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Spatiotemporal Analysis of Rainfall Variability in the Sana'a Basin, Yemen: An Integrated Remote Sensing and GIS Approach

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Abstract

Sana'a Basin in the Central Highlands of Yemen is critical economic importance for drinking water, as well as for rainfed and irrigated agriculture. Consequently, and any shift in rainfall patterns profoundly impact both groundwater recharge on the one hand, and crop ecosystems on the other hand. This study aims to analyze precipitation dynamics in the Sana'a Basin, by analyzing data from 26 meteorological stations distributed across the region to understand the temporal and spatial variations in rainfall. The research utilizes datasets from the National Water Authority for the period from 2010 to 2024. The results revealed significant spatial heterogeneity in rainfall distribution, with the northeastern and central regions experiencing minimal precipitation, while the western and southern areas recorded considerably higher levels. These patterns are largely driven by orographic lifting and atmospheric dynamics. The observed trends indicate that a systematic decline in rainfall at multiple stations suggests prolonged aridification in specific zones, which could detrimentally affect groundwater replenishment, agricultural productivity, and water security. Conversely, localized increases in rainfall at certain stations suggest potential climate-induced shifts that may elevate flood risks or, alternatively, improve water availability. Furthermore, the study validates the effectiveness of integrating satellite-based observations (TRMM) to complement field data, particularly in data-scarce regions. These findings underscore the urgent need for continuous monitoring and the implementation of adaptive water management strategies to mitigate the impacts of climate variability on the basin's fragile water resources.

Article Info

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Rainfall data, Spatial analysis , ArcGIS, Sana'a Basin , Yemen.

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1. INTRODUCTION

Rainfall is a pivotal climatic factor that influences water resources, agriculture, and hydrological processes within a river basin. Its spatiotemporal variability significantly impacts river flow, groundwater recharge, and the frequency of floods and droughts [1, 2]. Sana'a Basin is situated in the Central Highlands of Yemen, which includes the capital city of Sana'a. Sana'a Basin is predominantly an intermountain plain bordered by highlands to the west, south, and east [3]. The basin is characterized by localized rainfalls with intense precipitation events of relatively short duration. Rainfall serves as the primary source of runoff in the wadis and of groundwater recharge [4]. Comprehensive rainfall data analysis is a crucial aspect of hydrology, meteorology, and climate science [1]. It helps in understanding precipitation patterns, assessing water availability, enhancing water resource management, and predicting extreme weather events such as floods and droughts [5]. The analysis involves collecting, processing, and interpreting rainfall data to derive meaningful insights for various applications, including, water, agriculture, urban planning, and climate change studies [6]. Rainfall data analysis involves examining measurements like amount, intensity, duration, and spatial distribution to understand water cycles, climate trends, and water resource management. Rainfall data analysis using methods from simple averages and statistical tests (Mann-Kendall, [7]) for trends to probabilistic models (Gumbel distribution) for extreme event prediction, crucial for agriculture, flood control, and climate change impact assessment. Data comes from gauges and satellites, focusing on characteristics like frequency, intensity (mm/hr), and temporal patterns (wet/dry spells) [5]. The Descriptive statistical analysis of rainfall data from various sites provides insights into precipitation trends, variability, and distribution patterns [8, 9]. The mean and median values offer a measure of central tendency, while standard deviation, skewness, and kurtosis help assess dispersion and the shape of rainfall distributions across different locations [10].

The objective of the present study is to analyzes rainfall data in Sana'a Basin to identify patterns, trends, and variability. The results will help in understanding rainfall behavior and support better planning and management of water resources.

Several previous studies have investigated the hydrological and hydrogeological studies in Sana'a Basin. For example, Taher et al. (2013) analyzed rainfall distribution at period (1989-2004) and hydrological conditions in the Sana'a Basin as part of integrated water resources management planning [11]. Aljawzi et al. (2022) concluded the Sana'a Basin is characterized by an arid climate with limited rainfall and high evaporation rates [4]. Aklan et al., (2022) analyzed Site suitability of indigenous rainwater harvesting systems in arid and data-poor environments of Sana'a Basin [2]. Al-Falahi et al. (2024) assessed precipitation variability and its impacts on hydrological processes in the Yemeni highlands, including the Sana'a Basin [12]. This study presents and discusses the results of a spatiotemporal analysis of observed rainfall data collected from 26 rain gauge stations distributed across the sub-basins of the Sana'a Basin for the period 2010–2024. Unlike many previous studies that rely primarily on satellite-derived datasets, this research utilizes measured ground-based rainfall records, providing a more realistic representation and interpretation of rainfall distribution across the basin over a 15-year period. The analysis enabled the identification of spatial patterns, temporal trends, and variability in rainfall behavior within the Sana'a Basin. Although numerous studies have been conducted on the Sana'a Basin, most have not focused on a comprehensive spatiotemporal analysis of rainfall using long- or medium-term observed datasets. Therefore, this study contributes to filling this gap by providing a detailed assessment of rainfall variability and distribution based on long-term gauge observations.

2. GEOLOGIC SETTING

The Sana'a Basin is a tectonic depression surrounded by mountain ranges, characterized by complex geology and hydrogeology due to vertical fractures, differential subsidence, and varied lithology. The stratigraphic sequence of Sana'a Basin ranges from Precambrian to Recent with some periods missing. The Phenarozoic rocks of the Sana'a Basin mainly consist of sedimentary and volcanic rocks. The Sana'a Basin is characterized by a diverse rock formation, ranging from the Middle Mesozoic era to the Cenozoic era. Mesozoic sediments are widely distributed in Sana'a Basin. They are characterized by both clastic and carbonate deposits. The clastics were dominant during the late Triassic–early Jurassic and are represented by the Kohlan sandstone Group [13]. The Kohlan Group grades up into a predominantly carbonate (Amran Group). Towards the east and along the Sana'a-Marib Road, the evaporitic "Sabatayn Formation" or the "Sabatayn Group" is sandwiched between the Jurassic Amran limestone and the Cretaceous Tawilah groups. The Tawilah group of continental conditions continued to dominate in the late Cretaceous with locally marine clastics (Medi-zir Formation) during the Paleocene, and they become interspersed with volcanic extrusions in the early Tertiary [13].

At the end of the Mesozoic era, tectonic uplift, associated with erosion, removed most of the Jurassic and Cretaceous sediments from central Yemen. These movements were accompanied by intense volcanic and intrusive activity that extended throughout most of the Cenozoic, resulting in the formation of tertiary volcanic rocks and intrusions, which cover an area estimated at approximately 41% of the total area of the Sana'a Basin. This volcanic group is mainly composed of alternating lava flows (basalts, andesites, or trachyte porphyries) and different types of tuffs. Quaternary Volcanic rocks (Middle Miocene–Holocene) are exposed in the northwestern part of the Sana'a Basin, specifically in the Sana'a-Amran volcanic field, as well as in limited exposures in the western and northeastern parts of the basin. Alluvial deposits (Holocene) are exposed on slopes, valleys, and lowlands, where they are widespread in most parts of the Sana'a Basin, especially the Sana'a Plain [13].

Structural features, such as faults, fractures, joints, lineaments, and rift systems shaped by the Arabian Shield and Najd Fault System, strongly influence groundwater movement and the suitability of sites for water harvesting and recharge. High-density linear structures indicate zones of enhanced permeability, whereas the distribution of lithologies and topographic variation govern surface water flow and aquifer replenishment [13].

3. MATERIALS AND METHODS

Study Area

The Sana'a Basin is located in the capital city of Yemen and parts of the districts of Sana'a Governorate (Arhab, Nihm, Hamdan, Sanhan, Bani Bahlul, Bani Hishish, Bani Matar, and Khawlan Districts), in addition to a small part of Amran Governorate (Ayal Surayh District). The area of the Sana'a Basin is estimated to be approximately 3230.3 square kilometers. The basin was divided into 22 sub-basins (Figure 1).

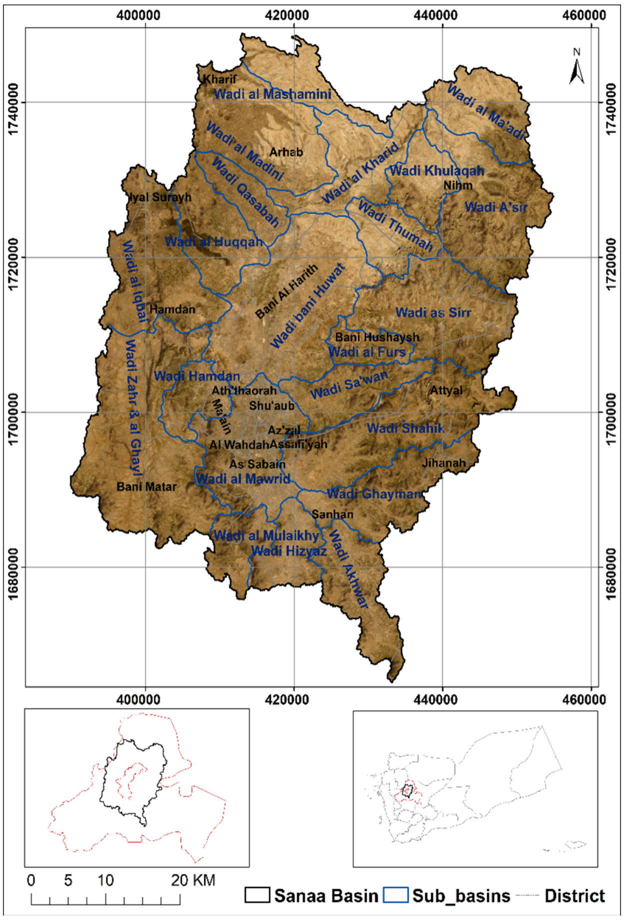

Figure 1. Geographical location of the study area

Methodology

Ground-based measurements, primarily collected using rain gauges and weather stations, provide the most direct and accurate rainfall data. Rain gauges, including manual and automated types, measure precipitation at specific locations, offering high precision but limited spatial coverage [14]. A comprehensive statistical analysis of rainfall data is essential for understanding precipitation patterns, their variability, and long-term trends [9]. Various statistical techniques, including descriptive statistics, trend analysis, and anomaly detection, have been employed to examine rainfall distribution over time and across different locations [15].

This study utilizes datasets from the National Water Resources Authority (NWRA) from 26 ground stations covering most of Sana'a Basin (Figure 2). Rainfall data were included for the period 2010–2024, given their continuity and regular recording. The annual rainfall dataset was analyzed using statistical techniques, such as mean calculation and standard deviation, to identify data gaps [8]. Rainfall data for the period 2010-2024 were collected from 26 rain gauge stations, and the data were cleaned and processed to ensure its accuracy and suitability for analysis, as shown in Table (1). Missing values were addressed using Mean Imputation methods for filling missing values with the average rainfall from the same station or nearby locations [16]. To identify and manage anomalies in the rainfall dataset, outlier detection methods were applied. Two primary statistical techniques were used: Z-score analysis and boxplot analysis [8]. A temporal analysis was conducted to estimate changes in precipitation over the studied years, facilitating the identification of periods with high and low rainfall. The spatial analysis tools in ArcGIS ver10.8 were employed to create maps depicting the distribution of rainfall, contributing to the identification of geographical differences among regions [17]. Satellite-based rainfall observations help overcome the limitations of terrestrial data by providing global coverage, particularly in areas lacking weather stations [18]. This study used rainfall data for the period 2010-2024 from the Tropical Rainfall Measurement Mission (TRMM), which focuses on tropical and subtropical regions and provides satellite-based estimates.

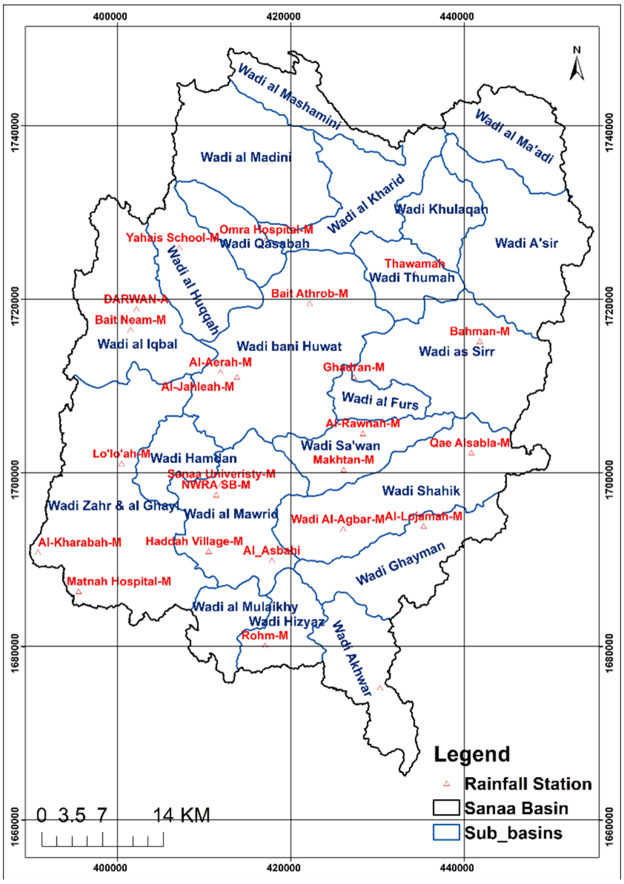

Figure 2. Rain gauge stations distribution map in Sana'a Basin

Table[1]: Annual rainfall data of rainfall stations in Sana'a Basin at period (2010-2024)

Rain Gauge Station	Annual Rainfall (mm)							
	2010	2011	2012	2013	2014	2015	2016	
Maqulah-M	441.7	225.2	214.9	301.4	194.5	103.1	186.7	
Al-Kharabah-M	364	394.5	398.6	481.9	217.6	232.2	261.0	
Bahman-M	254.0	205.5	254.7	286.6	98.5	145.8	250.7	
Walan_M	414.4	288.4	321.1	356.2	223.7	167.9	267.3	
NWRA SB-M	345.2	291.7	252.6	251.4	128.0	148.2	285.3	
Al-Aerah-M	330.4	230.7	233.7	286.2	101.5	188.6	223.4	
Sana'a University-M	296	249.0	210	189	181.9	144.2	340.9	
Darwan-A	372.7	349.3	302.7	284.9	217.9	75.0	384.02	
Bait Athrob-M	263.3	174.5	238.6	258.9	108.9	94.1	138.8	
Al-Jahleah-M	208.5	221.5	265.4	232	97.3	179.1	104.8	
Thawamah	100.9	102	82.2	77.9	98.0	87.0	87.2	
Omra Hospital-M	342.2	262.6	326.6	341.8	196.3	185.9	322.2	
Qae Alsabla-M	385.3	254.2	301.2	275.8	193.3	103.33	283.0	
Yahais School-M	199.4	156.8	178.9	188.8	85.1	130.0	198.8	
Haddah Village-M	244.0	246.5	236.2	177.3	195.0	97.6	148.5	
Al-Lojamah-M	269.0	266.7	330.2	355.2	176.2	121.1	304.6	
Al-Assbahi-M	302.0	328	304.3	352.8	246.3	164.5	415.6	
Ghadran-M	285.4	121.6	205.3	179.9	90.3	175.0	237.9	
Matnah Hospital-M	447.6	297.6	308.2	351.4	232.4	155.2	402.5	
Wadi Al-Agbar-M	226.0	198.6	335.1	409.2	130.2	88.6	325.0	
Makhtan-M	321.5	258.5	255.4	328.9	105.7	176.0	247.4	
Rohm-M	469.0	280.9	306.5	368.1	222.9	141.9	281.9	
Bait Neam-M	307.9	314.7	281.6	393.9	123.4	201.0	279.3	
Lo'lo'ah-M	401.2	320.4	273.1	400.7	108.8	186.0	265.8	
Al-Massajed-M	392.9	235.5	150.1	178.7	213.7	102.5	252.9	
Al-Rawnah-M	322.1	253.9	263.0	229.5	88.8	243.3	127.2	

Table 1. continued

Rain Gauge Station	Annual Rainfall (mm) 2017	2018	2019	2020	2021	2022	2023	2024
Maqualah-M	210.0	359.2	236.9	370.7	249.2	311.2	62.2	235.8
Al-Kharabah-M	381.9	372.1	474.8	598.4	294.4	353.2	145.2	261.2
Bahman-M	140.5	160.7	276.3	362.3	133.8	329.8	162.6	180.2
Walan_M	219.9	243.2	278.4	430.9	213.5	262.4	83.6	284.4
NWRA SB-M	156.1	185.0	211.8	466.9	236.0	315.2	81.8	398.0
Al-Aerah-M	137.5	153.7	157.0	240.0	129.8	202.4	71.8	218.8
Sana'a University-M	225.9	264.7	220.2	292.9	149.4	210.4	54.2	274.4
Darwan-A	219.5	289.7	453.6	490.8	194.4	360.2	125.4	225.4
Bait Athrob-M	91.2	124.3	64.6	329.8	226.0	215.2	45.8	182.4
Al-Jahleah-M	153.6	154.8	142.6	148.6	194.0	199.2	84.0	218.0
Thawamah	96.0	106.0	93.95	176.24	25.3	188.0	73.8	205.0
Omra Hospital-M	201.1	234.4	298.8	386.7	211.7	319.4	70.4	209.0
Qae Alsabla-M	168.5	258.4	248.6	425.0	180.0	387.4	65.2	237.8
Yahais School-M	146.0	166.76	258.66	308.2	202.0	158.4	240.6	294.2
Haddah Village-M	121.5	188.0	247.8	233.4	346.0	502.2	122.0	327.4
Al-Lojamah-M	170.8	195.4	330.2	488.6	227.8	263.2	136.2	237.0
Al-Assbahi-M	260.3	255.5	316.6	519.9	263.8	449.2	75.6	279.0
Ghadran-M	118.7	159.8	335.5	305.6	184.1	224.4	50.2	167.0
Matnah Hospital-M	189.3	248.1	340.6	475.0	468.8	495.2	64.4	453.8
Wadi Al-Agbar-M	247.4	125.0	265.6	303.0	217.0	309.0	87.8	134.0
Makhtan-M	121.8	206.6	193.2	468.0	188.2	250.2	38.4	335.8
Rohm-M	214.5	234.9	341.88	518.6	318.0	305.6	99.8	289.8
Bait Neam-M	172.6	266.9	308.2	409.8	204.0	232.4	71.2	231.0
Lo'lo'ah-M	222.6	277.5	415.4	402.0	249.0	253.4	200.8	317.4
Al-Massajed-M	151.9	263.5	338.7	353.4	247.8	400.0	226.4	371.0
Al-Rawnah-M	135.0	198.2	264.8	438.8	176.4	276.2	19.8	103.6

4. RESULTS AND DISCUSSION

Temporal analysis of rainfall data

When examining rainfall data from 2010 to 2024, rainfall patterns across different locations exhibited varying substantial degrees of fluctuation. Locations with high variability in rainfall showed pronounced increases over the years (Table 1 and Figure 3). For instance, rainfall in Dharwan-A surged from 75 mm in 2015 to 490.75 mm in 2020, marking a significant rise, and Matnah Hospital-M recorded an increase from 155.24 mm in 2015 to 475 mm in 2020. Another example is Al-Massajed-M, where annual rainfall fluctuated notably, increasing from 102.5 mm in 2015 to 353.4 mm in 2020. These variations highlight changing precipitation patterns that could be influenced by climatic and environmental factors. Conversely, some locations exhibit relatively stable rainfall trends with lower fluctuation. For example, Thawamah recorded rainfall values ranging from 77.85 mm in 2013 to 185.98 mm in 2015, indicating moderate variability. Similarly, Al-Jahleah-M maintained a more consistent pattern, with levels mostly within the range of 97.32 mm in 2014 to 265.35 mm in 2012, showing stable trends over time.

Several years exhibited notable spikes or drops in rainfall, which were identified as outliers. For instance, in 2020, Dharwan-A rainfall surged to 490.75 mm, a sharp increase compared to 453.55 mm in 2019, possibly due to an intense storm. Conversely, in Makhtan-M during 2023, rainfall dropped drastically to 38.4 mm, significantly lower than in previous years, suggesting the occurrence of severe drought conditions. Another unusual case was observed in Al-Massajed-M in 2015, where rainfall decreased to 102.5 mm, a substantial decline compared to the dataset average. These detected outliers likely resulted from exceptional weather events, such as major storms or prolonged droughts. Identifying and addressing these anomalies is crucial for improving data reliability and ensuring accurate trend analyses [7–10].

Spatial analysis of rainfall data

The spatial distribution of rainfall in the Sana'a Basin revealed a clear pattern of variability across different regions.

The basin is divided into sub-basins with distinct rainfall variations driven by topography, elevation, and prevailing weather patterns [2–4]. The northeastern and central parts of the basin experience the lowest rainfall, as indicated by the light blue shades (Figure 4). In contrast, the western and southern parts of the basin receive higher rainfall, shown in darker blue shades. This pattern suggests orographic influences, where elevated areas receive more precipitation, while lower-lying areas are drier as shown in Figure (4). The regions around Thawamah, Bait Athrob-M, Al-Jahleah-M and Al-Aerah-M have the lowest recorded rainfall, with values ranging from 106 mm to 193 mm per year. These areas, marked

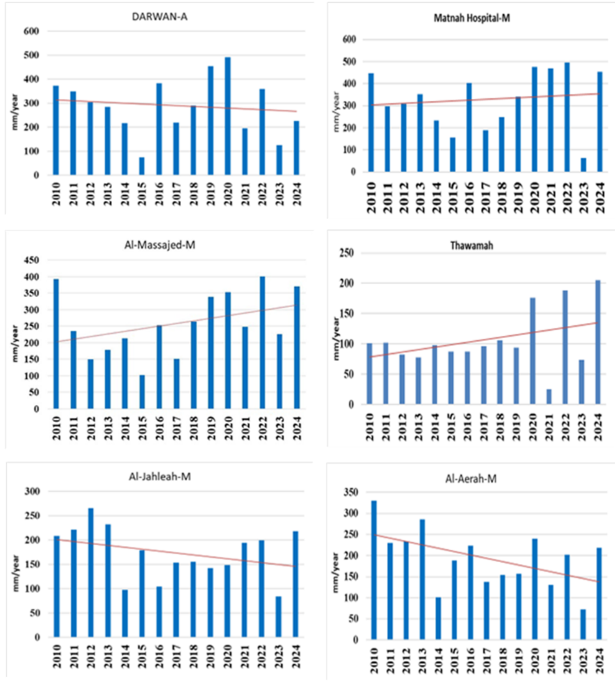

Figure 3. Charts of annual rainfall data for some rain gage stations in Sana'a Basin

by light blue shades, may experience rain shadow effects, where mountains block moist air, leading to drier conditions. This region is more vulnerable to droughts and water scarcity due to limited rainfall and higher evaporation rates. The central regions of the basin, including Bahman-M, Sana'a University, and Wadi Al-Agbar-M, receive rainfall in the range of 200 mm to 260 mm. The southern and western parts of the basin, including Maqualah -M, Matnah Hospital-M, Al-Kharabah-M, and Al-Massajed-M, exhibit the highest rainfall levels, with values exceeding 300 mm per year. This higher precipitation is likely due to orographic lifting, where moist air is forced to rise over the terrain, cools, and condenses to form rain [12, 13]. These areas serve as critical groundwater recharge zones. The spatial distribution map of average rainfall data for the period 2010-2024, derived from TRMM satellite data (Figure 5) corroborates the patterns observed from ground-based stations. The rainfall averages decrease towards the northeast of the Sana'a Basin and rainfall rates increase towards the south and west of the Sana'a Basin. This consistency strengthens the validity of the ground station data, although satellite-derived averages exhibit a slight positive bias compared to terrestrial measurements.

This study analyzed rainfall data within the in Sana'a Basin for the period 2010–2024 utilizing data from 26 ground-based rainfall stations and satellite-based TRMM observations for same period. Through comprehensive data processing, statistical analysis, and spatial mapping, the research provides valuable insights into the spatiotemporal variability and spatial distribution of rainfall across the basin. The results indicate that rainfall in the Sana'a Basin is highly variable in both time and space, reflecting the influence of local climatic conditions, topography, and elevation. The temporal analysis revealed significant interannual variability, with several stations exhibiting notable fluctuations and extreme rainfall events.

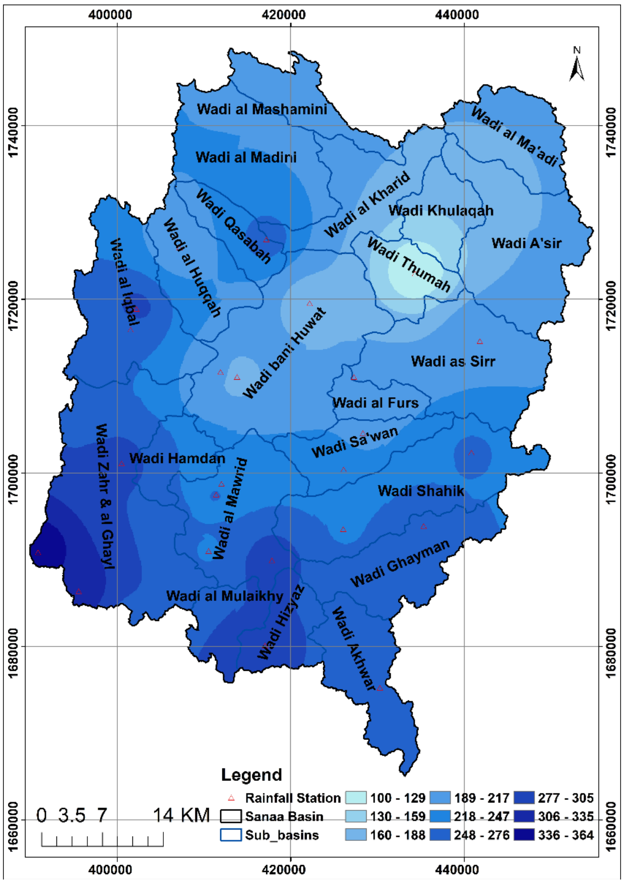

Figure 4. Spatial distribution map of the mean annual rainfall data for the period 2010-2024 in Sana'a Basin from Rain Gauge Stations

Notable increases in rainfall during certain years, particularly in 2019–2020, indicated the occurrence of intense precipitation events, whereas sharp declines in other years highlighted prolonged periods of drought. The identification and mitigation of outliers are essential for ensuring data reliability and distinguishing exceptional climatic events from long-term rainfall trends [10].

These findings underscore the vulnerability of the basin to both floods and droughts, posing significant challenges to sustainable water resource management.

Spatial analysis demonstrated a clear rainfall gradient across the Sana'a Basin, with lower rainfall in the northeastern and central regions and higher rainfall in the western and southern regions. This pattern is strongly associated with orographic effects, where elevated areas receive greater precipitation and contribute significantly to the groundwater recharge. Areas with low rainfall were identified as being more susceptible to water scarcity, whereas high-rainfall zones represent critical recharge areas that require protection and strategic management.

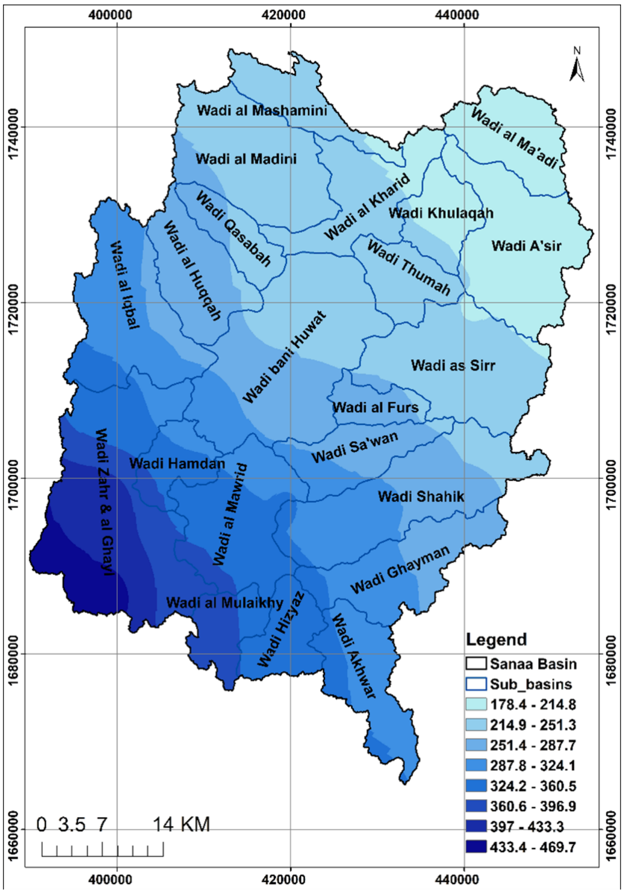

Figure 5. Spatial distribution map of the mean annual rainfall data for the period 2010-2024 in Sana'a Basin from (TRMM)

The close agreement between ground-based measurements and satellite-derived (TRMM) rainfall data further validates the robustness of the analysis and highlights the usefulness of remote sensing data in data-scarce regions. Overall, the findings of this study provide a scientific basis for improved water resource planning and management in the Sana'a Basin. Understanding rainfall variability and spatial distribution is essential for developing effective strategies to mitigate the impacts of climate variability, enhance groundwater recharge, and support agricultural and urban water demands [12].

5. CONCLUSION

Spatiotemporal analysis of rainfall data in the Sana'a basin reached the following conclusions:

- Spatiotemporal Variability: Rainfall exhibits pronounced interannual fluctuations (e.g., intense events in 2019–2020 and drought periods). A distinct spatial gradient was observed, with lower precipitation in the northeastern and central regions and higher precipitation in the western and southern areas. This variability increases the basin's vulnerability to flash floods and water scarcity, necessitating adaptive water management planning.
- Orographic Influence: Higher rainfall in the western and southern parts (e.g., >300 mm/year in areas like

Rohm-M, Alkharabah-M, and Bait Neam-M) this spatial distribution is primarily driven by orographic lifting, where moist air rises over elevated terrain, cools, and precipitates, making these zones critical for groundwater recharge.

- Recharge and Scarcity Zones: Elevated western and southern zones serve as primary groundwater recharge areas owing to higher precipitation levels. Conversely, the low-rainfall northeastern and central regions face heightened water scarcity, emphasizing the urgent need to protect high-rainfall sites and implement targeted interventions for sustainable water use.
- Remote Sensing Validation: Satellite based data (TRMM) for 2010–2024 closely mirrors the patterns observed at ground stations, showing lower rainfall in the northeast and higher totals in the southwest. This correlation reinforces the statistical reliability of the study, despite satellite data showing slightly higher averages than terrestrial measurements.

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