* (Salako et al., 2016). The primary factor shaping the montane vegetation is altitude, which is primarily made up of woods. These zones have lower surface temperatures and higher rates of precipitation (Agbo, Nkajoe, et al., 2023; Okono et al., 2022).

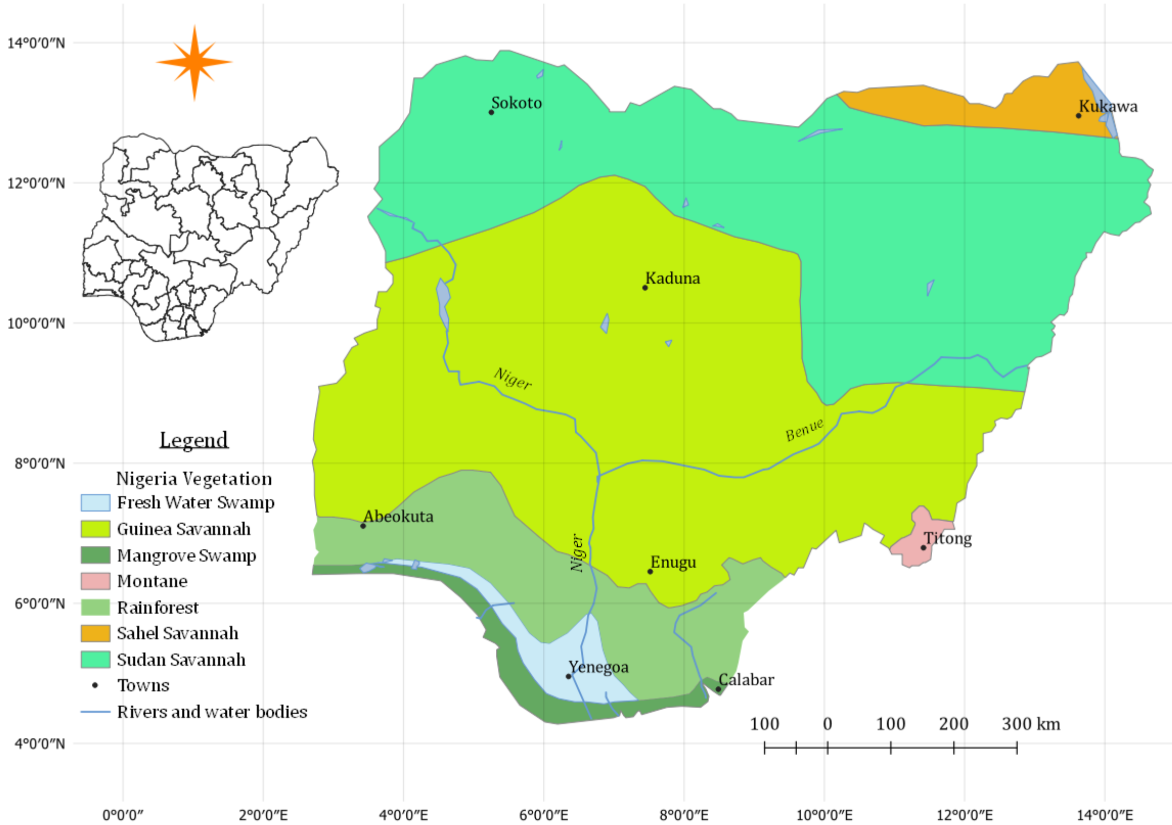

Figure 1. Map of study area showing vegetation zones and stations.

- The *Sudan Savannah* is distinguished by a low-lying, lush grass cover (Fashae & Obateru, 2023). There is less precipitation and a warm, dry climate. Throughout this area of vegetation, there are sporadic stands of short trees.
- Nigeria's *Sahel Savannah* is a narrow area of vegetation that stretches into the Sahara Desert. It is distinguished by extended dry seasons and brief wet seasons. It is an arid vegetation zone with little vegetation cover due to the presence of only small shrubs and grasses (Leroux et al., 2017).

For the locations shown in **Figure 1**, 42 years of monthly precipitation data from 1981 to 2022 were retrieved from the NASA POWER DATA archive for every location in each vegetation zone. Box plots were utilized to display the distribution of the data, and Sen's ITA test was employed to look for trends in the data. The link that provides the code for the analysis will be made available by the corresponding author on request.

3. Methodology

The Innovative Trend Analysis (ITA) approach, initially introduced by Şen (2012, 2017) for hydro-meteorological time series data, has garnered widespread application in various trend assessments. This method hinges on the recognition that identical time series, when plotted against each other, yield a scatter of points aligning along the Cartesian coordinate system's 1:1 (45°) line, as depicted in **Figure 2**. Likewise, a recorded time series, such as precipitation which is being studied in this research, can be divided into two equal segments, with each sub-series independently sorted in ascending or descending order.

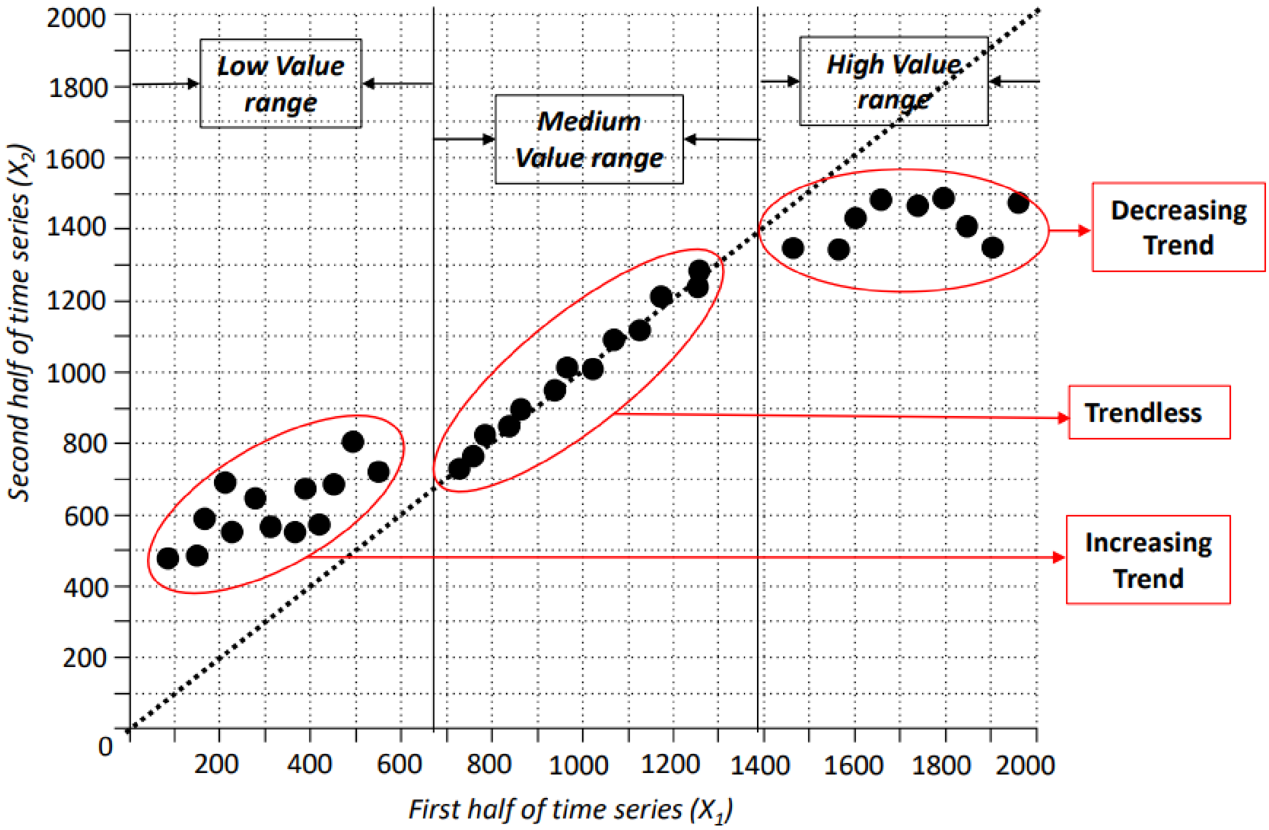

Figure 2. Sen's ITA methodology.

The first sub-series is on the x-axis, while the second sub-series is situated on the y-axis within the Cartesian coordinate system. The scatter plot will be trendless if all data points align on the 1:1 (diagonal) line. Detection of a monotonically increasing trend occurs when all data points from the plot are positioned above the 1:1 line, while a monotonically decreasing trend is identified when all data points are below the 1:1 line. In unique circumstances, certain data points may deviate below, above, or remain on the 1:1 line, warranting classification into low, medium, and high values, as illustrated in **Figure 2**.

The ITA method is especially useful for visually identifying monotonic and non-monotonic trends in precipitation data because it leverages the unique patterns that are seen when identical time series are divided into two halves and plotted against each other. This allows the data points to be classified into low, medium, and high values depending on specific conditions, and it also makes it easier to identify trends that are monotonically increasing or decreasing. The accuracy of trend analysis is improved by this sophisticated classification scheme. The ITA technique is important because it may be used to manage water resources sustainably and gives decision-makers important information about long-term precipitation patterns, especially across different data ranges.

4. Results

In Nigeria, the ITA test has been used to examine precipitation variations and characteristics across all vegetation zones. The distribution (skewness) of precipitation data was analyzed for each site using Box-Whisker plots for exploratory data analysis. The boxplots reveal the minimum, maximum, median, quartiles (25th and 75th percentiles), extreme and outlier values.

Figure 3a shows the precipitation box plots for the eight distinct stations across the vegetation zones. **Figure 3**b was created after removing one location (Calabar) from **Figure 3**a. This was done because the extreme precipitation values (or outliers) in Calabar (**Figure 3**a) increased the scale for other locations. The analysis, in particular, indicates major variances in precipitation patterns. The data show deviations from a normal distribution, which may be seen not only in the skewness but also in the existence of outliers and extreme values.

This feature supports the use of non-parametric tests for trend analysis, which are known for their robustness against non-normal data as well as their ability to account for seasonality and outliers (Kisi & Ay, 2014). This approach is especially appropriate for a targeted investigation of precipitation trends across multiple places, which aligns with the research emphasis on this specific parameter.

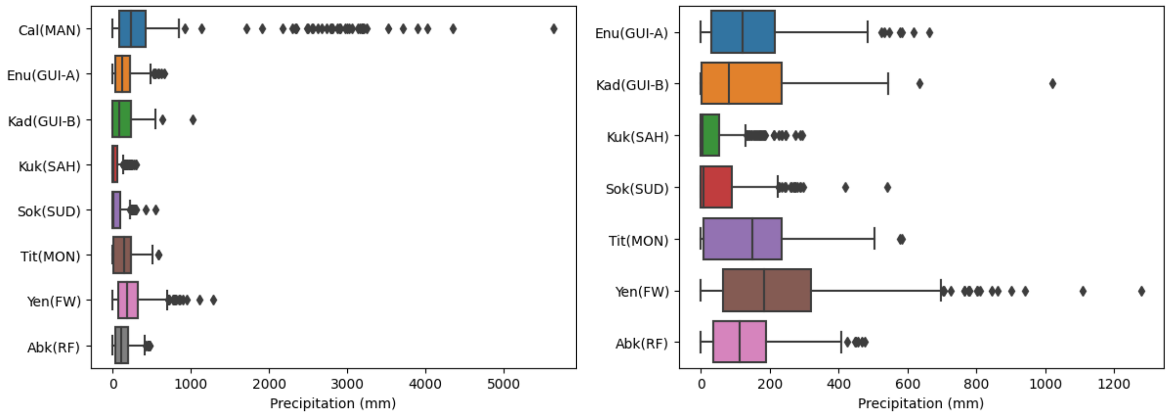

Figure 3. Box plot for all 8 locations showing data distribution (left panel) and Box plot for all locations (except Calabar) showing data distribution in context (right panel).

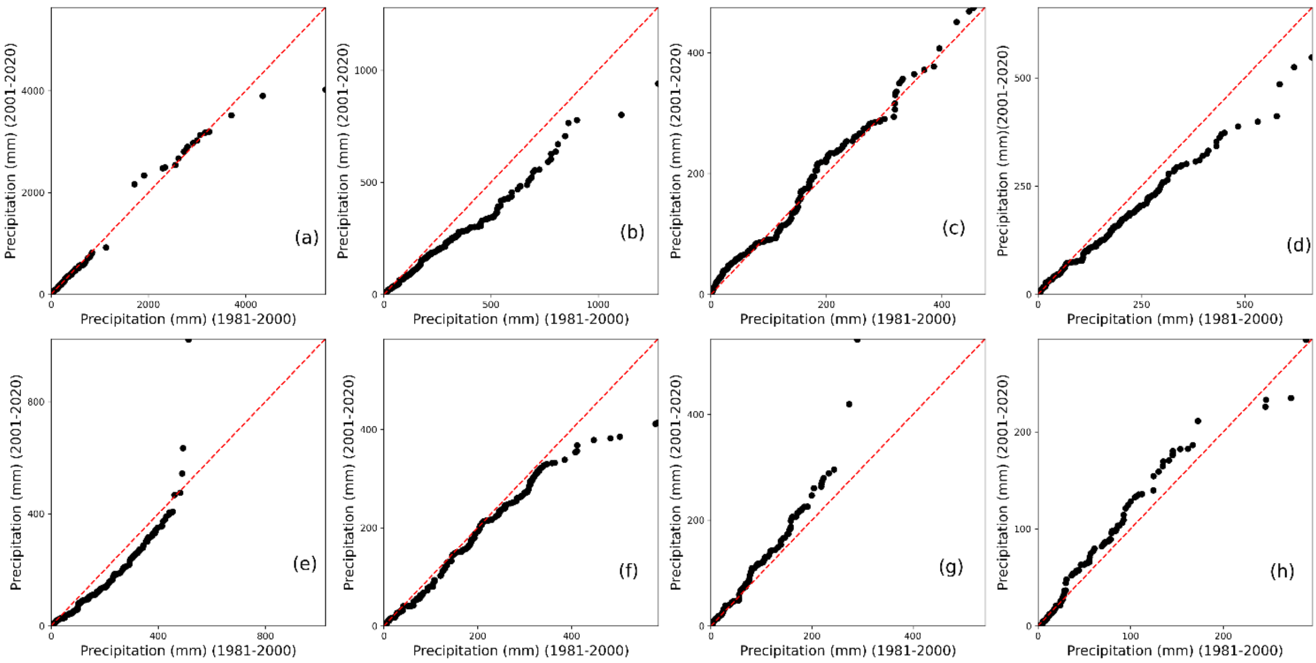

Figure 4. The results of Sen's ITA method for Precipitation over the following vegetation zones in Nigeria (a) Calabar (b)Yenagoa (c)Abeokuta (d)Enugu (e)Kaduna (f)Titong (g)Sokoto and (h)Kukawa.

Sen's ITA method has been applied to all locations and results have been obtained for the annual trend of all locations and the monthly trends of some selected locations. From **Figure 4**, Calabar (Mangroove), Yenagoa (Freshwater), Abeokuta (Rainforest), and Enugu (Guinea Savannah A) show results that depicts declining or trendless scatter points throughout all data ranges (low, medium, and high values). This was amid the high recorded precipitation levels in these locations (**Table 1**). Overall, peak values are decreasing for sites such as Calabar, Yenagoa, and Enugu, showing that the probability of excessive rainfall occurring is decreasing with the annual change in seasons. This could be ascribed to a rise in global surface temperature induced by long-wave radiation from greenhouse gases (GHGs), which has resulted in a positive feedback process that consistently limits the possibility of increased rainfall in the region. This has resulted in less precipitation at peak values.

Peak values for the Guniea and Sudan savannah sites exhibit increasing trends, indicating that the regions are protected from dry spells and drought impacts. The steep increase in precipitation peak value trends indicates that there is a possibility of flooding in certain areas, or at the very least very high and growing rainfall patterns. The opposite is true for the vegetation zone in Titong and Kukawa. All low values in the north and middle belt regions (Kaduna, Titong, Sokoto, and Kukawa) are trendless.

Table 1: Sen's ITA results for all precipitation across the stations in each vegetation zone in Nigeria

↑ - Indicates increasing trend

↓- Indicates decreasing trend

Location and Coordinates	Trend Interpretation		
	Low	Medium	High
Calabar	NO	NO	YES (↓)
Yenagoa	NO	YES (↓)	YES (↓)
Abeokuta	NO	NO	NO
Enugu	NO	YES (↓)	YES (↓)
Kaduna	NO	YES (↓)	YES (↑)
Titong	NO	NO	YES (↓)
Sokoto	NO	YES(↑)	YES (↑)
Kukawa	NO	YES (↑)	YES (↓)

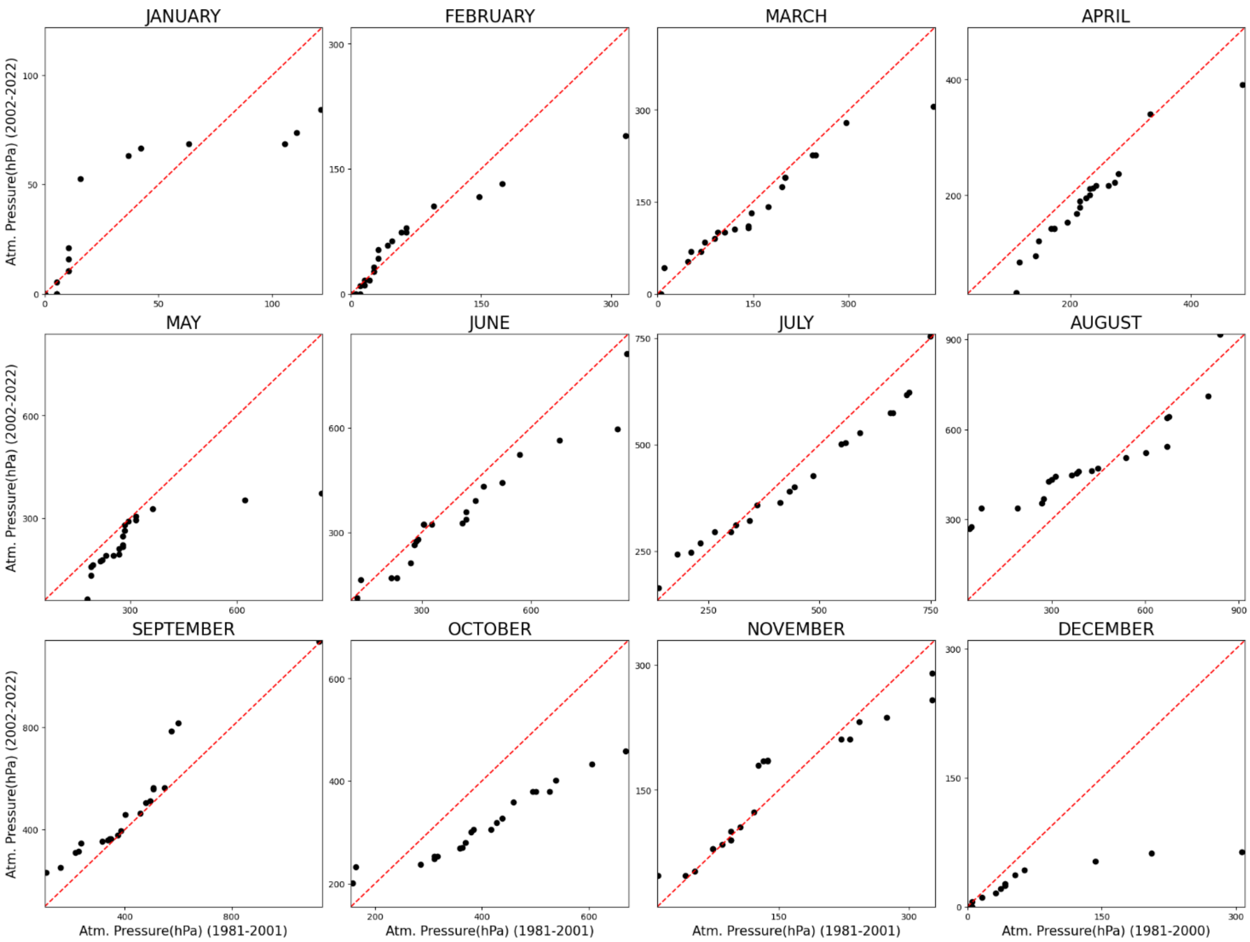

Figure 5. Sen's ITA scatter graphics for monthly precipitation for Calabar.

Figures 5, 6, 7, 8, and 9 show the Sen's ITA scatter graphics for monthly precipitation across selected locations. **Table 2** shows the results from the trend interpretation of these scatter graphics. The results show the trends for each month of the year across the locations. Calabar (Mangroove swamp) and Yenagoa (Fresh water vegetation) have almost similar scatter graphics especially in the wet months of the year where the high precipitation values are reducing.

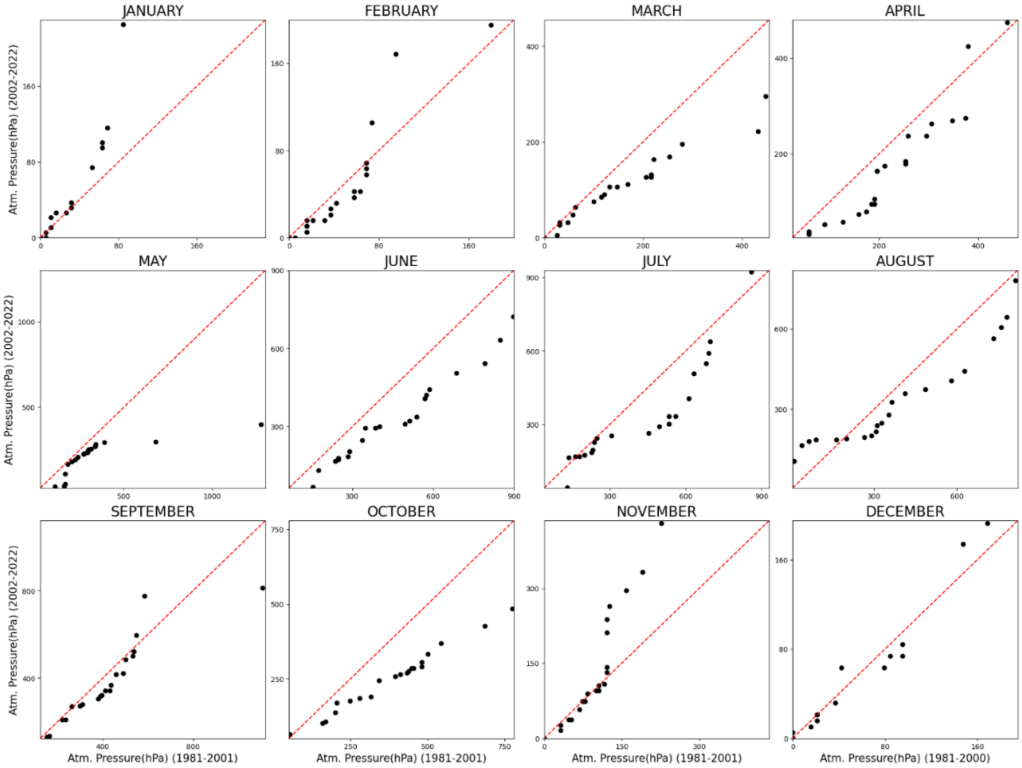

Figure 6. Sen's ITA scatter graphics for monthly precipitation for Yenagoa.

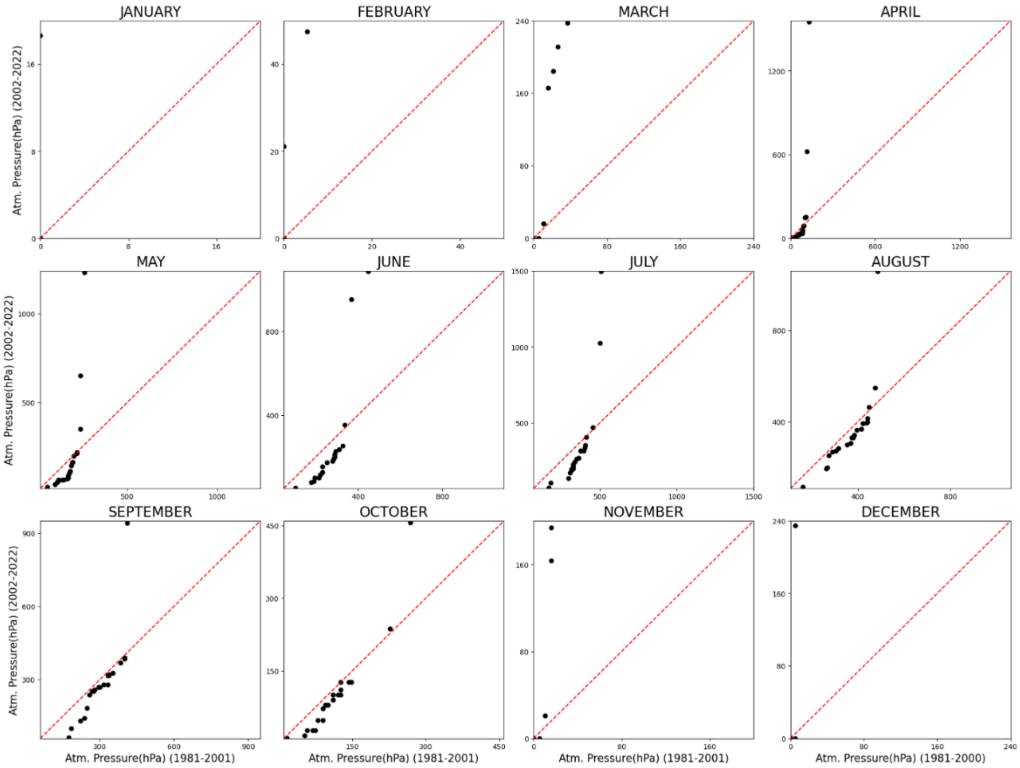

Figure 7. Sen's ITA scatter graphics for monthly precipitation for Kaduna.

The Savannah locations including Kaduna (Guinea Savannah), Kukawa (Sahel Savanah) and Sokoto (Sudan Savanah) all have months where there was no precipitations trend discerned; this is predominantly in peak of the dry months of the year between November and March. One thing to note also is that in these locations, the high precipitation values show increasing trends in spite of their low magnitudes.

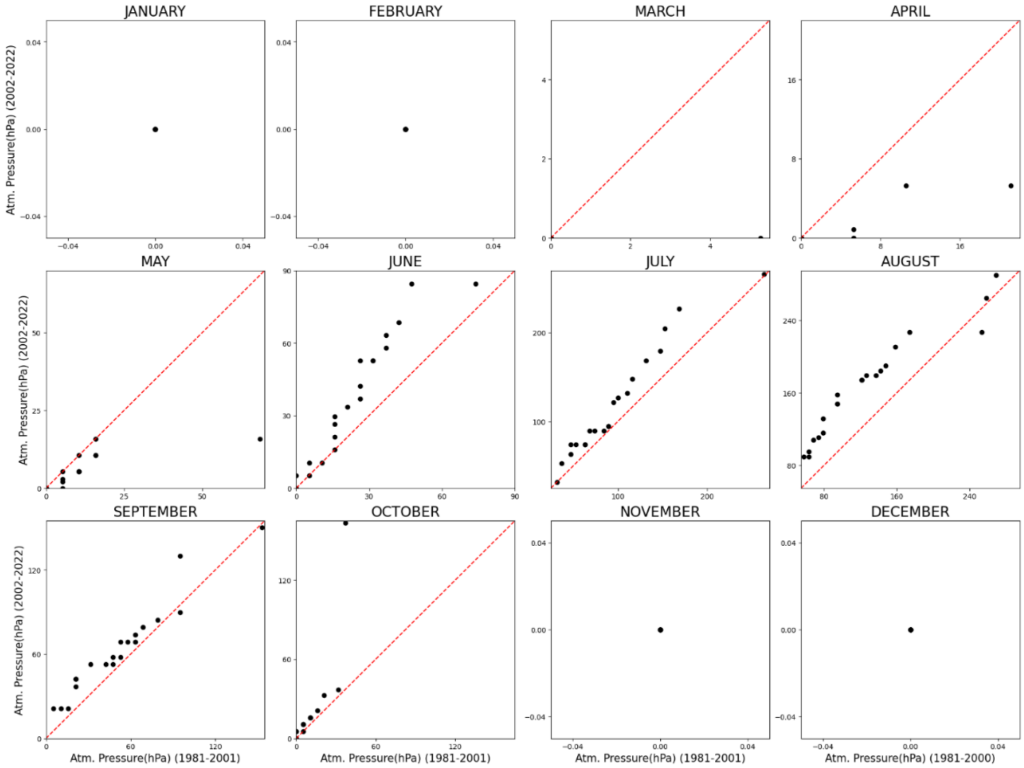

Figure 8. Sen's ITA scatter graphics for monthly precipitation for Kukawa.

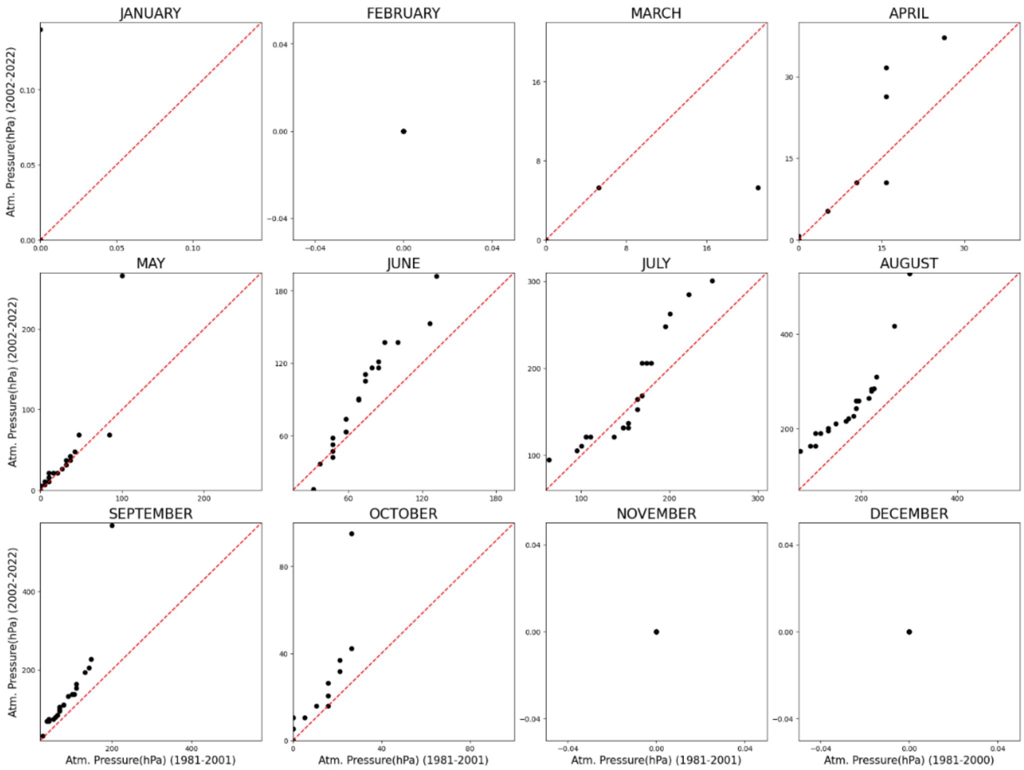

Figure 9. Sen's ITA scatter graphics for monthly precipitation for Sokoto.

Table 2: Sen's ITA results for precipitation across selected stations for all months

↑ - Indicates increasing trend
↓- Indicates decreasing trend

Location	Months	Trend Interpretation		
		Low	Medium	High
Calabar	Jan	NO	YES (↓)	YES (↑)
	Feb	NO	NO	YES (↑)
	Mar	NO	NO	YES (↑)
	Apr	YES (↓)	YES (↓)	YES (↓)
	May	YES (↓)	NO	YES (↓)
	Jun	NO	YES (↓)	YES (↓)
	Jul	YES (↑)	NO	YES (↓)
	Aug	YES (↑)	NO	YES (↓)
	Sept	YES (↑)	NO	YES (↑)
	Oct	YES (↑)	YES (↓)	YES (↓)
	Nov	NO	NO	YES (↓)
	Dec	NO	YES (↓)	YES (↓)
Yenagoa	Jan	NO	YES (↑)	YES (↑)
	Feb	NO	YES (↓)	YES (↑)
	Mar	NO	YES (↓)	YES (↓)
	Apr	YES (↓)	YES (↓)	YES (↑)
	May	YES (↓)	NO	YES (↓)
	Jun	YES (↓)	YES (↓)	YES (↓)
	Jul	NO	YES (↓)	YES (↑)
	Aug	YES (↑)	YES (↓)	YES (↓)
	Sept	NO	YES (↓)	YES (↑)
	Oct	YES (↓)	YES (↓)	YES (↓)
	Nov	NO	YES (↑)	YES (↑)
	Dec	NO	YES (↓)	YES (↑)
Kaduna	Jan	-	-	-
	Feb	-	-	-
	Mar	NO	YES (↑)	YES (↑)
	Apr	NO	YES (↑)	YES (↑)
	May	YES (↓)	YES (↑)	YES (↑)
	Jun	YES (↓)	YES (↓)	YES (↑)
	Jul	YES (↓)	NO	YES (↑)
	Aug	YES (↓)	NO	YES (↑)
	Sept	YES (↓)	NO	YES (↑)
	Oct	YES (↓)	NO	YES (↑)
	Nov	NO	YES (↑)	YES (↑)
	Dec	-	-	-
Kukawa	Jan	-	-	-
	Feb	-	-	-
	Mar	-	-	-

	Apr	YES (↑)	YES (↑)	YES (↑)
	May	NO	NO	YES (↑)
	Jun	NO	YES (↑)	YES (↑)
	Jul	NO	YES (↑)	YES (↑)
	Aug	YES (↑)	YES (↑)	YES (↑)
	Sept	YES (↑)	NO	YES (↑)
	Oct	NO	NO	YES (↑)
	Nov	-	-	-
	Dec	-	-	-
Sokoto	Jan	-	-	-
	Feb	-	-	-
	Mar	-	-	-
	Apr	NO	YES (↑)	YES (↑)
	May	NO	NO	YES (↑)
	Jun	NO	YES (↑)	YES (↑)
	Jul	NO	YES (↑)	YES (↑)
	Aug	YES (↑)	YES (↑)	YES (↑)
	Sept	YES (↑)	NO	YES (↑)
	Oct	NO	NO	YES (↑)
	Nov	-	-	-
	Dec	-	-	-

5. Discussion

5.1 Variations of precipitation patterns in Nigeria and its potential drivers

The results of precipitation patterns in Nigeria reveals significant changes over time, notably in the country's different vegetation zones. It is crucial to investigate its potential factors in order to appreciate these variations in precipitation patterns. Corroborating with previous literature, the findings show a link between global surface temperature rise, long-wave radiation from GHGs (Agbo, Ettah, et al., 2023), and observable constraints in the chance of excessive rainfall (Okono et al., 2022). This is consistent with a previous study showing the impact of climate change on precipitation patterns by Abaje et al. (2014). Further insights from the results of this research shows an increasing trend in peak precipitation values in the Guinea and Sudan savannah sites. This may indicate a greater vulnerability to climate extremes, underlining the importance of adaptive water management measures in these areas.

5.2 Impacts of results on future water policies and planning

The findings of atmospheric science research undertaken in Nigeria have important significance for future water policy and planning. The examination of precipitation patterns across different vegetation zones gives useful data that can influence strategic water resource management decisions.

First and foremost, the observed differences in precipitation patterns, particularly the reducing peak values in the southern regions and increasing values in others (northern/savannah regions), are one important discovery. This highlights the importance of adaptive solutions in water management, which includes demand management, reuse, recycling, and conservation, etc. (Light et al., 2013). This reveals a possible link between global surface temperature rise and constraints in the chance of excessive rainfall.

The rising trends in peak precipitation values in the savannah locations indicate a greater sensitivity to climatic nuances. A sudden emergence of increasing rainfall patterns after prolonged months of drought is valuable information. It is clear that atmospheric science research can help policymakers identify vulnerable areas and execute resilience-building measures by contributing to vulnerability assessments. Furthermore, systems to ensure sustainable water management especially during seasons of drought can be implemented. This is consistent with the broader literature on the effects of climate change on hydro-meteorological systems (Bodner et al., 2015).

Results show that a sophisticated and region-specific approach to water policy is required in light of the known regional disparities in precipitation trends. Distinct vegetation zones bring distinct challenges and opportunities, and policies and planning should be adjusted accordingly. This is in line with the recommendation made by Rannow et al. (2014) for context-specific adaptation techniques in the face of climate change.

Finally, the erratic patterns of precipitation highlight the significance of a careful design for water infrastructure. In order to effectively manage water scarcity, the southern regions which have declining maximum precipitation values might need to make infrastructural improvements, while those with growing tendencies in the same region should get ready for possible flooding hazards; thereby preparing for adaptive water management buttressed by Light et al. (2013).

5.3 Collaboration between stakeholders/researchers from different disciplines for better insights into sustainable water management in Nigeria?

Based on the results of this study, **Figure 10** shows how diverse stakeholders from different disciplines can contribute to the sustainable water management phenomenon.

Atmospheric scientists, using climate models, can predict precipitation changes, aligning with research findings on evolving patterns in the region (Ndehedehe et al., 2020). Chemists can further contribute by analyzing pollutants, contributing to strategies for mitigating their impact on water quality amidst changing precipitation (Sullivan et al., 2018).

Hydrologists can provide insights into water availability, collaborating with atmospheric scientists to identify regions prone to scarcity (Thompson et al., 2013). The observed declining precipitation in specific areas underscores the need for tailored conservation efforts. Ecologists study the ecological impacts of water scarcity (Ibáñez & Caiola, 2013), complementing chemists' work to understand pollutant effects on aquatic ecosystems. The collaboration helps develop conservation measures aligned with the changing precipitation landscape.

Economists contribute economic perspectives, assessing the costs and benefits of water management strategies. The recently concluded United Nations Climate Change Conference (COP28) theme encompassed climate adaptation and particularly climate finance, explaining the value of financing climate action (Carbon Brief, 2023). This is a perfect example of what and how stockholders (economists in this case), will contribute to this subject. Their insights will consider economic implications amid changing precipitation patterns, ensuring strategies are both environmentally sound and economically feasible.

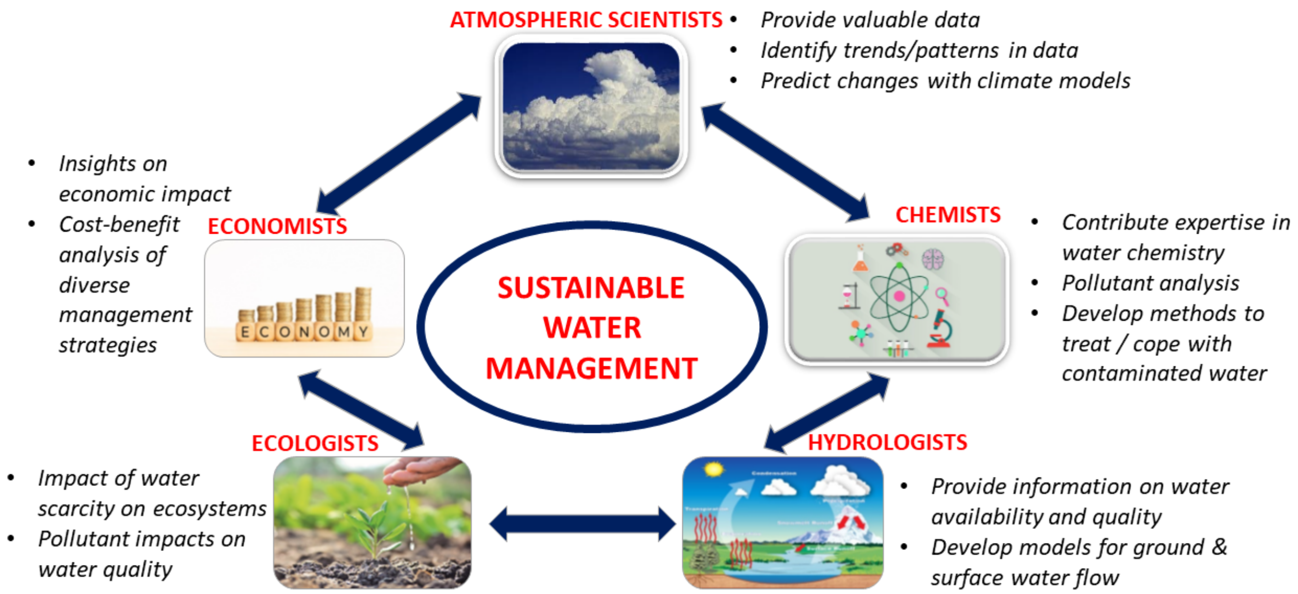

Figure 10. Relevant areas of expertise for Sustainable Water Management.

7. Conclusion

This study used the Innovative Trend Analysis (ITA) method to understand the complex interaction between precipitation dynamics and sustainable water management. The results provide subtle insights into precipitation trends in the past in several Nigerian locales across the vegetation zones. The understanding of the changing nature of precipitation patterns and its consequences for water resources has been made possible by the combination of modern modeling tools, interdisciplinary collaboration, and knowledge in atmospheric science. One limitation in this study is that the data obtained takes into account only the total monthly precipitation, and not the average daily precipitation which is always adopted for most trend analysis studies. This limitation was circumvented by the study's focus on the identification of low, medium and high values, reemphasizing the importance of the adoption of the ITA methodology.

The analysis of precipitation trends using the Innovative Trend Analysis method revealed a spectrum of patterns, from declining or trendless scatter points in the southern vegetation zones to increasing precipitation trends in the savannah regions. Such regional disparities emphasize the need for context-specific water management strategies. Regions experiencing declining precipitation trends may necessitate adaptive measures to address potential water scarcity, while those with increasing trends require strategies to mitigate potential flooding risks.

In response to the regions with increased precipitation, critical infrastructural solutions must address the heightened risk of flooding and erosion while also managing excess water for future use. Investments in reservoirs and water storage facilities are imperative to capture surplus water, mitigating flood risk and ensuring a reliable water supply during dry spells. However, the effectiveness of these solutions may be limited by financial constraints, land availability, and environmental concerns, highlighting the need for careful planning and prioritization to achieve sustainable outcomes. Furthermore, in regions facing decreased precipitation, infrastructural solutions must focus on conserving dwindling water resources and diversifying water supplies to mitigate the impacts of drought. Investments in water recycling, desalination, and drought-resistant agriculture can provide alternative sources of water and sustain agricultural productivity. However, these solutions may face challenges related to cost-effectiveness, technological feasibility, and environmental sustainability, underscoring the importance of balanced approaches and adaptive management strategies to address the complexities of water scarcity

The significance of these findings extends beyond meteorological considerations, impacting water availability, ecosystem resilience, and societal well-being. The adoption of the ITA approach facilitated a detailed analysis of trends, enabling the identification of areas requiring targeted interventions and adaptive strategies, and further buttressed on the importance of multidisciplinary collaboration to bring the results of this study into fruition.

Declarations

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Declaration of Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability: Data will be made available on request.

Code Availability: Codes for visualization will be made available on request.

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