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RESEARCH ARTICLE - PHYSICS

The spatiotemporal distribution of rainfall anomaly index (RAI) in Iraq

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Abstract

The patterns and distributions of rainfall systems determine the prevailing climatic characteristic for any region of the world. In this study, the spatiotemporal distribution of the rainfall anomaly index was revealed based on data from the Coupled Model Intercomparison Project (CMIP6) for daily rainfall amounts in twenty-four geographically and climatically diverse regions in Iraq for the time series (2016-2050) of the SSP2.5 simulation scenario projections. Overall, these results concluded that rainfall distribution varies temporally and spatially depending on the nature of the climate region and its geographical characteristics. Zakho station in Duhok Governorate within the northern region recorded the highest total rainy cases, followed by Baghdad Governorate in the central region, and finally, Diwaniya station in the south, leading these stations in the temporal and spatial variability of the rainfall anomaly index. The spatial variance amplitude of the total rainy days was approximately 10% among all stations. The non-parametric Mann-Kendall analysis of general rainfall anomaly trends showed clear temporal variability among the stations, with five stations showing a positive trend, seven stations showing a non-significant negative trend, and the remaining stations showing a neutral trend at the significance level (α=0.05). The analysis indicated that only Mosul station in the northwest had a significant negative trend, indicating a clear anomaly in the rainfall systems characteristic of Iraq's climate.

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Keywords: Rainfall Anomaly; Spatial; Temporal; Distribution; RAI, CMIP6; Iraq.

1. Introduction

Drought is a complex climatic phenomenon that results from dry weather or a notable lack of precipitation over an extended period, leading to a significant hydrological imbalance characterized by water scarcity and reduced surface runoff in the affected region [1]. Drought can be classified into several categories, the first of which is meteorological drought, which gives rise then to hydrological drought, agricultural drought, the first three approaches deal with ways to measure drought as a physical phenomenon and the last type is socioeconomic drought deals with water shortfall effects through socioeconomic systems [2].

Furthermore, the duration of each drought case can be evaluated and compared. Permanent drought is a characteristic of arid and desert regions, whereas seasonal drought is associated with the rainy season. In humid and semi-humid regions, temporary or emergency droughts result from fluctuations in precipitation levels [3]. Finally, Ecological drought when natural ecosystems are affected by drought. In this type of drought, a reduction in the percentage of atmospheric humidity or soil moisture results in agricultural consequences related to the area of vegetation cover and its diversity in the region exposed to drought. Drought is inextricably linked to a multitude of factors, including temperature, evaporation, precipitation and relative humidity [4].

Iraq is located in the southwest of Asia. The majority of its territory is characterized by a desert climate, which accounts for 70% of the total area. This is followed by the semi-desert region, which extends west and northwest by 17%. Finally, there is a narrow range within the Mediterranean climate zone, that located to the north and northeast which represents only 13% of Iraq's area. In 2021, Iraq experienced its second driest season in 40 years, with rainfall at a record low. Over the past four decades, the volume of water flowing from the Euphrates and Tigris rivers has decreased by 30–40%. These rivers provide up to 98% of Iraq's surface water [5], [6].

Climate change exerts a profound influence on a multitude of climatic elements, including precipitation [7] and the distribution of vegetation cover. Furthermore, it represents a significant threat to fundamental human rights, impedes sustainable development, and exacerbates the environmental and economic challenges currently facing our country [8], [9].

The precipitation in Iraq has been found to correlate significantly with the Mediterranean Rainfall Regime. The rainfall is concentrated in the winter season, with the rain of this system falling due to the passage of low-pressure systems, especially the Mediterranean and the cold fronts that accompany them, which generally move from west to east. In addition, Iraq's rain is subject to the influence of other secondary systems, namely the Red Sea and the Arabian Gulf depressions, which have been found to be less effective [10].

The temporal and spatial distribution of rainfall in Iraq is influenced by a number of natural factors, including the type of air masses, sea level altitude, geomorphological diversity of its surface, geographical location and continental degree. The latter represents the extent to which prevailing climate patterns are influenced by seas and water bodies [11]. Rainfall is subjected to the Mediterranean rainfall regime, with rainfall from October to June. Together, these factors influence the variation in rainfall patterns between different regions within the country [12], [13].

The aim of this research is to examine the rainfall characteristics across geographically diverse regions in Iraq, with a particular focus on statistical analysis based on the Rain Anomaly Index (RAI) from daily rainfall amounts. This analysis is conducted using projections from the Coupled Model Intercomparison Project, the sixth phase (CMIP6), within the specified time range (2016-2050) to identify the spatiotemporal distribution of rainfall in Iraq, with a particular emphasis on areas exhibiting varying climatic characteristics. Furthermore, the rainfall anomaly index also subjected to analysis process.

Nomenclature & Symbols

RAI	Rainfall Anomaly Index (unitless)
P	Actual rainfall per year (mm)
$\bar{P}$	Overall average of the rainfall time series (mm)
$\bar{M}$	Average of the maximum ten values (for positive anomaly) in (mm)
$\bar{N}$	Average of the minimum ten values (for negative anomaly) in (mm)

2. Methodology.

The RAI takes into account two anomalies, i.e. positive anomaly and negative anomaly. First, the rainfall data are arranged in descending order. The average of the first ten maximum values is calculated to form the positive anomaly threshold and the average of the ten minimum values is calculated to form the negative anomaly threshold. The thresholds are calculated by Equations (1) and (2), respectively [14], [15].

$$RAI = 3\left[\frac{P-\bar{P}}{\bar{M}-\bar{P}}\right], \text{ for positive anomalies} \quad (1)$$

$$RAI = -3\left[\frac{P-\bar{P}}{\bar{N}-\bar{P}}\right], \text{ for negative anomalies} \quad (2)$$

Table 1. shows the index classification used in this study [16], [17], [18].

Table 1. Rainfall Anomaly Index (RAI) Category

RAI Range	Classification
Above 4	Extremely Humid
2 to 4	Very Humid
0 to 2	Humid
-2 to 0	Dry
-4 to -2	Very Dry
Below -4	Extremely Dry

The data of this study included the daily rainfall amounts at twenty-four stations were distributed geographically over spatially diverse areas in Iraq within its three climate regions and from the projection data of the CMIP6 for the time range (2016-2050) according to the RCP4.5 scenario, which the Intergovernmental Panel on Climate Change (IPCC AR5 2014) described as an intermediate scenario, as emissions in (RCP4.5) peak around the year (2040), then decline in the middle of the twenty-first century. RCP 4.5 is the most likely baseline scenario due to the lack of binding climate policies for countries to reduce carbon emissions, taking into account the exhaustible nature of non-renewable fossil fuels, [19], [20] and RCP 4.5 is likely to lead to a global temperature increase of between 2 and 3 °C by 2100. CMIP6 represents a significant expansion over CMIP5, in terms of the number of modeling groups involved, the number of future scenarios examined and the number of different experiments performed. The energy modeling community has developed a new set of emission scenarios driven by different socioeconomic assumptions, the Shared Socioeconomic Pathways (SSPs), and selected a number of scenarios updated to (RCP4.5) including SSP2-4.5, each scenario having different radiative forcing levels than the others. [21], [22]

RAI index calculated for the daily series (2016-2050), comprising a total of 12,784 days. We also determined the maximum and minimum values, along with the coefficient of variation and the time of their occurrence in the rainfall series. The index frequencies for each classification were calculated based on the daily wet data only (excluding zero precipitation values). Furthermore, we computed trends in rainfall anomalies from their general daily and monthly averages based on the widely used Mann-Kendall (MK) rank test, which is a reliable statistical measure for detecting and determining the general trend of climatic series [23]. The null hypothesis (H_o) states that there is no trend in the rainfall series. The alternative hypothesis (H_1) suggests that there is a trend. The statistical significance then verified at the 5% level for this non-parametric test. We developed a MATLAB code to handle the large daily dataset and used ArcGIS 10.7.1 software to create contour maps to determine the spatial distribution of the index results and classifications for all 24 stations across Iraq.

3. Results and discussion.

Table 1, provides an overview of the daily frequency of anomaly indices for precipitation in Iraq, with data presented for each station according to the specified classification. Additionally, the table indicates the percentage of combined wet and dry frequencies, as well as the percentage of rainy days relative to the total number of days in the time series (2016-2050) for this study. It would appear that the station in the northern region of Iraq, classified under the Mediterranean climate according to Koppen classification, has the highest frequency of wet days (rainy days) and the highest frequency of rainy days among the stations. By contrast, the total number of rainy days at the Nasiriya station in southern Iraq was relatively low at 1,062 days, making it the station with the fewest rainy days. Overall, the frequency of dry days in the dry classification of this index was higher compared to other classifications, with extreme wet frequencies coming last, amounting to only a few days. These typically indicate cases of sudden floods resulting from heavy rainfall accompanying Atlantic, polar, or Mediterranean air masses. Baghdad has had 4,319 rainy days, making it the second-ranked station in terms of total rainy days. This is undoubtedly due to Baghdad's central location in Iraq, which, along with other central region stations, acts as a convergence point for frontal rainfall systems. Mosul station ranked second to last among the twenty-four stations, with a total of 1,231 rainy days [24]. This is undoubtedly due to the climatic fluctuations in northwestern Iraq, which alternates between the Mediterranean climate and the steppe climate. The four stations (Arbil, Salahaddin, Sulymaniyah, Zakho), situated within the Mediterranean climate region (Csa: C= Temperate, s = Dry summer a = Hot summer), exhibited a range of 0.03 to 0.08 for the percentage of wet days, while the percentage of dry days ranged from 0.92 to 0.97. With regard to the seven stations situated within the steppe region (Biji, Khanaqin, Kirkuk, Mosul, Rutbah, Sinjar and

Teleafer), the percentage of wet days ranged from less than 0.01 to 0.13, while the percentage of dry days ranged from 0.87 to 0.99. Finally, the thirteen stations within the desert region exhibited dry day percentages that ranged from 0.02 to 0.13, while the dry days spanned from 0.87 to 0.98.

The coefficients of variation values were as follows for each index: The index values were highest in the dry classification, with the lowest value in the extreme dry classification, with the following values: 48.58, 56.22, and 63.92, respectively. Meanwhile, in the wet classification, the coefficient of variation was as follows: 91.64, 82.03, and 64.22. This shows that the highest value was in the wet classification and the lowest in the extreme wet classification. This points to spatial variation in the index values depending on the climatic region to which the station belongs.

The percentages of total rainy days (number of rainy days relative to the total number of days in the time series, amounting to 12,748 days) also demonstrated clear spatial variability of 0.10 across the 24 stations. The highest percentage was recorded at Zakho station in Duhok Province, at 0.44, while Samawa station recorded the lowest at 0.08. This clearly shows that the average rainfall decreases irregularly towards the south. Rainy days at northern stations ranged between 0.30 and 0.44, while at central stations they ranged between 0.17 and 0.30, and at southern stations, between 0.08 and 0.17. The coefficient of variation (CV) for total rainy days was around 51.15%, which is about half a percent. It did not exceed 3.52% for dry conditions, while the highest values (58.93%) were observed for wet conditions. This proves that spatial variability is more pronounced in wet conditions than in dry ones, according to the binary classification (dry, wet) of the index.

Fig.1f. illustrates the spatial contour distribution, wherein the Khanaqin and Teleafer stations exhibit the highest frequency of days classified as wet according to the rainfall anomaly index. Fig. 1g illustrates the percentage of dry days (defined as the total number of dry days within the wet-dry classification). It demonstrates that the central and southern provinces exhibit the highest frequencies of dry days. The number of dry days within the dry classification of this index is illustrated in Fig. 1h, wherein the southern provinces, followed by the central stations including Biji, exhibited the highest frequencies. The spatial contour distribution of the total number of very dry days is illustrated in Fig. 1i, which shows that the Biji station in central Iraq leads in this category. Finally, the contour distribution within the extreme dry classification is clearly evident in both the central and southern stations. This can perhaps be attributed to the absence of Mediterranean air masses during the summer in Iraq, as the country falls under the influence of thermal depressions originating from the Indian Ocean or African lows that prevail during the summer [25].

Table 2: Daily Rainfall Anomaly Index & MK Analysis at 24 Stations for the Time Series 2016-2050

		RAI Category											
Station	Climatic Zone	Extremely Dry Below -4	Very Dry -4 to -2	Dry -2 to 0	Humid 0 to 2	Very Humid 2 to 4	Extremely Humid Above 4	Rainy Days	Percentage Dry	Percentage Humid	Percentage Rainy Days	Sen's Slope	Accepted Hypothesis
Al Hay	Bwh	866	155	254	59	12	4	3075	0.94	0.06	0.11	Negative	H_o
Amarah	Bwh	1018	169	352	51	7	2	3050	0.96	0.04	0.13	null	H_o
Anah	Bwh	888	567	423	257	19	4	4127	0.87	0.13	0.17	null	H_o
Arbil	Csa	2380	410	905	114	10	2	3021	0.97	0.03	0.30	null	H_o
Baghdad	Bwh	1105	171	378	27	3	2	4319	0.98	0.02	0.13	Positive	H_o
Basrah	Bwh	919	171	318	68	11	5	2158	0.94	0.06	0.12	Negative	H_o
Biji	Bsh	1553	630	53	2	0	1	1890	<0.99	>0.01	0.18	Negative	H_o
Diwaniya	Bwh	834	119	270	50	11	4	3539	0.95	0.05	0.10	null	H_o
Habbaniyah	Bwh	983	171	362	37	6	3	2162	0.97	0.03	0.12	null	H_o
Haditha	Bwh	1174	227	427	52	7	3	1562	0.97	0.03	0.15	null	H_o
Kerbela	Bwh	921	157	303	71	12	5	1686	0.94	0.06	0.11	null	H_o
Khanaqin	Bsh	2143	373	577	382	52	12	1350	0.87	0.13	0.28	Negative	H_o
Kirkuk	Bsh	1940	331	717	30	2	1	1350	0.99	0.01	0.24	null	H_o

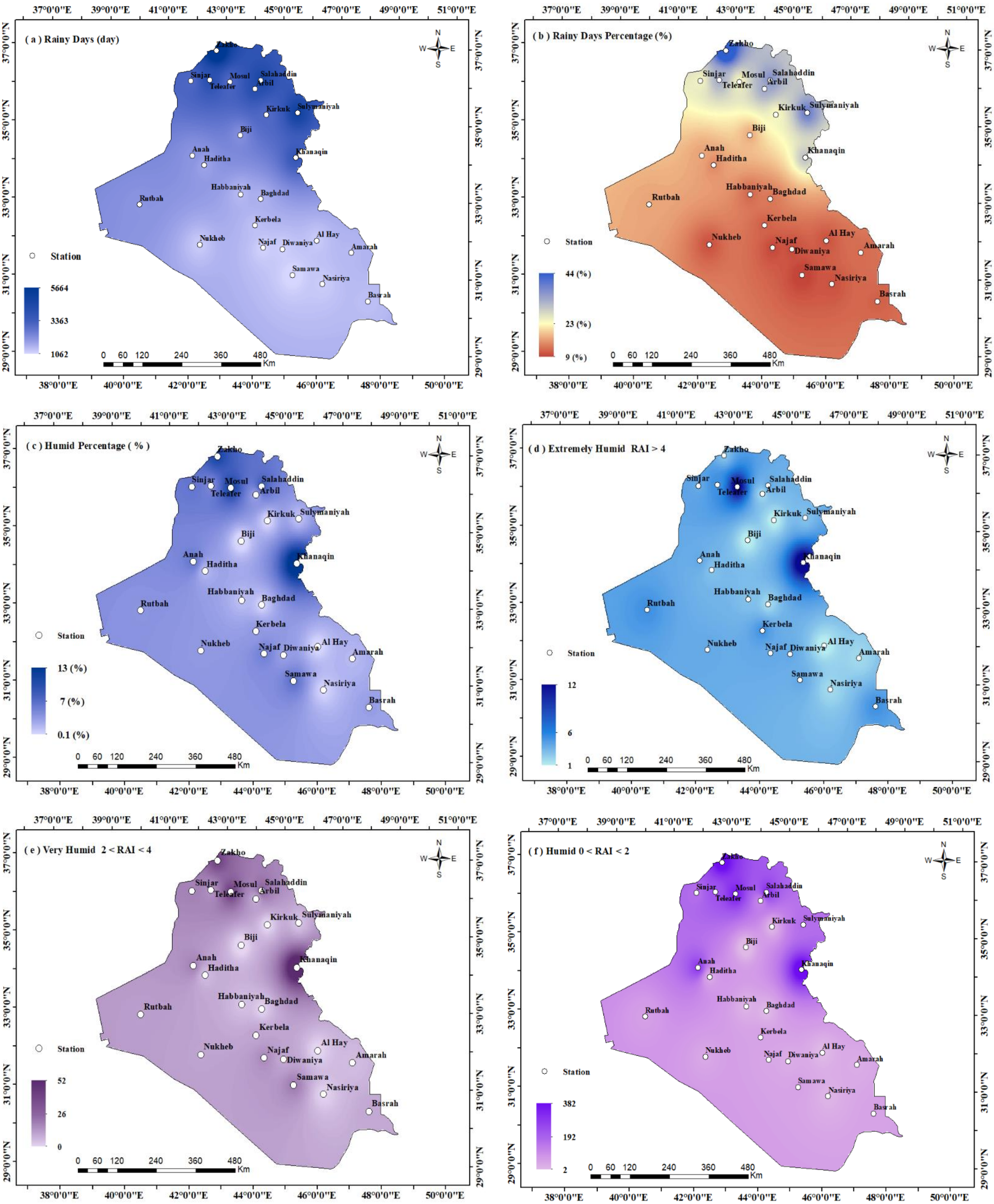
Mosul	Bsh	1773	374	547	311	34	11	1231	0.88	0.12	0.24	Negative	H_1
Najaf	Bwh	792	131	225	62	17	4	1288	0.93	0.07	0.10	null	H_o
Nasiriya	Bwh	855	160	275	36	3	2	1062	0.97	0.03	0.10	Negative	H_o
Nukheb	Bwh	866	155	254	59	12	4	1331	0.94	0.06	0.11	null	H_o
Rutbah	Bsh	1327	254	490	73	13	5	1599	0.96	0.04	0.17	Positive	H_o
Salahaddin	Csa	2367	480	969	281	26	4	1492	0.92	0.08	0.32	Negative	H_o
Samawa	Bwh	648	124	198	68	20	4	2239	0.91	0.09	0.08	Positive	H_o
Sinjar	Bsh	1850	358	678	166	19	4	3821	0.94	0.06	0.24	Positive	H_o
Sulymaniyah	Csa	2656	496	989	169	6	3	1469	0.96	0.04	0.34	null	H_o
Teleafer	Bsh	2218	435	888	215	15	5	3776	0.94	0.06	0.30	null	H_o
Zakho	Csa	3179	648	1436	366	33	3	5665	0.93	0.07	0.44	Positive	H_o
Mean		1468.96	302.75	512.00	125.25	14.58	4.04	2427.58	0.94	0.06	0.19		
Max		3179	648	1436	382	52	12	5665	1	0.13	0.44		
Min		648	119	53	2	0	1	1062	0.87	0.00	0.08		
S.D		713.55	170.21	327.28	114.77	11.96	2.60	1241.81	0.03	0.03	0.10		
C.V(%)		48.58	56.22	63.92	91.64	82.03	64.22	51.15	3.52	58.93	51.15		

The non-parametric Mann-Kendall analysis of the rainfall anomaly index from model projections for the years 2016-2050 reveals a distinct temporal variation across the twenty-four stations. A positive trend at the 5% significance level was identified in five stations, while a non-significant negative trend was observed in seven stations. The general trend remained neutral for the remaining regions in Iraq. In Mosul, located in northwestern Iraq, the general trend showed a significant negative direction (accepting the alternative hypothesis), indicating a declining behavior in rainfall and its distribution in this station, whose climate classification fluctuates between the steppe region and the Mediterranean region.

4. Conclusion

The results of the study contribute to our understanding the spatiotemporal distribution of rainfall anomaly for Iraq. The main findings are as follows:

- The rainfall anomaly index (RAI) is a key tool for analyzing rainfall and drought patterns in Iraq.
- Mann-Kendall rank analysis (2016-2050) indicates a positive trend in 5 stations and a non-significant negative trend in 7 stations, with no monotonic trend for the rest of Iraq.
- Significant negative rain anomalies in Mosul station highlight the volatile climate of northwestern Iraq.
- Over 35 years, wet days account for less than 19% of a 12,784-day period, with dry days being predominant.
- Wet days are more frequent in northern Iraq compared to central and southern regions.
- Dry days are more common in the southern region.
- Extreme dry values are more frequent in southern and central Iraq than in the north.


(a) Rainy Days (day)
Station
5664
3363
1062
(b) Rainy Days Percentage (%)
Station
44 (%)
23 (%)
9 (%)
(c) Humid Percentage (%)
Station
13 (%)
7 (%)
0.1 (%)
(d) Extremely Humid RAI > 4
Station
12
6
1
(e) Very Humid 2 < RAI < 4
Station
52
26
0
(f) Humid 0 < RAI < 2
Station
382
192
2
0 60 120 240 360 480 Km

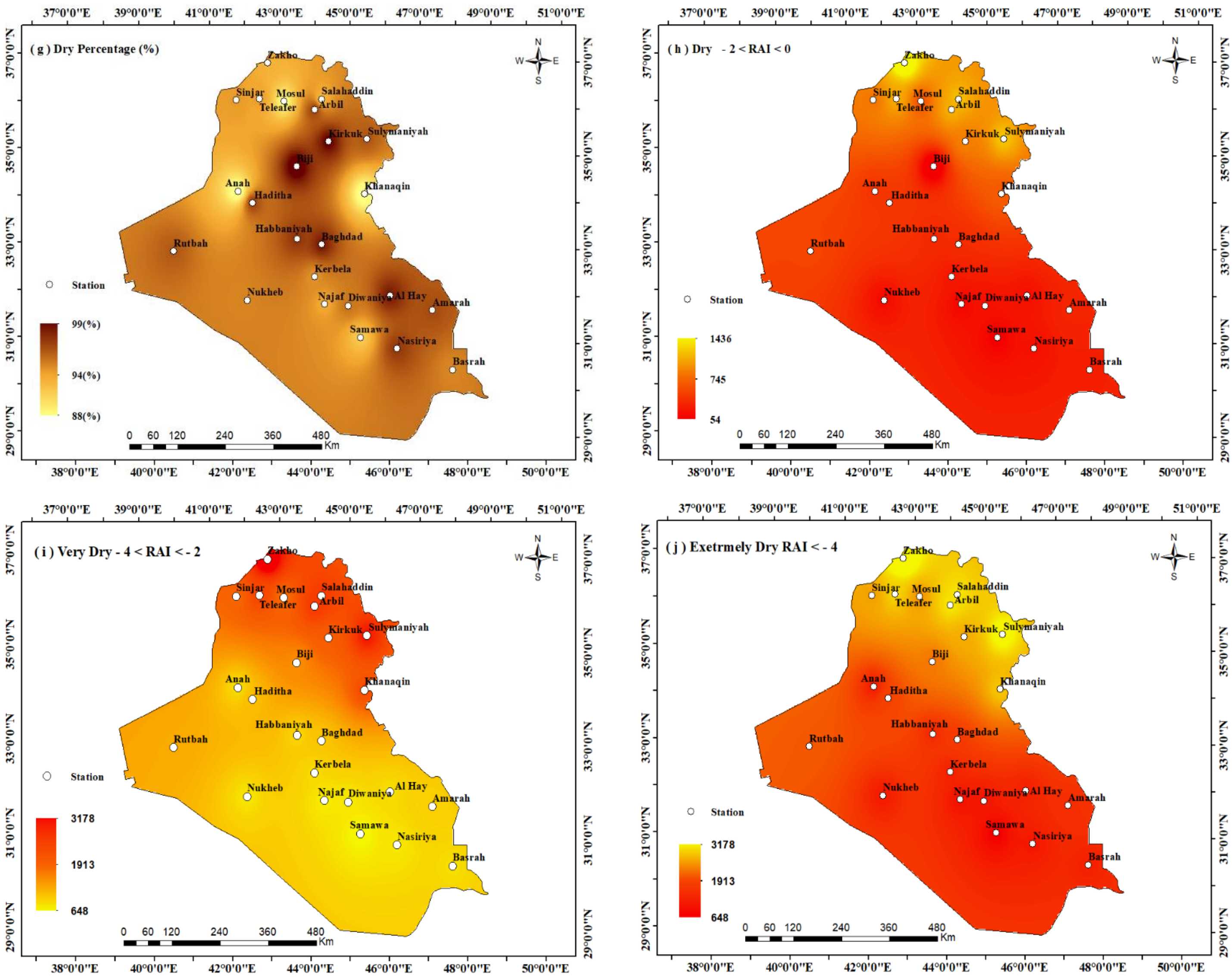


Fig. 1. The Spatial Distribution of Rainfall Anomaly Index (RAI) Classifications in Iraq.

- Extreme wet values are more common in northern Iraq.
- Rainfall amounts vary spatially and temporally in all of the 24 stations.
- The rainy season lasts from October to May, with Summer being the driest period.
- Zakho station is the most humid region based on RAI.
- Dry days are a negative anomaly even during rainy months, especially in Mosul.
- Rain anomalies in Iraq are linked to extreme climate globally.

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